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Characterization of the oceanic light field within the photic zone: Fluctuations of downward irradiance and asymmetry of horizontal radiance

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Characterization of the oceanic light field within the photic zone: Fluctuations of downward irradiance and asymmetry of horizontal radiance

A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy

in

Oceanography

by

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2016
The Dissertation of Ewa Gassmann is approved and is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2016
DEDICATION

Für meinen Martin.
# TABLE OF CONTENTS

Signature Page ................................................................. iii

Dedication ........................................................................ iv

Table of Contents ............................................................. v

List of Figures ..................................................................... vi

List of Tables ....................................................................... vii

Acknowledgements ............................................................ viii

Vita .................................................................................... xi

Abstract of the Dissertation ................................................ xii

Chapter 1  Introduction ....................................................... 1
  1.1 References ................................................................. 5

Chapter 2  Power spectral analysis of fluctuations in downward irradiance within the near-surface ocean under sunny conditions .................. 8
  2.1 Abstract ................................................................. 8
  2.2 Introduction ........................................................... 9
  2.3 Methods .................................................................. 11
    2.3.1 Data collection of downward plane irradiance ........... 11
    2.3.2 Power spectral analysis ....................................... 13
  2.4 Results and discussion ............................................... 16
    2.4.1 Dependence of irradiance fluctuations on collector size ..... 16
    2.4.2 Changes in irradiance fluctuations as a function of depth within 1 - 10 m (open ocean) .......................... 17
    2.4.3 Influence of solar zenith angle on irradiance fluctuations .... 19
    2.4.4 Influence of wind speed on irradiance fluctuations .......... 20
    2.4.5 Changes in irradiance fluctuations as a function of depth within 1 m (coastal waters) .................. 21
  2.5 Conclusions ............................................................ 23
  2.6 Acknowledgments ..................................................... 25
  2.7 References ............................................................. 38

Chapter 3  Spatiotemporal characteristics of wave-induced fluctuations in downward irradiance within the near-surface ocean under sunny conditions 41
  3.1 Abstract ............................................................... 41
  3.2 Introduction ........................................................... 42
3.3 Data and Methods ......................................................... 44
  3.3.1 Collection of field data ............................................. 44
  3.3.2 Statistical analysis of SQUID data .............................. 46
3.4 Results and Discussion .................................................. 48
  3.4.1 Statistical properties of irradiance fluctuations at different depths ................................................. 49
  3.4.2 Changes in irradiance fluctuations with solar zenith angle ...... 54
  3.4.3 Changes in irradiance fluctuations for different wind speeds ... 55
3.5 Conclusions ................................................................. 58
3.6 Acknowledgments .......................................................... 60
3.7 References ................................................................. 80

Chapter 4  Asymmetry of horizontal radiance within the solar principal plane in the upper ocean layer ......................................................... 83
  4.1 Abstract ........................................................................ 83
  4.2 Introduction .................................................................... 84
  4.3 Methods ....................................................................... 86
    4.3.1 Field measurements of horizontal radiance ................. 86
    4.3.2 Modeling of horizontal radiance ................................. 89
  4.4 Results and Discussion .................................................... 93
    4.4.1 Measured depth profiles and spectra of $L_{180}$, $L_0$, and $\gamma$ ......................................................... 93
    4.4.2 Simulated $L_{180}$, $L_0$, and $\gamma$ for the field stations ....... 96
    4.4.3 Generalized simulations of $L_{180}(\lambda)$ and $L_0(\lambda)$ .................. 100
  4.5 Conclusions ................................................................. 104
  4.6 Acknowledgments .......................................................... 107
  4.7 References ................................................................. 118

Chapter 5  Conclusions .......................................................... 122
| Figure 2.1 | Power spectral density (PSD) of irradiance fluctuations measured with cosine collectors. | 27 |
| Figure 2.2 | Power spectral density (PSD) of irradiance fluctuations measured at different depths. | 28 |
| Figure 2.3 | The depth dependence of the coefficient of variation (CV). | 29 |
| Figure 2.4 | The depth dependence of the peak frequency and their corresponding FWHM bandwidths. | 30 |
| Figure 2.5 | The depth dependence of the slope parameter for the high-frequency portion of irradiance PSDs. | 31 |
| Figure 2.6 | Power spectral density (PSD) of irradiance fluctuations measured at different solar zenith angles at near-surface depths. | 32 |
| Figure 2.7 | Power spectral density (PSD) of irradiance fluctuations measured at different wind speeds at depth of \( z \approx 1 \, m \) and two light wavelengths. | 33 |
| Figure 2.8 | The wind speed dependence of the coefficient of variation (CV) of the downward irradiance \((E_d)\). | 34 |
| Figure 2.9 | Power spectral density (PSD) of irradiance fluctuations measured at different depths. | 35 |
| Figure 2.10 | The depth dependence of the coefficient of variation (CV). | 36 |
| Figure 2.11 | Power spectral density (PSD) of irradiance fluctuations measured with 25 sensors of SQUID during the CAT experiment. | 37 |
| Figure 3.1 | Map showing the location of the experiment. | 61 |
| Figure 3.2 | The SeQuence of Underwater Irradiance Detectors (SQUID). | 62 |
| Figure 3.3 | Schematic configuration of the SQUID. | 63 |
| Figure 3.4 | Number of sensor pairs with the same sensor distance. | 64 |
| Figure 3.5 | Example of 1-s irradiance time-series data. | 65 |
| Figure 3.6 | Power spectral densities (PSDs) of \( E_d \) at \( \lambda = 532 \, nm \) at six different depths. | 66 |
Figure 3.7. The depth dependence of the coefficient of variation (CV) of $E_d$. 67
Figure 3.8. Spatial autocorrelation (SACs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of sensor distance. 68
Figure 3.9. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency and sensor distance. 69
Figure 3.10. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency. 70
Figure 3.11. Coherence lengths of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency for six depths. 71
Figure 3.12. Spatial autocorrelation (SACs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of sensor distance. 72
Figure 3.13. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency and sensor distance. 73
Figure 3.14. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency at nine different distances. 74
Figure 3.15. Coherence lengths of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency for relatively small (light blue) and relatively large (dark blue) solar zenith angles. 75
Figure 3.16. Spatial autocorrelation (SACs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of sensor distance for weak (1.8 $ms^{-1}$) and moderate (8 $ms^{-1}$) wind speeds. 76
Figure 3.17. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency and sensor distance for weak (1.8 $ms^{-1}$) and moderate (8 $ms^{-1}$) wind speeds. 77
Figure 3.18. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency at nine different distances for weak (1.8 $ms^{-1}$) and moderate (8 $ms^{-1}$) wind speeds. 78
Figure 3.19. Coherence lengths of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency for weak (light blue) and moderate (dark blue) wind speeds. 79
Figure 4.1. The radiometer used for underwater horizontal radiance measurements during a deployment. 109
Figure 4.2.  Results from measurements at the noon station. ..................... 110
Figure 4.3.  Results from measurements at the sunrise station. ............... 111
Figure 4.4.  Depth profiles of the asymmetry factor.  ......................... 112
Figure 4.5.  The asymmetry factor as a function of solar zenith angle. .... 113
Figure 4.6.  The asymmetry factor as a function of solar zenith angle at selected depths obtained from radiative transfer simulations. ............. 114
Figure 4.7.  Diffuseness of downwelling plane irradiance incident on the sea surface. ......................................................... 115
Figure 4.8.  The asymmetry factor, $\gamma$, as a function of solar zenith angle, $\theta$, at selected depths obtained from radiative transfer simulations. .... 116
Figure 4.9.  The asymmetry factor, $\gamma$, as a function of solar zenith angle, $\theta$, at selected depths for three different sky conditions obtained from radiative transfer simulations. ............................. 117
LIST OF TABLES

Table 4.1. Parameters of the five stations where the horizontal radiance measurements were conducted. ................................. 108
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ABSTRACT OF THE DISSERTATION

Characterization of the oceanic light field within the photic zone: Fluctuations of downward irradiance and asymmetry of horizontal radiance

by

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Dariusz Stramski, Chair

Two distinctive features of underwater light field in the upper ocean were examined: the wave-induced high-frequency light fluctuations within the near-surface layer under sunny skies, and the asymmetry of horizontal radiance within the photic layer of the ocean.

To characterize the spatiotemporal statistical properties of the wave-induced light fluctuations, measurements of downward plane irradiance were made with novel instrumentation within the top 10 m layer of the ocean at depths as shallow as 10 cm under sunny skies, different solar zenith angles, and weak to moderate wind speeds. It
was found that the maximum intensity of light fluctuations occurs at depths as shallow as 20 cm under the most favorable conditions for wave focusing, which correspond to high sun in a clear sky with weak wind. The strong frequency dependence of light fluctuations at shallow near-surface depths indicates dominant frequency range of $1 - 3 \, Hz$ under favorable conditions that shifts toward lower frequencies with increasing depth. The light fluctuations were found to be spatially correlated over horizontal distances varying from few up to $10 - 20 \, cm$ at temporal scales of $0.3 - 1 \, sec$ (at the dominant frequency of $1 - 3 \, Hz$). The distance of correlation showed a tendency to increase with increasing depth, solar zenith angle, and wind speed. The observed variations in spatiotemporal statistical properties of underwater light fluctuations with depth and environmental conditions are driven largely by weakening of sunlight focusing which is associated with light scattering within the water column, in the atmosphere and at the air-sea interface.

To investigate the underwater horizontal radiance field, measurements of horizontal spectral radiance in two opposite directions (solar and anti-solar azimuths) within the solar principal plane were made within the photic layer of the open ocean. The ratio of these two horizontal radiances represents the asymmetry of horizontal radiance field. In addition to measurements, the radiative transfer simulations were also conducted to examine variations in the asymmetry of horizontal radiance at different light wavelengths as a function of solar zenith angle at different depths within the water column down to 200 m. It was demonstrated that the asymmetry of horizontal radiance increases with increasing solar zenith angle, reaching a maximum at angles of $60^\circ - 80^\circ$ under clear skies at shallow depths ($1 - 10 \, m$). At larger depths the maximum of asymmetry occurs at smaller solar zenith angles. The asymmetry was also found to increase with increasing light wavelength. The results from radiative transfer simulations provided evidence that variations in the asymmetry with solar zenith angle are driven largely by the diffuseness of light incident upon the sea surface and the geometry of illumination of the sea surface,
both associated with changing position of the sun.

In addition to contributions to the field of ocean optics, the findings of this dissertation have relevance for oceanic animal camouflage and vision as well as photosynthesis and other photochemical processes.
Chapter 1
Introduction

The sunlight propagating from air into water undergoes several different processes at the air-water interface that affect the underwater light field. One of them is the focusing and defocusing of direct sunlight after differential refraction of the sun rays by the dynamic sea surface. Ocean surface waves act like lenses creating a complex optical field whose brightness increases and decreases as each wave passes by. However, a number of interacting processes associated with changes in surface curvature, slope, and elevation are responsible for these wave-induced light fluctuations. Such a complex optical light field within the near-surface ocean becomes a challenging environment for marine organisms to live in. Visual predation common in many of the near-surface species becomes extremely difficult as well as the ability to avoid detection where there are no physical objects to hide within or behind [McFarland and Loew, 1983; McFarland, 1991; Johnsen, 2014].

To survive many aquatic animals had to adapt to the dynamic properties of underwater light field within the upper layer of the ocean. This need led to the evolution of various strategies of camouflage and viewing [Johnsen and Sosik, 2003]. Despite the difficulties of the camouflage under fluctuating light conditions, some animals (like cephalopods) are excellent in responding to changes in both background pattern and illumination [Hanlon and Messenger, 1996; Hanlon, 2007; Hanlon at al., 2009]. Their
abilities extend even beyond brightness matching, and sometimes include matching the spectral and angular distribution of ambient light. There are animals, such as pelagic fishes, whose camouflage specifically relies on a horizontal radiance distribution around the vertical axis [Denton, 1970; Johnsen and Sosik, 2003]. Because of the temporal and spatial complexity of the overhead light field within the surface layer of the ocean, the optical background is very complicated for viewers trying to detect predators or prey from below, which led to adaptation of the horizontal viewing common among near-surface organisms [Johnsen and Sosik, 2003]. Furthermore, many shallow water fish species developed the capability of ultraviolet horizontal vision [Losey et al., 1999; Johnsen and Widder, 2001; Leech and Johnsen, 2003].

The wave-induced fluctuations of underwater light have been investigated over past few decades. The mechanism of fluctuations under sunny conditions has been addressed in a number of studies [e.g., Schenck, 1957; Snyder and Dera, 1970; Stramski and Dera, 1988]. The environmental conditions favoring the most intense fluctuations in downward irradiance within the near-surface ocean under sunny skies and the dependence of fluctuations on depth and environmental factors have been characterized [Dera and Stramski, 1986; Stramski, 1986a, 1986b]. However, only measurements of downward plane irradiance with a single sensor at a single point were included in these earlier studies, primarily because of technological and logistical limitations. As a result only the temporal statistics of the light fluctuations could be examined. In addition, the earlier studies on strong near-surface fluctuations were devoted mostly to the characterization of the statistics of wave-focusing events referred to as light flashes. The earlier analyses of other statistics, such as power spectra, were limited in a sense that relatively few studies reported on these statistics, and such data are particularly limited and fragmentary for the shallow depths within the near-surface ocean layer where the fluctuations are strongest [Gordon et al., 1971; Nikolaev et al., 1972; Li, Solovev and Tolkachenko,
Another limitation in the present characterization of wave-induced light fluctuations is associated with spatial statistical properties of these fluctuations. Probably because of the operational difficulty in measuring the spatial properties of fluctuating light field, especially near the sea surface, only one study presented preliminary data on that subject [Fraser et al., 1980]. Therefore, the knowledge of the spatial statistics of the underwater light field has remained very limited. It is noteworthy that this gap in knowledge has special significance considering the fact that the small-scale spatial structures of the wave-focusing events are likely relevant to the size of animals and their camouflage strategies.

Despite the significance for underwater camouflage and vision of animals, the horizontal radiance and its asymmetry around the vertical axis were little investigated. It has long been known that in the upper layers of the ocean the radiance distribution is dominated by direct sunlight, and as the depth increases the light field has a more diffuse character [Tyler, 1958]. It has been also known that the underwater light field eventually becomes symmetric around the vertical axis with increasing depth, regardless of the solar zenith angle [Jerlov, 1976 and Mobley, 1994]. While angularly resolved radiance measurements at shallow depths have been made [Jerlov and Fukuda, 1960; Voss, 1989; Wei et al., 2012; Antoine et al., 2013; Smith, 1974; McFarland, 1991] no study has focused specifically on horizontal radiance and its asymmetry around the vertical axis. Previous investigations of animal camouflage as a response to the dynamic variations of the light field have been also limited. Studies have been done under essentially static conditions that constitute an unrealistic representation of the actual dynamic optical environment [Hanlon and Messenger, 1988; Hanlon, 2007; Kelman et al., 2008; Osorio and Cuthill, 2013]. However, the effects of horizontal radiance asymmetry on the camouflage of silvery-sided pelagic fish have been recently examined [Johnsen et al., 2014]. Whereas this study included some data that are presented in this dissertation,
the underlying mechanisms affecting this asymmetry were not specifically investigated and the results were limited to the visible region of light spectrum.

The underlying goal of this dissertation is to advance the knowledge of two distinctive aspects of underwater light field in the upper ocean, first the wave-induced irradiance fluctuations within the near-surface layer under sunny conditions, and second, the asymmetry of horizontal radiance field within the oceanic photic layer. In chapter 2 the power spectra of irradiance fluctuations are presented and discussed using the field data. In chapter 3 the field data are used to present and discuss the spatial and temporal statistical characteristics of fluctuations. The statistical properties of fluctuations are examined for different depths within the near-surface ocean under various environmental conditions, especially the solar zenith angle and wind speed. In chapter 4 both the field data and modeling results from radiative transfer simulations are used to examine the asymmetry of horizontal radiance around the vertical axis. This feature of light field is examined throughout the water column within the photic layer across the near-UV and visible spectral ranges. The findings presented in this dissertation reveal novel insights into dynamic near-surface underwater light field and horizontal radiance field within the upper ocean. These advances in our knowledge contribute to better understanding of the optically complex environment which has potential significance in the context of important photochemical processes that take place in the upper ocean (e.g., photosynthesis, and photooxidation of organic matter) and the behavior, camouflage, and vision of aquatic animals that inhabit the upper ocean.
1.1 References


Stramski, D., and J. Dera (1983), Statistical analysis of the underwater irradiance fluctuations recorded in the near-shore zone of the Black Sea (In Polish), Studia i Materiay Oceanologiczne, 41, 63-87.


Chapter 2

Power spectral analysis of fluctuations in downward irradiance within the near-surface ocean under sunny conditions

2.1 Abstract

To quantify the dynamic characteristics of large, near-surface fluctuations caused by the focusing of sunlight by sea surface waves, power spectra of underwater irradiance fluctuations are analyzed using data collected with specially developed instruments, the Underwater Porcupine Radiometer System and the SeQuence of Underwater Irradiance Detectors (SQUID). The Porcupine instrument measures the downward plane irradiance at several light wavelengths with a sampling frequency of 1 kHz and a 2.5 mm diameter collector, which is required to resolve the temporal and spatial scales of wave focusing events occurring at near-surface depths under sunny conditions. The SQUID instrument measures the downward plane irradiance with the same high sampling frequency of 1 kHz and 2.5 mm diameter collector, but at a single light wavelength ($\lambda = 532 \text{ nm}$). Time series of irradiance were collected in the upper 10 m of the water column at four sites in the Pacific and Mediterranean. Power spectra of irradiance demonstrate significant decreases
in both the overall magnitude and high-frequency portion with increasing depth, and with increasing solar zenith angle. An increase in wind speed, accompanied by increasing surface roughness also results in weakening of wave focusing. The effect of collector size of the irradiance sensor on power spectra of light fluctuations is also demonstrated.

2.2 Introduction

Under sunny conditions the underwater light field within the near-surface ocean shows large fluctuations, which are produced by focusing and defocusing of direct sunlight by surface waves [e.g., Schenck, 1957; Snyder and Dera, 1970; Stramski and Dera, 1988; Zaneveld et al., 2001a]. Because the fluctuations produce the highest transient intensities of solar energy in nature, they are of interest for various problems in aquatic sciences, such as modeling and measurements of light fields within and leaving the ocean [Zaneveld et al., 2001a, 2001b; Zibordi et al., 2004; You et al., 2010], as well as ecophysiology of marine life [e.g., Dera et al., 1975; McFarland, 1983; Green and Gerard, 1990; Stramski et al., 1993; Johnsen, 2005]. For example, the underwater light field variability controls growth and cellular physiology of phytoplankton. The wave-induced fluctuations in downward irradiance within near-surface ocean depend on several interacting processes related to the focusing and defocusing of the sunlight [Dera and Stramski, 1986; Stramski, 1986a, 1986b; Stramski and Dera, 1988; Darecki et al., 2011], including changes in atmospheric conditions, the sea surface wave field, and the inherent optical properties (IOP) of water. Specially designed radiometers, data acquisition systems and sampling strategies are required to fully resolve these focusing effects and to ensure the adequacy of collected data for the characterization of high frequency light fluctuations.

Work over the past decades has significantly advanced the study of the underwater downward irradiance fluctuations. The largest fluctuations in downward irradiance are
created near the surface in clear waters under sunny skies with high sun altitude and medium wind speed [Schenck, 1957; Snyder and Dera, 1970; Dera and Stramski, 1986; Stramski, 1986a, 1986b].

When the solar zenith angle or wind speed increases, the intensity of the fluctuations decreases [Dera and Stramski, 1986; Stramski, 1986a, 1986b]. The focusing effect of direct sun rays refracted by surface waves decreases with increasing depth as a result of scattering within the water column [Snyder and Dera, 1970; Gordon et al., 1971; Nikolaev et al., 1977; Dera and Olszewski, 1978; Fraser et al., 1980; Dera and Gordon, 1986]. More recently Gernez et al. [2011] observed large vertical changes in the probability distribution of the fluctuating near-surface downward irradiance under sunny conditions. Near the surface the probability distribution is highly skewed and heavy-tailed because of the intense light flashes caused by surface-wave focusing, tending towards a more symmetrical (normal) distribution with increasing depth as the intensity of the fluctuations decreases. In contrast to studies of the fluctuations in intensity, the frequency content of the fluctuations has not been well explored, especially at shallow depths where the fluctuations are largest, except for a few studies with very limited discussions of power spectral analysis [Gordon et al., 1971; Nikolaev et al., 1972; Li, Solovev and Tolkachenko, 1975; Jakubenko and Nikolaev, 1977; Dera and Olszewski, 1978; Stramski and Dera, 1983]. These investigations briefly discussed the relationship between the shape of the spectra of irradiance fluctuations measured at different depths, as well as different solar elevation, and their power spectral density functions. However, considering the complexity of the phenomena, the power spectral analysis was very limited and more detailed examination of the frequency content of the fluctuations under different conditions is required to fully quantify the dynamic characteristics of those fluctuations.

In this paper we investigate the frequency dependence of underwater light fluc-
tuations. We describe the power spectra of wave-induced fluctuations in downward irradiance within near-surface ocean under sunny conditions calculated for 10 min time-series of data collected with two newly developed instruments, the Underwater Porcupine Radiometric System [Darecki et al., 2011] and the SeQuence of Underwater Irradiance Detectors (SQUID). Both instruments provide a unique capability for resolving the short temporal and small spatial scales of the irradiance fluctuations caused by surface waves within the top 10 m of water column. We quantify the effect of collector size of the irradiance sensor and the impact of different depths on the measured fluctuations. In addition, we discuss the influence of different environmental conditions, like solar zenith angle and wind speed, on the fluctuations. And finally, because very little research has been conducted on the influence of the light’s wavelength on the irradiance fluctuations, we investigate the wavelength dependence of their power spectra.

2.3 Methods

2.3.1 Data collection of downward plane irradiance

The irradiance data were measured with two specially developed instruments, the Underwater Porcupine Radiometer System [Darecki et al., 2011] and the SeQuence of Underwater Irradiance Detectors (SQUID). The Porcupine instrument consisted of 7 downward plane irradiance sensors that collected data at light wavelengths $\lambda = 365, 410, 443, 488, 532, 610$, and 670 nm, which are the center light wavelengths of their interference filters. The SQUID instrument is an improved version of the Porcupine and was equipped with 25 downward plane irradiance sensors (minimized version of the Porcupine sensors) positioned at different distances from one another along a 2.5 m long linear array and collected data at one light wavelength $\lambda = 532$ nm. All irradiance sensors were supplied with a cosine collector 2.5 mm in diameter as a standard one, which is
required to adequately resolve the small spatial scales of wave focusing at near-surface depths under sunny conditions [Dera and Gordon, 1968; Dera and Stramski, 1986]. The time-series data of wave-induced fluctuations in downward plane irradiance, $E_d(t)$, were collected during four field experiments in the Pacific and Mediterranean, three as part of the project ‘Radiance in a Dynamic Ocean’ (RaDyO), one as part of the project ‘Dynamic Camouflage in Benthic and Pelagic Cephalopods: An Interdisciplinary Approach to Crypsis Based on Color, Reflection, and Bioluminescence’ (within the Department of Defense Multidisciplinary University Research Initiative (MURI) Program). The RaDyO experiments were conducted in open ocean waters: in the Santa Barbara Channel (SBC) in September 2008 and south of the Hawaiian Islands (HAW) in September 2009, as well as in coastal waters of the northern Adriatic Sea 16 km off the coastline of Venice, Italy (VEN) in June 2009. The SBC experiment was conveyed at a fixed location at $34^\circ20.53'\ N$ and $119^\circ62.88'\ W$, where the water depth was 170 m. The HAW experiment was carried out along a track covering a distance of over 500 km, where water depth exceeded 4000 m. During those RaDyO experiments the Porcupine instrument was deployed from the Floating Instrument Platform (R/P FLIP). The experimental site in the Adriatic Sea was located at $45^\circ18.8'\ N$ and $12^\circ30.5'\ E$, where water depth was 16 m. The Porcupine instrument was deployed from the Aqua Alta Oceanographic Tower (AAOT). Both R/P FLIP and AAOT provided a stable platform, minimizing variations in depth of the instrument relative to the mean sea surface level and perturbation of the surface wave field by the platform. However, even with such a stable platforms we were not able to collect data within the top 1 m of the water column; instead we measured the fluctuations within $\approx 1 - 10 \ m$ layer depth. The measurements at shallower depths (within top 1 m) were conducted during the fourth experiment (MURI) in the near-shore waters in semi-closed bay of the Catalina Island (CAT) at the USC Wrigley Marine Science Center in September – October 2011, where both instruments, Porcupine and
SQUID, were deployed next to each other on the shallow ocean floor with water depth of $\approx 2\ m$ ranging from about 0.1 to 3 m due to changes in tide level at a distance of $\approx 10\ m$ from the shore. This special set up enabled unique measurements of the top 1 m layer with accuracy in the order of few centimeters. The linear array of SQUID was kept parallel to the sea surface and was oriented perpendicular to the direction of the surface waves by using an electric rotator. SQUID and Porcupine were equipped with a pressure sensor for measuring the depth of each of the instruments.

All the time-series data were collected in 10 min long intervals sampled at 1 kHz. This high sampling frequency of the instruments is necessary for resolving temporal scales of fluctuations, as the shortest duration of light flashes associated with wave-focusing events is on the order of milliseconds [Dera and Olszewski, 1978; Dera and Stramski, 1986; Stramski, 1986a]. The 10 min length of time-series is appropriate for characterizing the statistical properties of the fluctuations, because it is long enough to collect sufficient data for statistical analyses of fluctuations and short enough to minimize the possible effects caused by changes of environmental conditions. The measurements of the irradiance were performed under sunny sky conditions at near-surface depths, as well as various solar zenith angles and different wind speeds.

### 2.3.2 Power spectral analysis

Power spectral analysis was performed on time-series of downward plane irradiance. To prepare the data for the power spectral analysis, for every time-series measurement of 10 min duration, 10 values of time-averaged irradiance $\bar{E}_d$ were computed. The first value of $\bar{E}_d$ was calculated by averaging the $E_d(t)$ data over the first 1.5 min of the measurement from $t = 0\ min$ to $t = 1.5\ min$. The second value of $\bar{E}_d$ was calculated by averaging data collected over 2 min between $t = 0.5\ min$ and $t = 2.5\ min$, the third value by averaging between $t = 1.5\ min$ and $t = 3.5\ min$, etc. until the 10th value
based on averaging the $E_d(t)$ data between $t = 8.5\ min$ and $t = 10\ min$. These 10 average values are assumed to be representative of the time-averaged $\overline{E}_d$ for ten consecutive 1 $\min$ intervals within the 10 $\min$ period of measurement. This time-averaging method of the irradiance data was used to minimize the potential nonstationarity of the average irradiance during the 10 $\min$ period of the measurement. The averaging intervals of 1.5 or 2 $\min$ provide the best compromise in a sense that the intervals are short enough to minimize the potential nonstationary trends in $\overline{E}_d$ but still long compared to the longest components of the surface wave field. Then, for the set of ten $\overline{E}_d$ values for each 10 $\min$ measurement of $E_d(t)$, time-series of normalized downward irradiance, $E_d(t)/\overline{E}_d$ were computed.

For the normalized irradiance data the power spectral density (PSD) function was calculated with Welch’s averaging method [Welch, 1967] by splitting up the 10 $\min$ time-series into segments with a length of 212 (4096) data points, which overlapped each other by 50%. Each segment was multiplied by a Hamming window and then a 4096-point long Fast Fourier Transform (FFT) was applied to each segment. Finally, averaging over the set of FFTs of each segment formed the power spectral density. The upper limit of the frequency range of each PSD is $500\ Hz$ due to the sampling frequency of 1 $kHz$. However, we often do not show PSDs with the full frequency range because of the elevated instrument noise level at higher frequencies. The highest frequency at which a PSD is not dominated by instrument noise, $f_{\text{max}}$, is determined when the slope of the PSD starts to flatten. The values of each PSD at all frequencies greater than $f_{\text{max}}$ are omitted from the analysis.

The peak frequency, $f_{\text{peak}}$, and slope parameter of each PSD were estimated. $f_{\text{peak}}$ is defined as the frequency of the maximum PSD value. An exponential function of the form $ae^{-bx}$ was fitted to the $f_{\text{peak}}$ data with $a = 1.7762$ and $b = 0.1560$. The slope of each PSD was calculated by applying linear regression of log-transformed data with the
frequency interval ranging from $f_{\text{peak}} + \Delta f$ to $f_{\text{max}}$. The frequency range was selected on a case-by-case basis to ensure that the PSD function satisfies a power function with a single slope within this range. In addition, the coefficient of variation, CV, of irradiance was obtained from the ratio of the standard deviation, $\sigma_E$, to the mean of the irradiance data, $\bar{E}_d$. To investigate the influence of the light wavelength, $\lambda$, light wavelengths of $\lambda = 443$, 532 and 670 nm were selected (from SBC and HAW measurements) to cover most of the visible light spectrum.

To support the analysis of irradiance fluctuations, ancillary data including the inherent optical properties (IOPs) of water and wind speed were also collected. To measure IOPs different commercial in situ instruments were used. During the SBC experiment the IOP measurements were conducted from the R/P FLIP using the ac-s in situ spectrophotometer (WET Labs, Inc.). During the HAW experiment an ac-9 absorption and attenuation meter (WET Labs, Inc.) was used from the R/V Kilo Moana, which operated within 1 – 2 km of the R/P FLIP. During the VEN experiment an ac-9 was deployed from the AAOT. During the CAT experiment a C-Star transmissometer (WET Labs, Inc.), together with HydroScat-6 (HOBI Labs, Inc.) and LISST-100X (Sequoia Scientific, Inc.) were deployed from a dock. The approximate range of the total beam attenuation coefficient of the seawater at 555 nm, $c(555)$, measured at near-surface depths at the four experimental sites was $0.55 – 1.03$, $0.07 – 0.12$, $0.31 – 0.94$ and $0.26 – 1.08$ m$^{-1}$ for the SBC, HAW, the VEN and CAT respectively. Wind speed data were measured using anemometers mounted also on the platforms: during the SBC experiments on the R/P FLIP at a height of about 10.5 m above sea level and about 13 m in HAW. During the VEN experiment the anemometer was mounted on the AAOT at about 15 m above sea level. During the CAT experiment the wind speed was measured at about 5 m above sea level. For the analysis, the 10 min time-averaged wind speed data that corresponded to the 10 min time-series measurement of downward plane irradiance
were used. In addition, solar zenith angle was estimated for the start time of each 10 min time series using the Astronomy Application site of the U.S. Naval Observatory (http://aa.usno.navy.mil/), based on the location and time of the measurement.

2.4 Results and discussion

2.4.1 Dependence of irradiance fluctuations on collector size

It has long been known that size of the collector of the irradiance sensor has a large influence on the statistical properties of the fluctuations [Dera and Gordon, 1968; Dera and Stramski, 1986]. Light caustics produced by wave focusing of sunlight can become as small as millimeters near the sea surface, requiring a similarly small irradiance collector to resolve the spatial scales of the fluctuations.

The effects of collector size analysis were explored during the VEN experiment, in which six different sizes of irradiance sensors were used with an interference filter centered at 532 nm. For all collectors and both depths the PSD functions have similar shapes, with high values for the lower frequencies, a maximum located at frequencies between 1 and 2 Hz and dramatic decrease by approximately 5 orders of magnitude (with different slopes for different collector size) for the higher frequencies (Fig. 2.1). The signal obtained with the 2.5 mm collector has the highest values of the PSD; the magnitude of the PSD decreases faster for larger collectors, because the collector is essentially a spatial integrator. This effect is well pronounced near the surface, where the light beams are sharply focused (Fig. 2.1a), and decreases with depth (Fig. 2.1b). As the path length within the water column increases the intensity of the fluctuations weakens. The 2.5 mm size of the irradiance collector represents the best compromise for the collector being as small as possible for adequately resolving the small spatial scales of light fluctuations while still ensuring the collection of sufficient photons to record a
signal. This conclusion is consistent with earlier work [Dera and Gordon, 1968; Dera and Stramski, 1986; Darecki et al., 2011].

2.4.2 Changes in irradiance fluctuations as a function of depth within 1 - 10 m (open ocean)

Open ocean data from SBC and HAW experiments (RaDyO) were selected to examine the dependence of irradiance fluctuations on depth. The data were collected within 0.8 – 10 m layer of water column. In both locations measurements were conducted under high Sun ($\theta_s = 30^\circ - 45^\circ$). The wind speed ranged from $W \approx 4.1 \text{ ms}^{-1}$ to $W \approx 6.4 \text{ ms}^{-1}$. The PSD values decrease as the depth increases for the SBC (Fig. 2.2a, 2.2b, 2.2c), as well as for HAW (Fig. 2.2d, 2.2e, 2.2f) for three light wavelengths. The PSDs differ by approximately 4 orders of magnitude with increasing frequency, from around $10^{-2}$ (in relative units) for the low frequencies to around $10^{-6}$ (in relative units) for the higher frequencies. The significant decrease of the intensity of irradiance fluctuations with increasing depth most pronounced at high frequencies can be attributed to a decrease in the efficiency of wave focusing with depth due to light scattering within the water column. With increasing depth, the path length of sunlight underwater increases, causing an increase of the amount of light scattered over it. This general observation of changes in irradiance fluctuations as a function of depth agrees with previous studies [Schenck, 1957; Prokopov et al., 1975; Nikolaev et al., 1977; Jakubenko and Nikolaev, 1977; Jakubenko and Nikolaev, 1978; Nikolaev and Jakubenko, 1978; Dera and Stramski, 1986; Stramski, 1986a, 1986b; Darecki et al., 2011]. The depth dependence of irradiance fluctuations is also apparent in the coefficient of variation, CV, which is a simple proxy for the intensity of fluctuations. The CV of downward irradiance at three light wavelengths for time-series data corresponding to PSDs from the two experiments SBC and HAW is shown in Figure 2.3. The CV is in excess of 50% within the first 1 m layer of the ocean and decreases
rapidly with increasing depth for the SBC. The decrease is nearly exponential, resulting in the drop of the CV down to less than 10% at depths of 6 – 8 m, depending on light wavelength. It occurs primarily as a result of light scattering over increasing path length in the water column. For HAW there is no such significant decrease of the coefficient; however, the trend is still pronounced. The CV ranges from 25% to 50% within the 5 m layer of the ocean and shows a decrease with increasing depth. The differences between the SBC and HAW can be attributed to differences in water clarity, and possibly also sea surface conditions. The nearly exponential shape of the CV was documented previously by Li et al. [1975], though he presented it for deep-water data, without investigating the top 10 m in the water column. In addition, we observed changes in the 1 – 10 m layer depth-dependence CV within the spectral range of light wavelength, indicating lower values of the coefficient at blue wavelengths relative to the red light for both locations (SBC and HAW). This spectral effect occurs because the blue light entering the water is more diffuse relative to the red light and wave focusing is less effective when the light is more diffuse [Stramski, 1986b; Dera and Stramski, 1986]. The significantly higher CV values of the red light in HAW confirm higher clarity of the water there, compared to SBC.

At shallow near-surface depths the peak frequency, $f_{\text{peak}}$, at which the major maximum of PSD occurs, is located at frequencies between 1 and 2 Hz (Fig. 2.4). With increasing depth below a few meters the maximum shifts toward lower frequencies, approaching 0.5 Hz. According to Figure 2.4 the exponential fit suggests that the peak frequency decreases exponentially with increasing depth below approximately 1 m. The effect of dampening high frequencies occurs for both locations (SBC and HAW) for three different light wavelengths ($\lambda = 443, 532$ and 670 nm) and demonstrates significant decrease in intensity of irradiance fluctuations with increasing depth, due to a decrease in the efficiency of wave focusing with increasing depth caused by light scattering
within the water column. In addition, it manifests the weakening effect of irradiance focusing by the shorter in length surface waves with increasing depth. Longer surface waves have significantly deeper focal depth, leading to fluctuations at lower frequencies [Schenck, 1957; Snyder and Dera, 1970; Stramski and Dera, 1988; Zaneveld et al., 2001a]. With increasing depth below a few meters the value of the slope parameter of the irradiance PSDs decreases and the spectra exhibit steeper slopes at high frequencies due to weakening of the wave focusing (Fig. 2.5), especially for the shorter surface waves. This trend is observed for data sets from both experiments (SBC and HAW) for three light wavelengths ($\lambda = 443, 532$ and $670 \text{ nm}$).

### 2.4.3 Influence of solar zenith angle on irradiance fluctuations

The irradiance data set collected over a broad range of solar zenith angle during SBC and HAW (RaDyO) experiments allowed to use power spectral analysis to analyze the influence of Sun’s position on the underwater fluctuations. We examined data acquired near the surface in the SBC ($z = 1 \text{ m}$) and in HAW ($z = 1.5 \text{ m}$) under moderate wind speed ($W \approx 7 \text{ ms}^{-1}$ in SBC and $W \approx 10 \text{ ms}^{-1}$ in HAW). The solar zenith angles ranged from $\theta_s \approx 13^\circ$ to $\theta_s \approx 70^\circ$. For both locations the magnitude of PSDs decreases by approximately 5 orders of magnitude with increasing solar zenith angle (Fig. 2.6), due primarily to light scattering during the increasing path length through the atmosphere: the lower the Sun’s position, the longer the path length of light travelling between the Sun and the water surface. This leads to an increase in the diffuseness of irradiance incident on the ocean surface, which weakens the effects of wave focusing. A similar decline of the magnitude of the PSDs was documented in previous studies [Dera and Olszewski, 1978; Nikolaev et al., 1972], though these studies did not note other changes in the pattern of the PSD. In contrast, we observed a significant decrease of the PSD slope as the solar zenith angle increased, leading to spectra having steeper slopes at high
frequencies. Again, this is due to weakening of the wave focusing with increasing solar zenith angle.

### 2.4.4 Influence of wind speed on irradiance fluctuations

Data from the SBC and HAW were used to investigate the effect of wind speed on the irradiance fluctuations. At both locations the data were collected at depth of $z \approx 1 \, \text{m}$. The solar zenith angle ranged from $\theta_s \approx 30^\circ$ to $\theta_s \approx 69^\circ$ and the wind speed varied between $W \approx 4 - 10 \, \text{ms}^{-1}$. With an increase of the wind speed, and consequently an increase of sea surface roughness, the magnitude of the PSDs decreases by approximately 4 orders for both locations (Fig. 2.7). The decrease with wind speed is not as great as it was with depth (Fig. 2.2); however, it demonstrates that wave focusing effects decrease with increasing wind speed due to a more complex sea state and multiple different narrower surface waves' spectra [e.g., Schenck, 1957; Snyder and Dera, 1970; Stramski and Dera, 1988; Zaneveld et al., 2001a]. Based on our results, the strongest focusing of the sunlight by surface waves at $z \approx 1 \, \text{m}$ depth occurred for winds $W \approx 5 \, \text{ms}^{-1}$. This conclusion is consistent with earlier studies, which indicated that the most favorable conditions for wave focusing occur under relatively weak winds and that the efficiency of wave focusing decreases with increasing roughness of sea surface under stronger winds ($> 5 \, \text{ms}^{-1}$) [Dera and Stramski, 1986; Stramski, 1986a].

The wind-speed dependence of irradiance fluctuations is also apparent in the CV of downward irradiance (Fig. 2.8). For the SBC the CV is in excess of 50% for relatively weak wind ($\approx 5 \, \text{ms}^{-1}$) and decreases strongly to $\approx 20\%$ with increasing wind speed. This drop occurs primarily because of the weakening effect of the wave focusing with increasing wind speed. Though there are fewer data points for HAW, the decrease of the CV with increasing wind speed can still be observed. The differences between the locations can be explained with differences in water clarity and possibly sea surface
conditions. We also observed changes in the wind-speed dependence of CV with different wavelengths of irradiance. At both locations lower values of the CV were seen at blue wavelengths compared to the red light wavelengths, indicating greater diffuseness of the blue light relative to the red light, leading again to less effective wave focusing. The significantly higher CV values of the red light in HAW confirm higher clarity of the water there, compared to SBC.

2.4.5 Changes in irradiance fluctuations as a function of depth within 1 m (coastal waters)

Whereas the general pattern of depth dependence of wave-induced irradiance fluctuations was documented in a number of previous studies [e.g., Dera and Gordon, 1968; Snyder and Dera, 1970; Nikolaev et al., 1977; Fraser et al., 1980], there is very little published information about the irradiance fluctuations at depths smaller than 1 m, and essentially no published data on fluctuations within the top 0.5 m of the ocean [Dera, 1970; Snyder and Dera, 1970; Jankowski, 1974; Stramski and Dera, 1983]. The special set up used during the CAT experiment, described in ’Data and Methods’ section, enabled unique shallow depths measurements with accuracy in the order of few centimeters and with coverage of the top 1 m of water column, complementing the measurements of \( z \approx 1 - 10 \) m layer investigated in RaDyO experiments (subsection 2.4.2). We conducted the measurements under clear sky with solar zenith angle of \( \theta_s = 38^\circ - 69^\circ \) for very low wind speeds (below 5 m\(s^{-1}\)), acquiring data suitable for examining the fluctuations of downward irradiance induced by surface waves in near-shore waters of a semi-closed bay.

For all depths and wind speeds the PSD functions have similar shapes: high values for the lower frequencies decreasing with increasing frequency after a peak frequency, \( f_{\text{peak}} \), which is in order of couple of Hz (Fig.2.9). However, the values of the PSDs at
wind speeds of $W \approx 1.8\ ms^{-1}$ and $W \approx 0.9\ ms^{-1}$ have lower levels compare to PSDs for winds speeds higher than $W \approx 3.5\ ms^{-1}$ for frequencies up to 60 $Hz$. For wind speed lower than $W \approx 1.8\ ms^{-1}$ the level of the PSDs (Fig. 2.9, dashed lines) within top 20 cm of water column changes significantly with changing depth, but is actually driven by the wind speed. The PSD for wind $W \approx 0.9\ ms^{-1}$ at 0.15 $m$ depth is at all frequencies at least 1 order of magnitude lower than the PSD for wind $W \approx 1.8\ ms^{-1}$ at 0.2 $m$ depth. As the wind speed increases approaching $W \approx 5\ ms^{-1}$ the PSD values increase, because the relatively weak wind of $W \approx 5\ ms^{-1}$ is favorable to strong wave focusing (section 2.4.4). This dependence has been observed before at a fixed depth only [Dera and Stramski, 1986; Stramski, 1986a, 1986b], in contrast, we discovered that it is true as well for the shallow depths within the top 1 $m$ layer of water column.

In addition, the major maximum of the PSDs is pronounced much stronger for the wind speeds below $2\ ms^{-1}$ due to calmer sea state with one main slope and wider spectra of surface waves [Cox and Munk, 1954]. For wind speeds of $W \approx 3.6 - 4.9\ ms^{-1}$ the PSDs decrease faster for increasing depth with increasing frequency (Fig. 2.9, solid lines). However, the existence of maximum PSD for the preferable wind speed ($W \approx 5\ ms^{-1}$) is not clear, but it might be as shallow as 10 – 50 cm. The small difference in value between those PSDs can be attributed to the small range of depth (short layer of water column) that does not affect the efficiency of wave focusing due to light scattering within the water column. The depth dependence of irradiance fluctuations within the top 1 $m$ layer of the ocean is also pronounced in the CV (Fig.2.10). For the CAT the CV values at wind speed of $W \approx 5\ ms^{-1}$ exceed 50% for the data measured with SQUID as well as with Porcupine. There is a broad maximum of the coefficient at the very shallow depths of 10 – 50 cm confirming shallow maximum of the fluctuations that cannot be specified clearly. The CV for SQUID together with CV for Porcupine measurements (both for wind speed of $W \approx 5\ ms^{-1}$) present decrease of the fluctuations with increasing depth.
On the other hand, for the wind speed $< 2 \, ms^{-1}$ the CV has much lower values as they represent less favorable conditions for the focusing. The lower the wind speed the calmer the sea surface that leads to weakening of the focusing by the surface waves [Cox and Munk, 1954], that effects even as shallow as $10 – 40 \, cm$ depths. For SQUID the CVs of the downward irradiance for wind speeds of $W \approx 5 \, ms^{-1}$ vary across the 25 sensors less than for wind speeds $< 2 \, ms^{-1}$ by a factor of 0.5 or smaller due to wind-speed independent standard deviations and higher CV values at the preferable wind speeds (Fig. 2.10). Therefore wind speeds $> 3.5 \, ms^{-1}$ are more desirable for irradiance fluctuations measurement with higher accuracy. This conclusion is consistent with earlier studies [Dera and Stramski, 1986; Stramski, 1986a; Darecki et al., 2011] To investigate variations across the 25 sensors of SQUID, we computed the CV at each frequency of the 25 PSDs of downward irradiance (Fig 2.11). The CV of the 25 PSDs is approximately constant around $10\%$ up to $200 \, Hz$, demonstrating homogeneity of the PSDs along the $2.5 \, m$ long SQUID’s linear array that is not long enough to measure any changes of the PSDs because the focusing of sunlight over that distance is induced by low frequency long surface waves. For frequencies greater than $200 \, Hz$, the noise floor of SQUID is higher than irradiance values at those frequencies. Therefore, the CV increases dramatically up to $60\%$ at $500 \, Hz$. However, this increase might also be explained with inhomogeneity of the PSDs caused by more complex sea state with short surface waves and multiple surface waves’ spectra at the higher frequencies.

### 2.5 Conclusions

The power spectral analysis of high-frequency fluctuations in downward plane irradiance induced by sea surface waves has been described. Power spectral density (PSD) function was calculated for $10 \, min$ time-series irradiance data collected at high sampling frequency of $1 \, kHz$ at near-surface depths ($1 – 10 \, m$) under sunny conditions
with two newly developed instruments, the Underwater Porcupine Radiometer System and the SeQuence of Underwater Irradiance Detectors (SQUID) at four sites (SBC, HAW, VEN, CAT) in two different oceanic environments (open ocean and near-shore waters). The analysis investigated changes in the PSDs caused by different size of cosine collector and depth of the measurement, as well as different environmental conditions like solar zenith angle and wind speed.

The size of irradiance collector has a strong effect on the statistical properties of measured irradiance fluctuations at near-surface depths, indicated by significant decrease in the magnitude of the PSD with increasing diameter of the collector. The decrease is well pronounced near the surface, where the light beams are sharply focused. The conclusion that small collector of 2.5 mm in diameter is required to resolve the small spatial scales of wave focusing events, was confirmed.

Under sunny conditions the intensity of wave-induced irradiance fluctuations and their high-frequency content decrease rapidly with increasing depth within the top 10 m layer of the water (in the open ocean as well as in the near-shore waters) for the higher wind speed (W ≈ 5 ms⁻¹). This is determinable primarily to reduction in efficiency of wave focusing effects due to light scattering along increasing path length in water. The maximum fluctuations were found to occur within the layer of z ≈ 10 – 50 cm depth. The coefficient of variations, CV, confirms the rapid decrease in the efficiency of wave focusing with depth due to light scattering within the water column. It also indicates the spectral effect of the depth changes on the irradiance fluctuations. The lower values at blue light compared with red light wavelengths are attributable to higher diffuseness of the blue light in the water column and therefore weaker wave focusing effect. A shift of dominant peak frequency of the PSDs, f_{peak}, toward lower frequencies and decrease of the slope parameter of the PSDs with increasing depth were also observed, especially within the 1 – 10 m layer of water column.
The results demonstrated significant decrease in light fluctuations with increasing solar zenith angle. This effect is caused by an increase in the diffuseness of surface irradiance, which leads to weakening of the wave focusing of light. A shift of the major maximum of the PSDs, $f_{peak}$, toward lower frequencies and decrease of the slope parameter at high frequencies due to weakening of the focusing for the shorter surface waves with increasing solar zenith angle were also recognized.

A weakening effect of surface waves focusing was observed for increasing wind speed as well. Stronger wind ($W > 5 \text{ ms}^{-1}$) increases sea surface roughness causing a decrease in the overall magnitude of power spectra due to more complex sea state and multiple surface waves’ spectra. The coefficient of variations, CV, validates the decrease of the fluctuations as the wind speed increases, and also signifies the spectral effect of the wind speed changes on the irradiance fluctuations. The decrease of the fluctuations is true for stronger wind at $z \approx 1 \text{ m}$ depth (SBC and HAW) as well as within the top 1 m layer of the water column (CAT). In addition, a weakening of the focusing by the surface waves was observed within the top 1 m depth for weaker wind ($< 2 \text{ ms}^{-1}$) that flattens the sea surface.

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G. Chang, T. Dickey, S. Freeman, Twardowski, G. Zibordi, and J-F Berthon for providing the wind speed data and data of water inherent properties.

Chapter 2 is currently being prepared for submission for publication of the material. Gassmann, E., Stramski, D., Darecki, M. and Dubranna, J.; Power spectral analysis of fluctuations in downward irradiance within the near-surface ocean under sunny conditions. The dissertation author was the primary investigator and author of this paper.
Figure 2.1. Power spectral density (PSD) of irradiance fluctuations measured with cosine collectors of different diameters at two different depths $z = 0.5 \text{ m}$ and $z = 2.6 \text{ m}$ at light wavelength of $\lambda = 532 \text{ nm}$. The measurements were made in the Adriatic Sea, Italy (VEN) on June 6, 2009 at 10:37 A.M. and 11:01 A.M. local time, under clear sky, wind speed $W = 1.3 \text{ m s}^{-1}$ and $W = 0.9 \text{ m s}^{-1}$, and solar zenith angle $\theta_s = 29^\circ$ and $\theta_s = 26^\circ$, respectively. The plots cover the frequency range where the effect of instrumental noise is negligible or small.
Figure 2.2. Power spectral density (PSD) of irradiance fluctuations measured at different depths at three light wavelengths ($\lambda = 443, 532$ and $670 \, \text{nm}$) for two locations. (a, b, c) Results from measurements made in the Santa Barbara Channel (SBC) on September 9, 2008 between 11:35 A.M. and 12:56 P.M. local time under clear sky, solar zenith angle $\theta_s = 30^\circ - 33^\circ$ and wind speed $W = 4.1 - 6.4 \, \text{ms}^{-1}$. (d, e, f) Results from measurements taken south off Hawaiian Islands (HAW) on September 13, 2009 between 14:18 P.M. and 15:31 P.M. local time under clear sky, solar zenith angle $\theta_s = 29^\circ - 45^\circ$ and wind speed $W = 5.4 - 6.4 \, \text{ms}^{-1}$. The plots cover the frequency range where the effect of instrumental noise is negligible or small.
Figure 2.3. The depth dependence of the coefficient of variation (CV) of the downward irradiance ($E_d$) at three light wavelengths ($\lambda = 443, 532$ and $670$ nm) for time-series data corresponding to PSDs at the two locations SBC and HAW.
Figure 2.4. The depth dependence of the peak frequency, $f_{\text{peak}}$, (circles and squares) and their corresponding FWHM (Full Width of Half Maximum) bandwidths (horizontal lines) for time-series data corresponding to PSDs presented in Figure 2.2, for one light wavelength $\lambda = 532 \text{ nm}$ at the two locations SBC and HAW. An exponential function was fitted to the data (black line).
Figure 2.5. The depth dependence of the slope parameter for the high-frequency portion of irradiance PSDs for the SBC experiment at three light wavelengths of $\lambda = 443, 532$ and $670 \text{ nm}$. 
Figure 2.6. Power spectral density (PSD) of irradiance fluctuations measured at different solar zenith angles at near-surface depths ($z = 1 \, m$ and $z = 1.5 \, m$) and two light wavelengths ($\lambda = 443$ and $670 \, nm$) at two locations. (a, b) Results from measurements made in the SBC on September 16, 2008 between 1:55 P.M. and 4:17 P.M. local time under clear sky and wind speed $W = 6.3 - 7.8 \, ms^{-1}$. (c, d) Results from measurements made in the HAW on September 2, 2009 between 11:46 A.M. and 1:40 P.M. and on September 2, 2009 between 2:20 P.M. and 3:10 P.M. local time under clear sky and wind speed $W = 10.1 - 10.5 \, ms^{-1}$, and $W \approx 9.8 \, ms^{-1}$. The plots cover the frequency range where the effect of instrumental noise is negligible or small.
Figure 2.7. Power spectral density (PSD) of irradiance fluctuations measured at different wind speeds at depth of $z \approx 1 \, m$ and two light wavelengths ($\lambda = 443$ and $670 \, nm$) for two locations. Results from measurements done under clear sky on the following days: (a, b) in SBC (2008) on September 11 (11:35 A.M. local time, $\theta_s = 30.4^\circ$), September 17 (9:11 A.M., $\theta_s = 50^\circ$), September 16 (11:58 A.M., $\theta_s = 32^\circ$), September 19 (11:54 A.M., $\theta_s = 47^\circ$), and September 15 (12:46 P.M., $\theta_s = 34^\circ$); (c, d) in HAW (2009) on September 12 (9:17 A.M. local time, $\theta_s = 50^\circ$), September 9 (8:48 A.M., $\theta_s = 56^\circ$), and September 4 (4:21 P.M., $\theta_s = 58^\circ$). The plots cover the frequency range where the effect of instrumental noise is negligible or small.
Figure 2.8. The wind speed dependence of the coefficient of variation (CV) of the downward irradiance ($E_d$) at three light wavelengths ($\lambda = 443, 532$ and $670$ nm) for time-series data corresponding to PSDs at the two locations SBC and HAW.
Figure 2.9. Power spectral density (PSD) of irradiance fluctuations measured at different depths within the top 1 m layer of water column at one light wavelength ($\lambda = 532 \text{nm}$) for two different wind speeds, above $3.5 \text{ms}^{-1}$ and below $2 \text{ms}^{-1}$, as indicated (solid and dashed lines). The measurements were made in the Catalina Island (CAT) on September 29, 2011 under following conditions: 3:56 P.M. local time ($z = 0.1 \text{m}$, $W = 4 \text{ms}^{-1}$, $\theta_s = 69^\circ$), 2:45 P.M. local time ($z = 0.2 \text{m}$, $W = 4.9 \text{ms}^{-1}$, $\theta_s = 55.7^\circ$), 2:10 P.M. local time ($z = 0.5 \text{m}$, $W = 3.6 \text{ms}^{-1}$, $\theta_s = 50^\circ$) and 11:36 A.M. local time ($z = 0.15 \text{m}$, $W = 0.9 \text{ms}^{-1}$, $\theta_s = 36^\circ$), 1:18 P.M. local time ($z = 0.2 \text{m}$, $W = 1.8 \text{ms}^{-1}$, $\theta_s = 42^\circ$). The plots cover the frequency range where the effect of instrumental noise is negligible or small.
Figure 2.10. The depth dependence of the coefficient of variation (CV) of the downward irradiance ($E_d$) at one light wavelength ($\lambda = 532 \text{ nm}$) for time-series data (corresponding to PSDs) collected with SQUID (circles) and Porcupine (squares) during CAT experiment for two different wind speeds, above $3.5 \text{ m/s}^{-1}$ (h.w.) and below $2 \text{ m/s}^{-1}$ (l.w.). The SQUID measurements were conducted on September 29, 2011 between 1:43 P.M. and 3:56 P.M. local time under clear sky, solar zenith angle $\theta_s = 46^\circ - 69^\circ$ and wind speed $W = 2.2 - 5.8 \text{ m/s}^{-1}$, and between 11:13 A.M. and 1:18 P.M. local time under clear sky, solar zenith angle $\theta_s = 36^\circ - 42^\circ$ and wind speed $W = 0.9 - 1.8 \text{ m/s}^{-1}$. The Porcupine measurements were conducted on October 3, 2011 between 9:34 A.M. and 11:42 A.M. under clear sky, solar zenith angle $\theta_s = 38^\circ - 48^\circ$ and wind speed $W \approx 4.9 \text{ m/s}^{-1}$. For SQUID each circle represents the mean of the CVs across the 25 sensors with its standard deviation represented by a horizontal line.
Figure 2.11. Power spectral density (PSD) of irradiance fluctuations measured with 25 sensors of SQUID during the CAT experiment (color lines) and the coefficient of variation (CV) at each frequency of all 25 PSDs (black line). The measurement was made on September 29, 2011 at 2:24 P.M. local time, at $z = 0.2 \text{ m}$ depth, under clear sky, solar zenith angle $\theta_s = 56^\circ$ and wind speed $W = 4.9 \text{ m s}^{-1}$. 
2.7 References


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Chapter 3

Spatiotemporal characteristics of wave-induced fluctuations in downward irradiance within the near-surface ocean under sunny conditions

3.1 Abstract

Spatial and temporal light fluctuations induced by surface waves were investigated within the near-surface ocean (depths $\leq 3$ m) by measuring the downward plane irradiance, $E_d$, at different solar zenith angles and wind speeds. The fluctuations were measured with a unique system called the SeQuence of Underwater Irradiance Detectors (SQUID) consisting of a linear, 2.52 m long array of 25 $E_d$ detectors operating at a sampling frequency of 1 kHz. The $E_d$ data were collected in a semi-enclosed bay of Santa Catalina Island (Southern California) where SQUID was deployed on the sea floor in shallow waters. To statistically describe the spatiotemporal characteristics of $E_d$ fluctuations, the spatial autocorrelation function (SAC) and the frequency-dependent magnitude squared coherence (MSC) were computed for each of SQUID detector pairs, providing 300 sensor-to-sensor horizontal distances ranging from 1 cm to 252 cm.

The $E_d$ fluctuations were found to be spatially autocorrelated (SAC $> 1/e$) up to
distances (correlation lengths) of about 12 cm. The correlation lengths showed a tendency to increase with increasing measurement depth, solar zenith angle, and wind speed, which can be attributed to an increase in irradiance diffuseness at the air-sea interface and within the water column, which generally results in reduced effectiveness of wave focusing underwater. In addition, the MSC exhibits a strong frequency-dependence below 20 Hz. The maximum coherence lengths (distance at which $MSC = 1/e$) occurred at very shallow near-surface depths ($\leq 0.5 m$) at frequencies between 1 Hz and 2 Hz under weak to moderate wind speeds (1.8 – 8 ms$^{-1}$) and intermediate values of solar zenith angle (38.4° to 66.1°).

The reported spatiotemporal scales of underwater light fluctuations characterize an optical environment inhabited by a diversity of aquatic animals and can be of particular significance for animal camouflage.

3.2 Introduction

Prevalent and often dominant features of the near-surface light field under sunny conditions are the complex temporal and spatial fluctuations produced by the interaction of incident light with a randomly disturbed air-water interface. Alternating focusing and defocusing of direct solar beam by surface waves play a major role as a source of strong light fluctuations occurring on short temporal and small spatial scales [Schenck, 1957; Snyder and Dera, 1970; Stramski and Dera, 1988]. Through this highly variable optical environment the high frequency fluctuations of underwater irradiance can exert significant influence on marine organisms [Dera et al., 1975; Walsch and Legendre, 1983; Greene and Gerard, 1990; Stramski and Legendre, 1992; Stramski et al., 1993]. This optical environment is particularly challenging for the camouflage of animals such as cephalopods [Johnsen, 2003] as the small-scale spatial structures of wave-focusing events are relevant to the size of many animals.
There have been many studies investigating the temporal statistics of the downward irradiance fluctuations. It was determined that irradiance fluctuations induced by surface waves have a complex dependence on depth and environmental conditions, including wind speed (used as a proxy for surface wave conditions), solar zenith angle, and clarity of the atmosphere [Dera and Stramski, 1986; Stramski, 1986a, b]. Focusing of sunlight by waves was found to be most pronounced at shallow depths of $z \approx 1 \text{ m}$ or less under sunny skies, relatively weak winds ($W \approx 2 - 5 \text{ ms}^{-1}$) that produce slightly undulated sea surface, clear atmospheres with surface irradiance diffuseness of less than about 40%, and relatively high sun elevation (i.e., low solar zenith angles generally $\theta < 40^\circ$) [Dera and Stramski, 1986; Stramski, 1986a]. However, due to data limitations, the spatial structure of the dynamic light field remains poorly understood. With the exception of one fragmentary study by Fraser et al. (1980) the spatial statistics of fluctuations in the near-surface light field have not been examined at all. The limited data of Fraser et al. indicated that spatial correlation length scales are a function of depth.

The present study investigates the spatiotemporal characteristics of the near-surface wave-induced fluctuations in downward plane irradiance by developing statistical descriptors of the dynamic light field. The analysis was conducted using field data collected with a newly developed instrument suitable for measuring both spatial and temporal statistics of light fluctuations. The challenge of the analysis stems from the fact that the spatial and temporal statistics of the light field are highly sensitive to a number of environmental factors that show a broad range of variability. In particular, the statistics of wave focusing events strongly depend on the depth within the water column, water turbidity, state of the sea surface, as well as solar zenith angle and clarity of atmosphere. These factors affect scattering of light travelling through the atmosphere and hence the degree of diffuseness of light incident on the sea surface, as well as scattering of light at the disturbed water surface and subsequently by molecules and particles within the water
column. We present the data of statistical descriptors of light fluctuations such as the spatial autocorrelation function (SAC) and the frequency-dependent magnitude squared coherence (MSC) and discuss the relationships between these descriptors and the depth, solar zenith angle, and wind speed used as a proxy for the surface wave field.

3.3 Data and Methods

3.3.1 Collection of field data

To characterize the spatiotemporal properties of light fluctuations induced by surface waves, the downward plane irradiance, $E_d$, was measured as a function of space and time in near-shore waters in a semi-enclosed bay of the Santa Catalina Island ($33^\circ 26.675'$N, $118^\circ 29.030'$W, Figure 3.1) in September and October 2011.

A novel instrument, referred to as SeQuence of Underwater Irradiance Detectors (SQUID) was developed for the specific purpose of resolving both the temporal and spatial scales of wave focusing events at shallow near-surface depths in the ocean. The SQUID instrument is a linear array of 25 sensors for measuring downward plane irradiance, $E_d$, which are spaced non-uniformly over a total length of 2.52 m (Figure 3.2). To measure spatial variations in $E_d$ over scales ranging from centimeters to meters, the array consists of 6 groups ($k = 0, 1, \ldots, 5$) in which the sensor spacing is given by $2^k$ cm (Figure 3.3). For example, the sensors of the 0th group are spaced at 1 cm ($= 20$ cm). Each of the 25 irradiance sensors had a standard cosine collector with a diameter of 2.5 mm to adequately resolve the small spatial scales of wave focusing events occurring at near-surface depths under sunny conditions [Dera and Gordon, 1968; Dera and Stramski, 1986; Darecki et al., 2011]. The key component of the sensors is the silicon photodiode (custom-built at the Institute of Electron Technology in Warsaw) characterized by a high-speed response (0.35 A/W at 600 nm) and a low dark current (max. 10 nA). Each sensor was equipped
with a narrow band optical interference filter centered at a light wavelength $\lambda = 532 \text{ nm}$.

The development of SQUID was based upon previous experience with the Underwater Porcupine Radiometer System [Chapter 2.2.1], which was constructed for measuring the temporal statistics of downwelling irradiance and radiance at a given point in space [Darecki et al., 2011]. The photodetectors and data acquisition system of SQUID are very similar to those used in the Porcupine system and meet the requirement of simultaneous sampling with multiple detectors at $1 \text{ kHz}$. This high sampling frequency is necessary for resolving the temporal scales of the fluctuations because the shortest duration of light flashes associated with wave-focusing events is on the order of milliseconds [Dera and Olszewski, 1978; Dera and Stramski, 1986; Stramski, 1986a]. The linear array of SQUID detectors can be oriented in any desired direction (e.g., predominant wind and wave direction, solar principal plane) by using an electric single-axis rotator controlled by the output from a compass measuring tilt, roll, and azimuth. In addition, SQUID was also equipped with pressure and temperature sensors for photodiode dark current correction. The instrument was deployed on the sea floor in shallow waters at a distance of about 10 m from the shore. Changes in tide level allowed to take measurements at depths ranging from about 0.1 to 3 m below the sea surface with an accuracy of a few centimeters. The SQUID array was oriented perpendicular to the direction of dominant surface waves and kept parallel to the sea surface. 140 time-series measurements of downward plane irradiance were acquired during the Santa Catalina Island experiment, each being 10 min long. This length of time-series was long enough to collect sufficient data for statistical analyses and short enough to minimize the possible effects due to changes in environmental conditions. The measurements were conducted under clear and sunny sky conditions at different solar zenith angles and wind speeds.

Coincident ancillary data were collected to support the analysis of light fluctuations including wind speed, inherent optical properties (IOPs) of sea water, and bulk
concentrations of suspended particulate matter (SPM) and particulate organic carbon (POC) in surface water. Wind speed was measured using an anemometer at approximately 5 m above sea level. For each underwater time-series measurement of 10 min length, the average wind speed was computed from the continuous recordings of the wind speed for the corresponding 10 min time interval. The IOPs of seawater were characterized by a measurement of beam attenuation coefficient with a C-Star transmissometer (Wet Labs, Inc.). In addition, data characterizing light scattering by seawater were collected with a HydroScat-6 (HOBI Labs, Inc) and LISST-100X (Sequoia Scientific, Inc.). All three optical instruments were deployed from a dock in the vicinity of location where SQUID was deployed. The approximate range of the total beam attenuation coefficient of seawater at a light wavelength of 555 nm was \( c(555) = 0.26 - 0.39 \, m^{-1} \). To obtain estimates of suspended particulate matter (SPM) and particle organic carbon (POC), samples of surface water were also collected from the dock. SPM and POC values ranged from 0.21 to 1.3 \( gm^{-3} \) and 0.09 to 0.13 \( gm^{-3} \), respectively. These ranges are characteristic of intermediate values in the world’s oceans.

3.3.2 Statistical analysis of SQUID data

To describe the spatiotemporal properties of the downward plane irradiance \( E_d \) for different depths, wind speeds, and solar zenith angles, two statistical descriptors were used: the spatial autocorrelation function (SAC) and the magnitude squared coherence (MSC). For each sensor pair of the 25-element array, the SACs were computed to analyze how correlated the two \( E_d \) time-series were, while the MSCs were used to investigate the temporal frequency dependence of the coherence of the \( E_d \) fluctuations.

Although there are 300 \( \binom{25}{2} \) sensor pairs, only 140 of them have a unique separation distance (Figure 3.4). The number of sensor pairs with the same sensor separation decreases with increasing sensor separation. For example, SQUID has four
sensor pairs with a separation of 1 cm, but only one sensor pair with a separation of 124 cm. To take advantage of the redundancy in sensor separation, the values of the SACs and MSCs of different sensor pairs but with the same sensor separation were averaged. The SAC value for each sensor pair with its two unique $E_d$ time-series, $E_{dx}$ and $E_{dy}$, measured respectively by sensor $x$ and $y$, is computed by:

$$SAC = \frac{C_{xy}}{\sqrt{C_{xx}C_{yy}}}$$  \hspace{1cm} (3.1)

with $C_{xy}$ being the covariance (and similarly for $C_{xx}$ and $C_{yy}$), defined as:

$$C_{xy} = E[(x - E[x])*(y - E[y])]$$  \hspace{1cm} (3.2)

where $E[]$ is the expected value operator and $*$ represents the conjugate complex operation. SAC values are $\leq 1$ with $SAC = 1$ representing maximum correlation. The MSC as a function of frequency $f$ was computed as shown for sensor pair $x - y$:

$$MSC(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}$$  \hspace{1cm} (3.3)

where $P_{xx}(f)$ and $P_{yy}(f)$ are the power spectral density (PSD) of the two unique $E_d$ time-series ($E_{dx}$ and $E_{dy}$) measured by sensors $x$ and $y$, respectively, while $P_{xy}(f)$ is the cross-spectral density (CSD) of sensor pair $x - y$. Due to the normalization by $P_{xx}(f)P_{yy}(f)$, the MSC values range between 0 (fully incoherent) and 1 (fully coherent). In addition to these two descriptors, the changes in PSDs (computed already for the MSCs) for different instrument depths, wind speeds, and solar zenith angles were investigated. However, only the PSD analysis for different depths will be discussed here. To compute the PSDs using Welch’s averaging method [Welch, 1967], the $E_d$ time-series were time-averaged and normalized as described in Chapter 2.3.2. To describe the variation in the $E_d$ data
in terms of a simple proxy for the intensity of fluctuations, the coefficient of variation (CV) of irradiance was obtained from the ratio of the standard deviation to the mean of the irradiance data [see chapter 2].

### 3.4 Results and Discussion

An example of the irradiance time-series data obtained with the SQUID is shown in Figure 3.5, where the evolution of a single wave-focusing event can be observed over spatial and temporal scales of up to several tens of centimeters and several hundreds of milliseconds.

In the following sections, changes in irradiance fluctuations are discussed for different depths (Section 3.4.1), solar zenith angles (Section 3.4.2), and wind speeds (Section 3.4.3). As the depth within the water column increases the statistical properties of light fluctuations are expected to change owing to the fact that the geometry of wave focusing varies with the distance between the sea surface and depth of observation and also because the underwater light field becomes more diffuse with increasing depth [e.g., Schenck, 1957; Stramski and Dera, 1988]. To present a comparison of results at different depths we carefully selected data that were collected at similar environmental conditions (e.g., similar solar zenith angles and wind speeds) in order to minimize the effects of these environmental conditions. With regard to the analysis of the effects of solar zenith angle, the statistical properties of underwater light fluctuations are expected to vary because of varying geometry of sea surface illumination and hence the geometry of wave focusing as well as the effects associated with an increase in the degree of diffuseness of irradiance incident on the sea surface with increasing solar zenith angle [e.g., Dera and Stramski, 1986; Stramski, 1986b]. Finally, with regard to the analysis of the effects of wind speed, it is natural to expect that the statistical properties of underwater light fluctuations depend strongly on surface wave conditions. We simply use the wind speed
as a proxy for wave conditions in this analysis [e.g., Dera and Stramski, 1986; Stramski, 1986a]. For presenting the effects of solar zenith angle and wind speed we selected data that were collected at specific example depths under different solar zenith angles and winds speeds, respectively.

3.4.1 Statistical properties of irradiance fluctuations at different depths

3.4.1.1 Power spectral density functions

In this section the features of the power spectral density function (PSD) are described by expanding on the previous work of chapter 2. Examination of variations in the PSD based on data from several selected sensors rather than the mean of all 25 sensors of the SQUID instrument is presented. Specifically, Figure 3.6 shows the power spectra based on measurements with 6 sensors covering the distance of about 2.5 m along the SQUID linear array for six near-surface depths between 0.1 and 3 m. It is remarkable that for each depth the six PSDs corresponding to the measurements with the six sensors are nearly identical, which indicates that the process of light fluctuations is statistically homogeneous over the distances of about 2.5 m. Both the magnitude and shape of PSDs change significantly with increasing depth. The magnitude decreases with depth which is indicative of the reduction in light fluctuation intensity. With regard to the shape, the PSD initially increases at low frequencies until reaching a maximum within the frequency range of $1 - 4 \text{ Hz}$. Beyond the maximum, the PSD decreases by several orders of magnitude with increasing frequency into the high frequency domain. The position of the PSD maximum and the slope of PSD in the high-frequency portion of the function beyond its maximum depend on depth. The peak frequency decreases from $3.4 \text{ Hz}$ at 0.1 m (Figure 3.6a) to $1.5 \text{ Hz}$ at 0.85 m depth (Figure 3.6d). At the largest examined depth of 3 m, the maximum is located at somewhat higher frequency of $1.95 \text{ Hz}$ but the
The magnitude of PSD is comparatively low (Figure 3.6f). The high-frequency slope of the PSDs becomes steeper with increasing depth, especially at and below 0.85 m (Figure 3.6a-f).

The decrease of the intensity of irradiance fluctuations with increasing depth can be attributed to a weakening of the wave focusing effect within the water column. As surface waves only efficiently focus collimated sunlight, the scattering of solar rays along a longer path within the water weakens the focusing effect [Dera and Stramski, 1986; Stramski, 1986a, b]. While longer waves effect irradiance fluctuations at greater depths (although these fluctuations are weak there), which leads to fluctuations at lower frequencies (shift of the dominant peak frequencies of the PSDs toward lower frequencies), the shorter waves cause the points of maximum focus to be closer to the surface [Schenck, 1957; Dera and Gordon, 1968; Snyder and Dera, 1970; Nikolaev et al., 1972; Stramski and Dera, 1988] and the high frequency components of irradiance fluctuations become damped with depth, resulting in a sharpening of the PSDs (Figure 3.6).

The strong decrease in the coefficient of variation of irradiance, CV, throughout the near-surface layer with the exception of the shallowest depths within the top few tens of centimeters confirms the strong depth-dependence of the irradiance fluctuations (Figure 3.7), which is caused by the reduction of the effectiveness of the focusing due to the scattering of light beams occurring over an increasing pathlength in the water column. A very interesting feature observed, to our knowledge, for the first time is the presence of the maximum of vertical profile of CV at very shallow depths of about 20 cm below the sea surface.

**3.4.1.2 Spatial autocorrelation**

The spatial autocorrelation function (SAC) as a function of sensor separation distance is shown in Figure 3.8 for seven depths ranging from 0.1 m to 3 m. In order to
ensure meaningful comparison of SACs at different depths, we selected data that were collected at these different depths under similar environmental conditions. Nevertheless, for practical reasons the selected data unavoidably cover some range of environmental conditions, in particular the solar zenith angle $\theta$ between $40.2^\circ$ and $69.1^\circ$ and wind speed between $3.6 \, ms^{-1}$ and $5.8 \, ms^{-1}$. Therefore, although the effect of depth is dominant in the presented data, the superposition of some additional effects associated with somewhat variable environmental conditions is possible. The SACs are shown only up to a sensor separation of 150 cm because the values of these functions remain very close to zero at larger separation distances indicating essentially no correlation (SACs in sections 3.4.2 and 3.4.3 are also presented up to 150 cm). Six of the seven SACs within the depth range of $0.1 - 1.5 \, m$ decrease rapidly with increasing sensor separation until reaching the zero-crossing between 7 cm and 32 cm. The SAC for the largest examined depth of 3 m decreases only to a value of 0.6 at 23 cm and then keeps oscillating around that value for all subsequent sensor separations. For the depth range of $0.1 - 1.5 \, m$ two groups of SACs can be distinguished based on their slope of the decrease: the first group consists of SACs for the three shallowest depths (i.e., 0.1 m, 0.25 m, and 0.5 m) which have a steeper slope, and the second group consists of SACs for the next 3 deeper depths (0.85 m, 1 m, and 1.5 m) which have a more gentle slope. The SACs of the shallower depth group reach zero at distances of 7 cm, 17 cm, and 18 cm, respectively. The SACs of the deeper depth group cross zero at 13 cm, 20 cm, and 32 cm. Beyond their zero-crossings, the SACs for both groups generally oscillate around zero up to the maximum examined distance of 150 cm, with the exception of SAC for 0.85 m, which exhibits somewhat different pattern. The near-zero magnitudes of the SACs for six depths (0.1 m, 0.25 m, 0.5 m, 0.85 m, 1 m, and 1.5 m) indicate no spatial autocorrelation beyond the first zero crossing. In contrast, the magnitude of SAC around 0.6 for the depth of 3 m implies high autocorrelation over the entire distance of 150 cm. To characterize the distance
over which the irradiance is spatially autocorrelated (correlation length), the e-folding criterion has been chosen rather than the zero-crossings or minima of the SACs. The value of $1/e(\approx 0.37)$ is well above the mean SAC associated with the instrument noise, which for all sensor separations is 0.05 and $-0.05$ for positive and negative SAC values, respectively. This e-folding criterion is also applied to results presented in sections 3.4.2 and 3.4.3. The e-folding correlation length of the irradiance fluctuations for the deeper depths (the second group of SACs for 0.85 $m$, 1 $m$, and 1.5 $m$) is significantly larger than for shallower depths (the first group of SACs for 0.1 $m$, 0.25 $m$, 0.5 $m$) (Figure 3.8). Furthermore, the largest correlation length can be observed for the deepest depth (3 $m$). The increase of light diffuseness with depth is responsible for this increase in distance over which the irradiance is spatially autocorrelated with increasing depth. As the depth of observation increases, the underwater light gets more diffused due to the light scattering along a longer pathlength in the water [Schenck, 1975; Dera and Stramski, 1986; Stramski, 1986a, b]. Hence, the focusing effect becomes less effective at deeper depths, yielding an increase in correlation length.

3.4.1.3 Magnitude squared coherence

To examine the irradiance fluctuations in frequency domain for different depths the magnitude squared coherence function (MSC) was calculated. It is evident that the highest MSC ($> 0.75$) occurs at a depth of 0.85 $m$ and deeper for relatively low frequencies ($< 7 Hz$) and short distances ($< 3 cm$) (Figure 3.9). The trend associated with low frequencies and short distances can also be discerned at shallower depths (0.1 $m$, 0.25 $m$, and 0.5 $m$) but the values of MSC are insignificantly low.

To explore the frequency dependence of MSC for the two different wind speeds in greater detail, we chose nine different sensors separations and examine changes in the coherence for each separation individually. This approach is also applied to MSC
results in sections 3.4.2 and 3.4.3. The MSC spectra for the selected six depths and nine different sensor separations demonstrate more clearly the differences in the coherence (Figure 3.10). At 1 cm separation the MSCs at deeper depths (0.85 m, 1 m, and 1.5 m) peak at $\approx 1.2 \, Hz \, (MSC = 0.95)$, whereas the MSCs at shallower depths (0.1 m, 0.25 m, and 0.5 m) peak at $\approx 3.6 \, Hz$, $\approx 2.4 \, Hz$, and $\approx 2.4 \, Hz$ respectively ($MSC = 0.6 - 0.75$) (Figure 3.10a). Beyond these peak frequencies, the MSC spectra decrease with increasing frequency for all depths. Two depth groups can be distinguished based on the values of MSC and the high-frequency slope of MSC decrease: the first group of the shallower depths (0.1 m, 0.25 m, and 0.5 m) has higher values of MAC with steeper slopes, and the second group of the three deeper depths (0.85 m, 1 m, and 1.5 m) shows lower values of MAC with gentler slopes. In addition, with increasing sensor separation the irradiance fluctuations become less coherent.

The coherence lengths for different depths depend strongly on frequency (Figure 3.11). The largest coherence lengths of the fluctuations (9 – 12 cm) occur at low frequencies (1.2 – 1.5 Hz) but only at the deeper depths (0.85 m, 1 m, 1.5 m and 3 m). In contrast, the largest coherence lengths for the shallower depths (0.1 m, 0.25 m, and 0.5 m) occur at higher frequencies (1.7 – 4 Hz) and are approximately 4 times smaller. At frequencies greater than 4 Hz, the coherence lengths for all depths coincide within 1 cm, which suggests little to no dependence on depth.

The significant difference in coherence length between the shallowest and somewhat larger depths within the examined near-surface layer can be explained by the reduction in the efficiency of surface wave focusing due to light scattering along the increased path lengths in water with increasing depth [Dera and Stramski, 1986; Stramski, 1986a]. The frequency-dependence of the coherence length is expected to be also related to the properties of the gravity-capillary wave field.
3.4.2 Changes in irradiance fluctuations with solar zenith angle

3.4.2.1 Spatial autocorrelation

The changes in the correlation length for relatively small and relatively large solar zenith angle ($\theta = 38.4^\circ$ and $\theta = 66.1^\circ$, respectively) are presented in Figure 3.12. Data used for these results were acquired at a depth $z = 1.05 \, m$ under moderate wind speeds of $6.7 \, ms^{-1}$ and $8 \, ms^{-1}$. The spatial autocorrelation function (SAC) for both solar zenith angles decreases significantly with increasing sensor separation. At a separation of $20 \, cm$ for $\theta = 38.4^\circ$ and $25 \, cm$ for $\theta = 66.1^\circ$, the SAC crosses zero and then continues to maintain low values close to zero. This indicates little to no spatial autocorrelation at sensor separations longer than about $25 \, cm$.

In Figure 3.12, the correlation length of $12 \, cm$ at the larger solar zenith angle is almost twice as large as that for the smaller solar zenith angle ($7 \, cm$). This significant increase of correlation length with increasing solar zenith angle can be attributed to changes in the diffuseness of irradiance incident upon the sea surface. Compared to smaller solar zenith angles the pathlength of sunlight traveling within the atmosphere is significantly longer. As the sun goes down towards the horizon (solar zenith angle increases), the proportion of direct light in the total downward irradiance decreases: the light travelling between the sun and the water surface becomes more diffuse owing to the molecular scattering occurring along the longer pathlength in the atmosphere [Jerlov, 1976; Dera and Stramski, 1986; Stramski, 1986b]. The increase in the diffuseness of irradiance incident on the sea surface and entering the water leads to weakening of the wave focusing effect. As a result, the weaker and less pronounced fluctuations are observed as the sun approaches the horizon. Hence, the distance over which the irradiance fluctuations are spatially autocorrelated increases.
3.4.2.2 Magnitude squared coherence

The magnitude squared coherence (MSC) of the irradiance fluctuations is most significant (> 0.75) at relatively low frequencies (< 7 Hz) and short distances (< 4 cm) for small solar zenith angle (θ = 38.4°). For the larger solar zenith angle (θ = 66.1°) the coherence is most significant for frequencies and distances < 10 Hz and < 8 cm, respectively (Figure 3.13). By examining changes in the MSC spectra for the two solar zenith angles and for each separation individually we observe that the coherence peaks at ≈ 1.5 Hz for θ = 38.4° and ≈ 1.2 Hz for θ = 66.1° at 1 cm (Figure 3.14). After reaching the maximum of ≈ 1 and ≈ 0.95 the MSCs decrease with increasing frequency for both solar zenith angles: the irradiance fluctuations become less coherent with increasing sensor separation. The peak frequencies of 1.5 Hz and 1.2 Hz move toward lower frequencies by ≈ 0.2 – 0.3 Hz beyond the 5 cm separations for both solar zenith angles.

The maximum coherence length for θ = 38.4° and for θ = 66.1° is 12 cm at 1.3 Hz and 18 cm at 1 Hz, respectively (Figure 3.15). At higher frequencies (> 1.3 Hz and > 1 Hz) the coherence lengths decrease significantly until they reach the minimum sensor spacing of 1 cm. For frequencies smaller than the peak frequency, the coherence lengths also decrease dramatically from 12 cm to 5 cm for θ = 38.4° and from 18 cm to 12 cm for θ = 66.1°. The fact that the coherence length depends closely on the frequency of light fluctuations can again be attributed to spatiotemporal scales of ocean surface wave field.

3.4.3 Changes in irradiance fluctuations for different wind speeds

3.4.3.1 Spatial autocorrelation

The spatial autocorrelation function (SAC) for weak and moderate wind speeds (1.8 ms⁻¹ and 8 ms⁻¹ respectively) is depicted in Figure 3.16. The results presented were obtained from data collected at a depth z = 1.05 m when the solar zenith angle
θ varied slightly between 50.2° and 56.5°. The SACs decrease rapidly with increasing distance for both low and high wind speeds until reach zero at distances of 12 cm and 21 cm, respectively. Then the SACs continue to decrease reaching small negative values at about 23 cm and 33 cm, respectively. With further increase in the sensor separation distance, the two SACs initially increase towards zero and then remain close to zero, which indicates little to no spatial autocorrelation at these larger separations. In Figure 3.16, the correlation length for the high wind speed is four times larger than for the low wind speed (12 cm at 8 ms$^{-1}$ versus 3 cm at 1.8 ms$^{-1}$). The higher wind speed causes an increase in the roughness of the sea surface [e.g., Cox and Munk, 1954; Pierson and Stacy, 1973]. Strong wind dependence is typically observed at lower wavenumbers and therefore longer wavelengths [e.g., Jaehne and Riemer, 1990; Elfouhaily et al., 1997]. Longer surface waves along with superimposed short (capillary) waves and ripples of steep slopes (with length less than 1 cm and steepness extending to over 0.5) are then predominant features of surface wave field [e.g., Schooley, 1958; Burcev and Pelevin, 1979]. The increased roughness of the sea surface under higher winds is efficiently diffusing the incident direct solar radiation and, as a result, the focusing effects are greatly reduced and light fluctuations are not pronounced as well as under weaker winds [Dera and Stramski, 1986]. This leads to an increase in the distance over which the fluctuations in $E_d$ are autocorrelated with an increase in wind speed and accompanying increase in the roughness of sea surface.

3.4.3.2 Magnitude squared coherence

The magnitude squared coherence (MSC) of the irradiance fluctuations is most significant (> 0.75) at relatively low frequencies and short sensor separations at weak (< 5 Hz and < 2 cm) and moderate wind speeds (< 10 Hz and < 7 cm) (Figure 3.17a and b, respectively). Note that the irradiance fluctuations at higher wind speed (8 ms$^{-1}$)
are significantly coherent over a much larger frequency range (2 time larger) and sensor separation (>3 time larger) than at low wind speed (1.8 m s⁻¹).

The MSC spectra for a separation of 1 cm peak at ≈ 1.5 Hz (MSC = 0.9) for low wind speed and ≈ 1.2 Hz (MSC = 1) for higher wind speed (Figure 3.18a). At higher frequencies (>1.5 Hz and >1.2 Hz) the MSC spectra decrease with increasing frequency for both wind speeds. The increase in the MSC spectra with minor local maxima between 10 and 100 Hz is due to instrument noise (Figure 3.18a-d). The irradiance fluctuations become less coherent as the sensor separation increases and the peak frequencies of 1.5 Hz for low wind speed and 1.2 Hz for higher wind speed are observed at small sensor separations up to 15 cm.

The strong frequency-dependence of $E_d$ fluctuations is also observed in Figure 3.19, where the coherence length (distance over which the irradiance is spatially coherent with MSC > 1/e) is presented as a function of frequency for both wind speeds. The maximum coherence length for the low and higher wind speed occurs at approximately 1.3 Hz and 1.1 Hz, respectively. The coherence length for the higher wind speed is almost two times larger than for the low wind speed (13 cm and 7 cm, respectively). For both wind speeds, the coherence length decreases with increasing frequency and eventually become similar, which suggests little to no dependence on wind speed at frequencies higher than 8 Hz (Figure 3.19). At low frequencies (<1.2 Hz), coherence lengths of the fluctuations decrease from 7 cm to 3 cm and from 13 cm to 8 cm for the low and higher wind speeds, respectively.

With regard to the correlation length (Figure 3.16), the increase in irradiance diffuseness at the air-sea interface increases the coherence length at higher wind speeds. With increasing wind speed, the sea state gets more complex causing the underwater light to be more diffuse [Dera and Stramski, 1986; Stramski, 1986a; Dera et al, 1993]. Because the focusing is less effective when the light is more diffuse, weaker fluctuations
lead to larger coherence lengths [Stramski, 1986b; Dera and Stramski, 1986; chapter 2]. As a result, the strong frequency-dependence of the coherence length is linked to the surface wave field that induces the fluctuations in underwater irradiance. However, the complex relationship between the statistical properties of light fluctuations and the surface wave field is unknown as no wave measurements were conducted during this experiment.

3.5 Conclusions

The spatiotemporal properties of the near-surface underwater light field fluctuations caused by sea surface waves were investigated in near-shore waters under sunny conditions in a semi-enclosed bay of the Santa Catalina Island in the Pacific Ocean (off Southern California). The temporal and spatial scales of the underwater light field were resolved down to short time scales of 1 ms and small spatial scales down to 1 cm using a novel instrument called the SeQuence of Underwater Irradiance Detectors (SQUID), which was deployed on a sea floor in shallow waters. This instrument measures the downward plane irradiance, $E_d$, with a sampling frequency of 1 kHz, and includes a linear array of 25 sensors that are spaced over a total horizontal distance of 2.52 m. The near-surface underwater light were statistically analyzed in terms of the spatial auto-correlation ($SAC$) function and the frequency-dependent magnitude squared coherence ($MSC$) function at depths between 0.1 and 3 m for solar zenith angles in the range of $38.4^\circ - 66.1^\circ$ and different wind speeds in the range 1.8 – 8 ms$^{-1}$.

We found that the near-surface underwater light fluctuations are spatially correlated over increasing horizontal distances up to a maximum of about 12 cm when the depth of observation, wind speed, and/or solar zenith angle increases is larger. The increase in correlation length at larger depths, solar zenith angles, and higher wind speeds can be generally explained by a reduction of the focusing effect of direct sunlight which
is caused by light scattering occurring over a greater distance within the water column, along a longer pathlength in the atmosphere, and/or at a rougher air-sea interface. Due to light scattering the light field becomes more diffuse and fluctuations are less pronounced, leading to larger correlation lengths. It is important to indicate that at a maximum examined depth of 3 m the light field is correlated over the entire distance of the 2.52 m long array of SQUID, which can be attributed to the predominant scattering within the water column. Furthermore, the maximum coherence lengths were found within a frequency range of $1 - 2 \, H_z$ below 0.5 m depth for weak to moderate wind speeds ($1.8 - 8 \, m s^{-1}$) and moderate solar zenith angles (38.4° and 66.1°). At higher frequencies ($> 10 \, H_z$), the near-surface underwater light field becomes incoherent.

In order to better understand the statistical properties of light field fluctuations, the development of relationships between the statistics of underwater irradiance (presented in this study) and the statistics of surface sea structure (e.g., slope, curvature, and elevation statistics) would be essential. The theoretical modeling of wave-induced light fluctuations is challenging, primarily because of the complexity of the dynamics of the sea surface [Schenck, 1957; Snyder and Dera, 1970; Nikolayev and Khulapov, 1976; Stramski and Dera, 1988; Zaneveld et al., 2001; You et al., 2010], and often requires significant oversimplifying assumptions, including those pertaining to the surface wave field. Conducting detailed measurements of the surface wave field simultaneously with the irradiance measurements would be critical for advancing the interpretation of wave-induced light fluctuations in terms of surface wave properties. The insufficient knowledge of the quantitative details of the surface wave structure due to a lack of wave measurements is a limitation of this investigation. It would be highly desirable to acquire surface wave measurements simultaneously with irradiance fluctuation measurements in future experiments. This would provide the opportunity to better investigate the spatiotemporal dependence of the fluctuations on the surface wave field and could
potentially allow for some properties of the surface wave field (e.g., speed, amplitude, wavelength and phase of surface waves) to be inferred from the information on the underwater light field.

Nevertheless, the results presented in this study reveal novel and important insights into the spatiotemporal properties of the dynamic underwater light field within the near-surface layer of the ocean where the fluctuations are strongest. Our findings also improve an understanding of the complex near-surface optical environment inhabited by a diversity of aquatic organisms which can be critical to biological studies, for example in the area of animal camouflage and vision [Johnsen, 2003]. As the spatial scales of wave-induced fluctuations range from millimeters to tens of centimeters, these fluctuations are expected to be of significance to aquatic animals of comparable sizes.

### 3.6 Acknowledgments

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Chapter 3 is currently being prepared for submission for publication of the material. Gassmann, E., and Stramski, D., Spatiotemporal characteristics of fluctuations in downward irradiance within the near-surface ocean under sunny conditions. The dissertation author was the primary investigator and author of this paper.
**Figure 3.1.** Map showing the location of the experiment (red star) in a semi-closed bay of Santa Catalina Island in the Southern California Bight. Color and black contour lines with 10 m spacing represent water depth in meters (data: NOAA/NGDC).
Figure 3.2. The SeQuence of Underwater Irradiance Detectors (SQUID).
Figure 3.3. Schematic configuration of the SQUID.
Figure 3.4. Number of sensor pairs with the same sensor distance.
Figure 3.5. Example of 1 s irradiance time-series data obtained simultaneously with 11 SQUID sensors located at different distances. The measurement was conducted at $z = 1.05 \, m$, weak wind of $1.8 \, ms^{-1}$ and $\theta = 50.2^\circ$. 
Figure 3.6. Power spectral densities (PSDs) of $E_d$ at $\lambda = 532 \, nm$ at six different depths measured by sensors #1, #6, #10, #14, #18, #22. The results were obtained from data collected at wind speed of $3.6 - 5.8 \, ms^{-1}$ and solar zenith angle of $\theta = 40.2^\circ - 69.1^\circ$. The plots cover the frequency range where the effect of instrumental noise is negligible or small.
Figure 3.7. The depth dependence of the coefficient of variation (CV) of $E_d$ at $\lambda = 532 \text{ nm}$ at six different depths measured by sensors #1, #6, #10, #14, #18, #22 for time-series data corresponding to PSDs presented in Fig. 3.6.
Figure 3.8. Spatial autocorrelation (SACs) of $E_d$ at $\lambda = 532 \, nm$ as a function of sensor distance for seven depths measured at a wind speed range of $3.6 - 5.8 \, m/s$ and solar zenith angle range of $\theta = 40.2^\circ - 69.1^\circ$. 
Figure 3.9. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532\ nm$ as a function of frequency and sensor distance for six depths measured at a wind speed range of $3.6 - 5.8\ ms^{-1}$ and solar zenith angle range of $\theta = 40.2^\circ - 69.1^\circ$. 
Figure 3.10. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency at nine different distances for six depths measured at a wind speed range of $3.6 - 5.8 \text{ m s}^{-1}$ and solar zenith angle range of $\theta = 40.2^\circ - 69.1^\circ$. 
Figure 3.11. Coherence lengths of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency for six depths at a wind speed range of $3.6 - 5.8 \text{ m/s}$ and solar zenith angle range of $\theta = 40.2^\circ - 69.1^\circ$. 
Figure 3.12. Spatial autocorrelation (SACs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of sensor distance for relatively small ($\theta = 38.4^\circ$) and relatively large ($\theta = 66.1^\circ$) solar zenith angles measured under moderate wind speeds of 6.7 $ms^{-1}$ and 8 $ms^{-1}$, respectively and at depth of $z = 1.05 \text{ m}$. 
Figure 3.13. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 nm$ as a function of frequency and sensor distance for relatively small ($\theta = 38.4^\circ$) and relatively large ($\theta = 66.1^\circ$) solar zenith angles measured under moderate wind speeds of 6.7 $ms^{-1}$ and 8 $ms^{-1}$, respectively and at depth of $z = 1.05 m$. 
Figure 3.14. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532\, nm$ as a function of frequency at nine different distances for relatively small ($\theta = 38.4^\circ$) and relatively large ($\theta = 66.1^\circ$) solar zenith angles measured under moderate wind speeds of $6.7\, ms^{-1}$ and $8\, ms^{-1}$, respectively and at depth of $z = 1.05\, m$. 
Figure 3.15. Coherence lengths of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency for relatively small (light blue) and relatively large (dark blue) solar zenith angles at an array depth of $z = 1.05 \text{ m}$ measured under moderate wind speeds of $6.7 \text{ ms}^{-1}$ and $7.15 \text{ ms}^{-1}$, respectively.
Figure 3.16. Spatial autocorrelation (SACs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of sensor distance for weak ($1.8 \text{ m/s}^{-1}$) and moderate ($8 \text{ m/s}^{-1}$) wind speeds measured at solar zenith angles of $\theta = 50.2^\circ$ and $\theta = 56.5^\circ$, respectively, and at a depth of $z = 1.05 \text{ m}$. 
Figure 3.17. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency and sensor distance for weak ($1.8 \text{ms}^{-1}$) and moderate ($8 \text{ms}^{-1}$) wind speeds measured at solar zenith angles of $\theta = 50.2^\circ$ and $\theta = 56.5^\circ$, respectively, and at a depth of $z = 1.05 \text{ m}$. 
Figure 3.18. Magnitude squared coherence (MSCs) of $E_d$ at $\lambda = 532$ nm as a function of frequency at nine different distances for weak (1.8 $ms^{-1}$) and moderate (8 $ms^{-1}$) wind speeds measured at solar zenith angles of $\theta = 50.2^\circ$ and $\theta = 56.5^\circ$, respectively, and at a depth of $z = 1.05$ m.
Figure 3.19. Coherence lengths of $E_d$ at $\lambda = 532 \text{ nm}$ as a function of frequency for weak (light blue) and moderate (dark blue) wind speeds at an array depth of $z = 1.05 \text{ m}$ measured at solar zenith angles of $\theta = 50.2^\circ$ and $\theta = 56.5^\circ$, respectively.
3.7 References


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Chapter 4

Asymmetry of horizontal radiance within the solar principal plane in the upper ocean layer

4.1 Abstract

To quantify the asymmetry of the underwater horizontal radiance field around the vertical axis, measurements of horizontal spectral radiance in two opposite directions within the solar principal plane were collected with two hyperspectral sensors deployed within the upper layer of the Pacific Ocean. The underwater radiance field was also simulated using a radiative transfer model to investigate the underlying variations in the asymmetry under different environmental conditions. The values of the asymmetry factor, $\gamma$, defined as a ratio of horizontal radiance associated with photons traveling away from the sun to that associated with photons traveling towards the sun, varied from one (symmetric radiance field) to more than six (highly asymmetric field) over the examined range of solar zenith angles (0 to 90°), light wavelengths (350 to 650 nm), depths within the water column (1 to 200 m), water optical properties, and sky conditions (clear and overcast skies). Our results indicate that the highest asymmetry of horizontal radiance occurs under clear skies at shallow depths when the solar zenith angle, $\theta$, is about 60° to 70°. The asymmetry tends to decrease with increasing depth and the zenith angle.
at which maximum asymmetry occurs also decreases with depth. Also, the asymmetry shows a significant spectral variation with the lowest asymmetry in the ultraviolet and blue spectral regions and the highest in the red. Overall the patterns of variation of asymmetry are driven by the illumination geometry of the sea surface and the degree of diffuseness of light field incident upon the surface and within the water column. In particular, the distinctive pattern of variation of asymmetry as a function of solar zenith angle with a maximum when $\theta \approx 60^\circ$ to $70^\circ$ can be attributed largely to changes in the diffuseness of irradiance incident upon the sea surface as function of solar zenith angle. For large zenith angles, $\theta > 70^\circ$, the diffuseness of surface irradiance increases sharply and hence the asymmetry of underwater horizontal radiance decreases at very large solar zenith angles.

4.2 Introduction

The quantitative study of the underwater horizontal light field has important applications in aquatic ecology. Large changes in the magnitude, spectral composition, and angular distribution of the underwater light field occur throughout the oceanic water column, which creates a challenging environment for marine organisms that rely on visual predation, or for organisms which need to avoid detection. In the near-surface ocean, the visual background of the overhead light field is particularly complex owing to features such as rapid wave-induced light fluctuations [Schenck, 1957; Snyder and Dera, 1970; Dera and Stramski, 1986]. As a result, horizontal viewing is common within the surface ocean layer [Johnsen and Sosik, 2003]. In addition, certain camouflage strategies of aquatic organisms in the pelagic zone of the ocean, such as the mirrored lateral surfaces of many pelagic fish, rely on a horizontal radiance distribution that is symmetrical around the vertical axis in order to be successful [Denton, 1970; Herring, 1994].

There have been few studies quantifying the asymmetry of the underwater hori-
horizontal radiance field. In the upper layers of the water column the radiance distribution is often dominated by direct sunlight and is sensitive to the solar zenith angle, but with increasing depth becomes increasingly diffuse [Tyler, 1958]. It is also well-known that at depth the underwater radiance field becomes increasingly symmetrical around the vertical axis, regardless of the solar zenith angle [Jerlov, 1976; Mobley, 1994]. A number of angularly resolved radiance measurements have been made in the ocean, but the horizontal asymmetry was not specifically examined in these studies [Jerlov and Fukuda, 1960; Smith, 1974; Voss, 1989; McFarland, 1991; Wei et al., 2012; Antoine et al., 2013].

Recently, we reported model results and field observations of underwater horizontal radiance and examined the implications for the mirror-based crypsis of silvery-sided pelagic fish under specific viewing geometries [Johnsen et al., 2014]. This study showed that the maximum asymmetry of the horizontal light field occurred at zenith angles significantly smaller than 90°, as low as 45° at the 100 m depth. However, the underlying mechanisms mediating this asymmetry pattern were not investigated, and the results were limited to the visible region of the spectrum.

The present study expands on the previous work of Johnsen et al. [2014] by examining variations in the distribution of horizontal spectral radiance in the upper ocean and the mechanisms that influence these variations. We describe the horizontal radiance field using results from both field measurements and radiative transfer simulations. The ratio of horizontal radiance in two opposite directions (solar and anti-solar azimuths) within the solar principal plane is used to quantify the asymmetry of horizontal radiance around the vertical axis. This measure of asymmetry is examined as a function of solar zenith angle in relatively clear oceanic waters using the measured data and for optically different water bodies under various sky conditions using the simulated data. In addition to the visible spectral region, our results extend to the near-ultraviolet (near-UV) spectral range including wavelengths between 350 and 400 nm. The intensity of UV radiation can
be relatively high in clear near-surface oceanic waters and can contribute a significant fraction of photons traveling in the horizontal directions, which may have biological implications as many fish species have the capability of UV vision [Losey et al., 1999; Johnsen and Widder, 2001; Leech and Johnsen, 2003].

4.3 Methods

4.3.1 Field measurements of horizontal radiance

To characterize the horizontal radiance field, depth profiles of horizontal radiance were measured on a cruise of the R/V Kilo Moana off the Island of Hawaii in May and June of 2012. We note that we have also reported on a subset of radiance measurements from this cruise in the previous study [Johnsen et al., 2014]. Horizontal spectral radiance was measured with an Optical Profiler II (HyperPro, Satlantic Inc.) fitted with two hyperspectral radiance sensors (HyperOCR, Satlantic Inc.) oriented horizontally to view at 180° relative to each other (Fig. 4.1). Each of the sensors had a full field-of-view of 8.5° in water, a spectral resolution of 10 nm with a sampling interval of 3.3 nm, and a manufacturer-calibrated radiometric response over the spectral range of 350 to 800 nm. Water temperature and pressure were additionally measured by the profiler, as well as tilt in two perpendicular axes of the instrument. Vertical profiles to depths of 160 m were obtained for measurements of horizontal radiance in two opposite directions (solar and anti-solar azimuths) within the solar principal plane (i.e., where the sun and both sensors are in one plane). The horizontal radiances in two opposite directions measured within the solar principal plane are represented as $L_{180}(\lambda)$, which is the radiance associated with photons of light wavelength $\lambda$ (in vacuum) propagating in the horizontal direction away from the sun, i.e., measured with the sensor facing the sun but not direct solar photons which never propagate horizontally underwater, and $L_0(\lambda)$, which is the radiance
associated with photons propagating in the horizontal direction towards the sun, i.e., measured with the sensor facing away from the sun. Data for $L_{180}(\lambda)$ near the sea surface were acquired at a maximal sampling rate of approximately 3 Hz, whereas for near-surface measurements of $L_0(\lambda)$, as well as for both sensors deeper in the water column, the sampling rate was reduced to values as low as 0.4 Hz owing to lower radiance signals requiring longer integration times.

Measurements were made at five stations at which solar zenith angle varied over a broad range under predominantly clear skies with direct sunlight always present during the measurement (Table 4.1). The solar zenith angle was calculated based on the location and time of the measurements using the Astronomical Applications site of the U.S. Naval Observatory (http://aa.usno.navy.mil/). At the time of measurement, the ship was moved to orient the starboard side to within a degree of the sun, and the instrument was deployed in such a way that the $L_{180}(\lambda)$ sensor was pointing towards the sun and the $L_0(\lambda)$ sensor was pointing away from the sun. Specifically, the instrument was attached to a weighted cable and lowered via a winch at $0.25 - 0.30 \text{ ms}^{-1}$, using tension applied by opposing guy lines to maintain a nearly-constant orientation within the solar principal plane (Fig. 4.1). Data were collected during the downcast until radiance values for blue light wavelengths ($\approx 480 \text{ nm}$) became indistinguishable from instrument background noise, typically at depths ranging from 120 to 160 m depending on the solar zenith angle. At all five stations the water depth was greater than 4000 m.

Raw radiance data together with calibration files of the profiler were first read into the manufacturer’s software program (SatCON, Satlantic) to convert recorded voltages to calibrated radiometric units, and subsequently processed with custom software. After the background dark noise levels related to each gain were subtracted from the data, the arrays of profiler data and dark-corrected data from each radiometer were interpolated to a common time vector (that of the radiometer with the slower sampling rate) to merge depth,
tilt, and other ancillary measurements with the radiance data. The time-interpolated radiance data were then interpolated to a common wavelength vector, spanning the spectral range of 350 to 800 nm at 2 nm intervals. In this study only data from 350 to 650 nm are presented. All values measured with an instrument tilt greater than 5° were rejected, and the remaining data were binned and averaged into 2 m depth bins. Horizontal radiance measurements from the upper 12 m layer were excluded from the analysis to avoid potential artifacts caused by reflections or shadowing by the ship. As an additional criterion to exclude data exhibiting high noise, the signal-to-noise-ratio (SNR) was estimated by comparing the measured values of spectral radiance with the results of the dark noise measurements made at the highest gains (longest integration times). Radiance data exhibiting magnitudes that were within 20% of the mean dark-noise level were excluded. As a result of low SNR, most measurements within the long-wavelength portion of the spectrum (wavelengths longer than 600 nm) were removed. At the deepest depths with low magnitudes of horizontal radiance, the cut-off wavelength was sometimes less than 600 nm.

As a last step in the processing, the ratio of horizontal radiances in the two opposite directions within the solar principal plane was calculated to characterize asymmetry around the vertical axis. The spectral asymmetry factor, $\gamma(\lambda)$, is defined as

$$\gamma(\lambda) = \frac{L_{180}(\lambda)}{L_0(\lambda)}.$$  \hspace{1cm} (4.1)

The $\gamma$ value of 1 obviously indicates that the horizontal radiance in both horizontal directions is identical, so the horizontal radiance field is symmetric around the vertical within the solar principal plane. The $\gamma(\lambda)$ values larger than 1 indicate the asymmetry of horizontal radiance field with higher radiance associated with photons traveling away from the sun and lower radiance associated with photons traveling towards the sun.
4.3.2 Modeling of horizontal radiance

To better understand the observed variations in the horizontal radiance asymmetry and discern the underlying driving mechanisms, horizontal radiances within the solar principal plane were simulated using a radiative transfer model (HydroLight 5.1, Sequoia Scientific, see [Mobley and Sundman, 2008]). Oceanic radiance distributions have been modeled with reasonable accuracy in previous studies using this model [Mobley et al., 1993]. The model computes the full angular distribution of spectral radiance \( L(z, \theta, \phi, \lambda) \) at each preselected output depth \( z \) in the ocean (positive downward), where \( \theta \) is the zenith (or nadir) angle and \( \phi \) is the azimuth angle, which together identify the direction of light propagation. The zenith (\( \theta_z \)) and nadir (\( \theta_n \)) angles in this model represent the direction of photon travel relative to the vertical. In the case of downwelling radiance, this direction is defined by the nadir angle \( \theta_n \), and for the upwelling radiance, the zenith angle \( \theta_z \). For the special case of horizontal radiance \( \theta_n = \theta_z = \pm 90^\circ \), where the sign depends on direction of photon travel or the portion of the azimuthal plane within which the radiance is calculated. For the solar principal plane of interest in this study, \( \theta = -90^\circ \) is within the half-plane containing the sun (i.e., photons traveling away from the sun) and \( \theta = +90^\circ \) within the opposite half-plane (photons traveling towards the sun). The horizontal radiances represent an average of radiances over the angular ranges \( \theta = -90^\circ \pm 5^\circ \) and at \( \theta = +90^\circ \pm 5^\circ \). The azimuth angle varies clockwise between 0° and 360° (with 15° intervals), with the angle \( \phi = 180^\circ \) corresponding to the half-plane of the solar principal plane containing the sun, and \( \phi = 0^\circ \) to the opposite half-plane. The simplified notation used in this study of \( L_{180}(\lambda) \), which represents the horizontal radiance associated with photons traveling away from the sun within the solar principal plane, corresponds to the HydroLight notation of \( L_H(\theta = 90^\circ, \phi = 180^\circ, \lambda) \). Similarly, the simplified notation of \( L_0(\lambda) \) which represents the horizontal radiance associated with
photons traveling towards the sun within the solar principal plane corresponds to the HydroLight notation of $L_H(\theta = 90^\circ, \phi = 0^\circ, \lambda)$. We also note that the symbols $L_{180}(\lambda)$ and $L_0(\lambda)$ in this paper have the opposite meaning as the same symbols used in the previous study of Johnsen et al. [Johnsen et al., 2014]. This is because in this paper we have chosen to have subscripts '180' and '0' that are consistent with the HydroLight notation of azimuth directions. Two sets of simulations were conducted, each with a different approach to estimating the inherent optical properties (IOPs) of seawater required as input. The first set simulated case 1 oceanic waters using a chlorophyll-based bio-optical model embedded within HydroLight, in which IOPs were derived from depth profiles of chlorophyll-a concentration ($Chl$) obtained from chlorophyll fluorescence depth profiles measured with WET Labs ECO-AFL fluorometer at each station. The so-called 'classic case 1' bio-optical model was used. Chlorophyll-a concentration at multiple depths was determined from the analysis of discrete water samples using High Performance Liquid Chromatography following the method described in [Van Heukelem and Thomas, 2001].

These determinations were used to scale the fluorescence depth profiles to obtain the depth profiles of $Chl$. The values of $Chl$ ranged from 0.08 $mg m^{-3}$ at the near-surface depths to 0.3 $mg m^{-3}$ at the chlorophyll-a maximum around 140 m. The second set also simulated case 1 oceanic waters using the chlorophyll-based bio-optical model embedded within HydroLight, but in these simulations three chlorophyll-a concentrations were used (0.02, 0.2 and 2 $mg m^{-3}$). In each of these three scenarios $Chl$ was assumed constant with depth. This range represents most oceanic situations and allowed us to study the depth-dependence of the horizontal radiance for optically different water bodies.

For both sets of simulations the spectral absorption coefficient of seawater, $a(\lambda, z)$
(units are $m^{-1}$), was modeled as a sum of three components,

$$a(\lambda, z) = a_w(\lambda) + a_p(\lambda, z) + a_g(\lambda, z), \quad (4.2)$$

where $a_w(\lambda)$ represents the absorption coefficient of pure water, $a_p(\lambda, z)$ represents the absorption coefficient of suspended particles, and $a_g(\lambda, z)$ represents the absorption coefficient of colored dissolved organic matter (CDOM). The pure water absorption values of $a_w(\lambda)$ for $\lambda < 380 \text{ nm}$ and those for longer wavelengths were simulated according to [Sogandares and Fry, 1997] and [Pope and Fry, 1997], respectively. The $a_p(\lambda, z)$ coefficient was calculated from the relation

$$a_p(\lambda, z) = 0.06 A_{Chl}(\lambda) [Chl(z)]^{0.65}, \quad (4.3)$$

where $A_{Chl}(\lambda)$ is the non-dimensional wavelength-dependent chlorophyll-specific absorption coefficient given in [Prieur and Sathyendranath, 1981] and [Morel, 1988]. The value of $a_g(\lambda, z)$ was also assumed to vary with $Chl$ and calculated using

$$a_g(\lambda, z) = 0.2 a_p(440, z) e^{-0.014(\lambda-440)}. \quad (4.4)$$

The scattering coefficient of seawater, $b(\lambda, z)$, was calculated as the sum of scattering by pure seawater, $b_w(\lambda)$, and suspended particles, $b_p(\lambda, z)$,

$$b(\lambda, z) = b_w(\lambda) + b_p(\lambda, z), \quad (4.5)$$

where $b_w(\lambda)$ was obtained from [Smith and Baker, 1981] and $b_p(\lambda, z)$ was calculated
from

\[ b_p(\lambda, z) = \left( \frac{550}{\lambda} \right) 0.30 Chl(z)^{0.62} \]  

(4.6)

according to [Gordon and Morel, 1983]. In addition to absorption and scattering coefficients, the model inputs require the scattering phase function. In all simulations the total scattering phase function was parameterized as the sum of the contributions by pure water and particles [Mobley, 1994]. The particle component was specified from a given particle backscattering fraction, \( b_{bp}/b_p \) where \( b_{bp} \) is the particulate backscattering coefficient (the dependence on light wavelength is omitted for brevity), from which the Fournier-Forand phase function was generated by the model [Mobley et al., 2002]. The simulations were carried out for two different backscattering fractions of the particle phase function, 0.005 and 0.05, to investigate the sensitivity of the horizontal radiance to different phase functions. These particle backscattering fractions, and hence the particle phase functions, were assumed to be independent of light wavelength. Therefore, the dependence of total phase function on light wavelength in our simulations is associated solely with the spectral dependence of the pure seawater component of phase function. We also note that the phase function in our simulations (for a given particle backscattering fraction) does not vary with depth. However, the volume scattering function (VSF), which is the product of phase function and scattering coefficient, does vary with depth.

The contributions of inelastic radiative processes to the light field were also included in all simulations. Chlorophyll-a and CDOM fluorescence were calculated from phytoplankton and CDOM absorption spectra respectively specified in each simulation, using the default fluorescence efficiency of 0.02 for chlorophyll fluorescence and the default CDOM fluorescence quantum efficiency function taken from [Hawes et al., 1992]. All of the radiative transfer simulations included Raman scattering by water molecules
Simulations spanned the range 300 to 800 nm at 2 nm intervals, allowing accurate calculation of the contribution of these processes to wavelengths longer than 350 nm. In the presentation of results, data at wavelengths longer than 650 nm are not considered.

An infinitely deep ocean was assumed, with chosen output depths of 1, 5, 10, 20, ..., 200 m with 10 m intervals for depths greater than 10 m. The wind speed for all simulations was set at 5 m s$^{-1}$, representing a relatively calm sea surface. A broad range of solar zenith angles was simulated, from the sun at its zenith ($\theta = 0^\circ$) to sunrise or sunset ($\theta = 90^\circ$), with 10 degree intervals between $\theta = 0^\circ$ and $\theta = 40^\circ$ and 5 degree intervals between $\theta = 40^\circ$ and $\theta = 90^\circ$. Most of the simulations were done for clear skies, but we also simulated cloudy (100% overcast) and black sky conditions to examine the sky effect on the horizontal radiance. The black sky scenario allowed us to examine a hypothetical situation when only direct solar beam illuminates the sea surface in the absence of diffuse skylight. The surface boundary conditions included atmospheric irradiance calculated with a spectrally-extended version of the RADTRAN model, and the sky radiance angular distribution was calculated with a semi-empirical model [Gregg and Carder, 1990; Harrison and Coombes, 1988; Mobley and Sundman, 2008]. Both of the models, embedded within HydroLight, account for atmospheric effects such as the increase in the proportion of diffuse component of irradiance incident on the sea surface as the sun approaches the horizon.

### 4.4 Results and Discussion

#### 4.4.1 Measured depth profiles and spectra of $L_{180}$, $L_0$, and $\gamma$

Examples of measured depth profiles of $L_{180}(\lambda)$ and $L_0(\lambda)$ at three light wavelengths (410, 480, and 550 nm) are depicted for both a noon station exhibiting a small
solar zenith angle ($\theta \approx 3.5^\circ$) and a sunrise station with a large solar zenith angle ($\theta \approx 81^\circ$) in Figures 4.2a and 4.3a, respectively (for simplicity of notation, the dependence of radiance on depth $z$ is dropped from the symbols of radiance). The light wavelength of 480 nm is very close to the most penetrating wavelength in the investigated waters. Both $L_{180}(\lambda)$ and $L_0(\lambda)$ demonstrate a characteristic decrease of radiance magnitude with depth at both stations. These semi-logarithmic plots of radiance exhibit a pronounced curvature in the depth profiles in the violet and blue wavebands. This curvature does not result from changes in surface irradiance ($E_s$) during the acquisition of profile data. For the noon station the surface irradiance, $E_s$, remained nearly constant with time during deployment of the underwater radiance instrument (Fig. 4.2b). For the sunrise station $E_s$ increased with time during underwater profiling measurements (Fig. 4.3b), however, this variation would act to cause an opposite curvature in the depth profiles of underwater radiances compared with observations. Therefore, the curvature in the depth profiles of underwater radiance can be attributed to changes in the diffuse attenuation coefficient with depth as a consequence of a non-uniform depth profile of inherent optical properties of seawater as evidenced by a non-uniform profile of Chl (not shown). For the noon station the values of $L_{180}(\lambda)$ and $L_0(\lambda)$ are similar to each other throughout the water column, whereas at sunrise the value of $L_{180}(\lambda)$ is significantly higher than $L_0(\lambda)$. This result is consistent with the expectation that the $L_{180}(\lambda)$ sensor receives more light than the $L_0(\lambda)$ sensor when the sun position in the sky is low, and the difference disappears when the sun reaches its zenith. The spectra of $L_{180}(\lambda)$ and $L_0(\lambda)$ at selected depths for these stations (Fig. 4.2c,d, Fig. 4.3c,d) exhibit a relatively broad maximum in the blue spectral region between 400 and 500 nm, a sharp decrease on both sides of the maximum (in the UV range and green-red range), and narrowing of the maximum with increasing depth. These are general features which are also typically observed in other radiometric characteristics of the underwater light field in clear ocean waters. However,
there are significant spectral differences in $L_{180}(\lambda)$ and $L_0(\lambda)$ between the noon and sunrise measurements. At noon, the two spectra are nearly identical at each depth (Fig. 4.2c, d) but differ markedly when the sun is near the horizon (Fig. 4.3c, d). In the latter case, the peak of the $L_{180}(\lambda)$ spectrum in the upper 100 m is shifted towards longer wavelengths relative to $L_0(\lambda)$ and exhibits maximum values at about 470 nm. For $L_0(\lambda)$ the maximum is about 415 nm. This observation can be attributed to differences in the spectral composition of light incident on the sea surface at different directions when the sun is near the horizon. The light coming from the direction of sun near the horizon is enriched with longer-wavelength radiation compared to light coming from the opposite directions because of the strong spectral dependency of molecular scattering of sunlight along an increased pathlength through the atmosphere.

The vertical profiles of the asymmetry factor $\gamma(\lambda)$ of horizontal radiance differ between the two stations as well. For the noon station the asymmetry is very small with the spectral values of $\gamma(\lambda)$ within 10 – 20% of 1 (Fig. 4.4a). Such small asymmetry remains fairly stable throughout the water column. In contrast, for the sunrise station the asymmetry shows a clear decrease with depth within the upper 50 m, with the $\gamma(\lambda)$ values significantly greater than 1 at shallow depths and tending towards 1 with increasing depth (Fig. 4.4c). This result is consistent with the expectation that at shallower depths the $L_{180}(\lambda)$ sensor receives more light than the $L_0(\lambda)$ sensor when the sun position in the sky is low.

There are also remarkable differences in the spectral patterns of the asymmetry factor $\gamma(\lambda)$ among the two stations. The decrease of the asymmetry with depth for the sunrise station is more pronounced in the green than in the blue wavelengths (Fig. 4.4c). In the green spectral band (550 nm), the values of asymmetry factor exceed 3 at depths smaller than 20 m and decrease with depth to about 1 around 55 m. In addition, at noon $\gamma(\lambda)$ shows very little spectral dependence regardless of depth (Fig. 4.4b), whereas
at sunrise it shows significant increase with increasing wavelength (Fig. 4.4d). The degree of this spectral dependency decreases with depth but is still observed below 100 m. Within the top 30 m of the ocean, the asymmetry factor at the sunrise station exceeds 2 for wavelengths > 550 nm, reaching 5 at the longest wavelengths. The asymmetry in the UV range (350 – 400 nm) for both stations was very low but $\gamma(\lambda)$ was still detectably different from 1, especially at shallow depths. Overall the values of $\gamma(\lambda)$ in this spectral region exhibit very little spectral dependence regardless of depth, varying around 1.

4.4.2 Simulated $L_{180}$, $L_0$, and $\gamma$ for the field stations

4.4.2.1 Dependence of $\gamma$ on solar zenith angle and light wavelength

To extend the analysis of the field observations, radiative transfer simulations were used to examine the dependence of the spectral asymmetry factor $\gamma(\lambda)$ on solar zenith angle and depth. Figure 4.5 depicts a comparison of the results obtained from simulations with measured values at light wavelength of 480 nm. Modeled results were obtained from simulations with IOPs derived from a single measured Chl depth profile from station #4 ($Chl$ varies from 0.1 to 0.3 mg m$^{-3}$ throughout the water column) assuming a particle backscattering fraction of $b_{bp}/b_p = 0.005$. We note that the measured results in this figure represent five stations where $\theta$ ranges from $\approx 3^\circ$ to $81^\circ$ with slightly different Chl and hence IOP profiles. However, as water properties were generally similar at all stations, our approximation based on station #4 about input IOPs to simulations is sufficient to allow qualitative comparisons of modeled and measured data. For all depths, the measured values of the asymmetry factor $\gamma(\lambda)$ initially increase with increasing solar zenith angle, exhibit a maximum value for the station representing $\theta \approx 60^\circ$, and then drop distinctly for the largest solar zenith angle of $\theta \approx 80^\circ$. A similar trend in asymmetry can be observed in the upper 50 m for the modeled results, with the maximum value of the asymmetry occurring at a solar zenith angle of $\theta \approx 60^\circ$ for surface waters and declining
asymmetry at larger values of $\theta$. This result is consistent with the previous observation that the highest asymmetry of the horizontal light field at relatively shallow depths occurs not when the sun is near the horizon, but at the zenith angles of $\theta \approx 60^\circ - 70^\circ$ [Johnsen et al., 2014]. Although the radiance measurements were made at fewer solar zenith angles than the simulations, the overall behavior of $\gamma(\lambda)$ as a function of zenith angle is similar for both modeled and measured results.

The pattern of changes in $\gamma(\lambda)$ with varying $\theta$ in surface waters observed in Fig. 4.5 is also evident in other spectral bands for the simulation results, but the maximum magnitude of $\gamma(\lambda)$ increases significantly with increasing light wavelength (Fig. 4.6). In the UV spectral band ($\lambda = 350 \text{ nm}$) the asymmetry factor reaches a maximum value of about 1.35 at $\theta \approx 70^\circ$ within the first 10 m of the water column (Fig. 4.6a). In the red spectral region ($\lambda = 650 \text{ nm}$) the value of this maximum increases to 3.6 (Fig. 4.6d).

For the top 10 m layer of the ocean under clear sky conditions, differences in the relative proportions of skylight and the direct solar beam in the total irradiance incident on the sea surface appear to be primarily responsible for these observed patterns in $\gamma(\lambda)$. In general, increased values of $\gamma(\lambda)$ are expected to result when contributions of the direct solar beam increase relative to diffuse skylight. Previous observations have shown that the diffuseness of surface irradiance is strongly dependent on solar zenith angle and light wavelength [e.g., Jerlov, 1976; Stramski, 1986]. The relative diffuseness of light incident upon the sea surface at any given light wavelength, $d_E$, can be expressed as a ratio of the proportion of downwelling plane irradiance consisting of diffuse skylight, $E_d(sky)$, to the total downwelling plane irradiance

$$d_E = E_d(sky) / [E_d(sky) + E_d(sun)],$$

(4.7)

where $E_d(sun)$ represents the irradiance associated with the direct solar beam. For the
simulations representing clear sky conditions, we examined variations in $d_E$ with solar zenith angle as computed by the atmospheric model provided by HydroLight (Fig. 4.7). For the sun near zenith, the contribution of the direct solar beam to incident surface irradiance predominates and $d_E$ has the lowest values ($< 0.3$ for the visible spectrum and $> 0.4$ in the UV). Values of $d_E$ at any given light wavelength increase with increase in solar zenith angle. In the visible spectral region diffuse skylight becomes predominant ($d_E > 0.5$) for $\theta$ of about $70^\circ$ and then $d_E$ further increases sharply as the sun approaches the horizon. It is natural to expect that the pattern of increasing diffuseness with an increase in solar zenith angle will persist in the light field immediately below the sea surface, and as the depth increases the diffuseness of light field will further increase owing to light scattering by seawater. We also note that as Fresnel reflectance of the direct solar beam increases sharply for incident angles above $\theta = 50^\circ$, the diffuseness of downwelling irradiance at any given wavelength at large solar zenith angles is expected to be higher just below the surface compared to just above the surface. In principle, this can be expected to reinforce the effect associated with variation of diffuseness of surface irradiance on the observed pattern of $\gamma(\lambda)$ as a function of $\theta$ at large solar zenith angles.

The distinctive spectral pattern of $d_E$ is also observed in the results of the simulations. At any given value of $\theta$, $d_E$ increases with decreasing wavelength as a result of strong wavelength-dependence of molecular scattering of atmospheric constituents (Fig. 4.7). Values of $d_E$ are considerably higher in the UV spectral region than in the visible, and skylight predominates over direct sunlight in the UV for $\theta > 40^\circ$. In consequence, this spectral band exhibits the lowest asymmetry with the smallest range of $\gamma(\lambda)$ values, in contrast to the red spectral region where the largest variations and maximal values of asymmetry are observed (Figs. 4.4, 4.6).

In both the field measurements and the simulations of field stations, the largest asymmetry for most spectral bands is generally observed in surface waters for solar
zenith angles between about 60° and 80° (Figs. 4.5, 4.6). In general, as depth increases \( \gamma(\lambda) \) is expected to decrease and tend towards a more uniform distribution of horizontal radiance owing to the increased prevalence of elastically-scattered light with increasing depth in the water column. In addition, for some spectral regions, in particular from the green through red, the increasing contribution of photons originating from inelastic radiative processes such as Raman scattering by water molecules or fluorescence of dissolved organic matter or chlorophyll-a will also serve to decrease asymmetry as these sources are isotropic or nearly so [Marshall and Smith, 1990; Berwald et al., 1998; Li et al., 2014]. Over the entire depth range of measurements and simulations, this expected pattern is observed in the results for large zenith angles (Figs. 4.5, 4.6). In consequence, the increasingly diffused light field at depth is less influenced by the position of the sun and the maximum value of the asymmetry factor shifts towards lower solar zenith angles with increasing depth. For example, in the simulated results the maximum value of \( \gamma \) at 10 m occurs at \( \theta \approx 70^\circ \), but shifts to \( \theta \approx 50^\circ \) at 150 m depth (Fig. 4.6).

However, for a range of intermediate zenith angles (10° – 60°) values of \( \gamma(\lambda) \) are sometimes observed to have slightly higher (by less than 20%) values at depth compared with those closer to the surface (Fig. 4.6a, b). This feature is most prevalent for the more penetrating wavelengths such as the blue spectral region (480 nm), and can be seen in both measurements and simulations (Figs. 4.5, 4.6b). This observation is not easy to interpret, as it likely results from the interplay of several factors such as vertical distribution of IOPs including angular scattering properties of seawater and proportions of direct and diffuse light.
4.4.3 Generalized simulations of $L_{180}(\lambda)$ and $L_0(\lambda)$

4.4.3.1 Asymmetry of horizontal radiance in optically different water bodies

It has long been known that phytoplankton and covarying materials are primarily responsible for determining the variability in optical properties of oceanic waters that are often referred to as case 1 waters [Morel and Prieur, 1977]. We performed additional radiative transfer simulations using different chlorophyll-a concentrations in surface waters to examine the behavior of the asymmetry factor $\gamma(\lambda)$ in different water bodies exhibiting different inherent optical properties. The concentrations of 0.02, 0.2, and 2 $mgm^{-3}$ were chosen to span a range from very clear ultra-oligotrophic waters to eutrophic scenarios. The value of 0.2 $mgm^{-3}$ is similar to the global mean value of oceanic surface Chl as estimated from satellite observations [Gregg and Conkright, 2002]. The vertical distribution of chlorophyll-a, and thus computed IOPs, were assumed to be constant in these simulations. The results for the asymmetry factor as a function of solar zenith angle are presented in Fig. 4.8 for the three values of Chl, several depths, and four light wavelengths. All these simulations assumed a particle backscattering fraction of $b_{bp}/b_p = 0.005$. At shallow depths (the top 10 m layer) the values of the asymmetry factor at all wavelengths increase significantly with increasing Chl. This increase is clearly seen for most solar zenith angles with the exception of very small solar zenith angles because the asymmetry approaches 1 for the sun at zenith for all Chl cases. The observed trend of increasing asymmetry with increasing Chl is well-pronounced for the maximum values of asymmetry observed at solar zenith angles of about $60^\circ - 70^\circ$. For low Chl (0.02 $mgm^{-3}$) the value of $\gamma(\lambda)$ at 1 m depth peaks between 1.2 and 3.4, depending on the wavelength (Fig. 4.8a, d, g, j), whereas for high Chl (2 $mgm^{-3}$) the maximum values of $\gamma(\lambda)$ range between 2.4 and 6 (Fig. 4.8c, f, i, l), around twice the low Chl case.

At first glance the increase in asymmetry with increasing Chl may seem to be
counterintuitive because the turbidity of water increases with Chl, and hence the light field is expected to be more diffuse. However, the trend observed in our results for shallow depths can be explained in terms of angular structure of light field and variations in the volume scattering function (VSF) of seawater with changing Chl. We first recall that the light field at shallow depths is dominated by radiance associated with direct solar photons propagating underwater along the direction of refraction defined by Snell’s law [e.g., Jerlov, 1976]. When the sun position is away from the zenith, the direction of refracted light is also away from the vertical. It is also reasonable to assume that the major contribution to the horizontal radiance $L_{180}(\lambda)$ at shallow depths comes from scattering of refracted solar beam at some appropriate forward scattering angle into the horizontal direction pointing away from the sun. Similarly, the major contribution to the horizontal radiance $L_0(\lambda)$ comes from scattering of refracted solar beam at some appropriate backward scattering angle into the horizontal direction pointing towards the sun. With increasing Chl the scattering by particles becomes increasingly predominant over that of pure water, and the VSF of seawater becomes more peaked in forward directions, so the proportion of forward-scattered light increases compared with backward-scattered photons. As a result, we observe an increase in the asymmetry of horizontal radiance with increasing Chl and water turbidity at shallow depths. This pattern is not observed at deeper depths, however. For example, at a depth of 50 m the asymmetry for turbid waters ($Chl = 2 \text{ mg m}^{-3}$) is lower compared with clearer waters (Fig. 4.8). This result can be attributed to light scattering occurring along a longer optical pathlength within the water column and increasing contribution of multiple scattering events that become more prevalent with increasing depth or increasing water turbidity. In general, values of the asymmetry factor decrease with depth in the water column as the contribution of the direct solar beam to the underwater light field decreases and scattering of photons results in an increase in the diffuseness of light field.
The increase of the asymmetry factor with increasing Chl at shallow depths (1 − 10 m) was also observed for higher particle backscattering fraction $b_{bp}/b_p = 0.05$ (not shown). However, for all four example light wavelengths the values of the asymmetry at shallow depths were lower compared to those for $b_{bp}/b_p = 0.005$. The reduction of the asymmetry compared to the case of $b_{bp}/b_p = 0.005$ was also significant for turbid waters ($Chl = 2 \text{ mg m}^{-3}$). The higher $b_{bp}/b_p = 0.05$ causes a decrease in the proportion of forward scattered light relative to backward scattered light, leading to relative decrease in the amount of light measured by the $L_{180}(\lambda)$ sensor compared with the $L_0(\lambda)$ sensor, and hence to overall lower values of the asymmetry. The increase of the asymmetry factor with increasing Chl at shallow depths (1 − 10 m) was also observed for higher particle backscattering fraction $b_{bp}/b_p = 0.05$ (not shown). However, for all four example light wavelengths the values of the asymmetry at shallow depths were lower compared to those for $b_{bp}/b_p = 0.005$. The reduction of the asymmetry compared to the case of $b_{bp}/b_p = 0.005$ was also significant for turbid waters ($Chl = 2 \text{ mg m}^{-3}$). The higher $b_{bp}/b_p = 0.05$ causes a decrease in the proportion of forward scattered light relative to backward scattered light, leading to relative decrease in the amount of light measured by the $L_{180}(\lambda)$ sensor compared with the $L_0(\lambda)$ sensor, and hence to overall lower values of the asymmetry.

4.4.3.2 Influence of different sky conditions on the asymmetry of horizontal radiance

The results presented in section 4.4.2 suggest that changes in the diffuseness of light field incident upon the sea surface under clear sky conditions strongly influence the asymmetry of underwater horizontal radiance. Using the radiative transfer model, we further investigated the effect of sky conditions on the asymmetry factor $\gamma$ through simulations of different scenarios, including the extremes of a clear sky (both direct sunlight and diffuse skylight present), an overcast sky (diffuse skylight only), and a black
sky (direct sunlight only). Figure 4.9 depicts changes in $\gamma$ for the three sky scenarios at selected depths for a light wavelength of 480 nm and single chlorophyll-a concentration of 0.2 $mg m^{-3}$. For the black sky where there is no contribution of diffuse skylight to light incident on the sea surface, the asymmetry factor is significantly greater than observed under other sky conditions, exceeding the value of 7 for the example wavelength of light in the blue spectral region (Fig. 4.9a). In this scenario, the asymmetry factor $\gamma$ increases with increasing solar zenith angle over the entire range of angles, reaching a maximum when the sun is at the horizon ($\theta = 90^\circ$). The results presented in Fig. 4.9a support the expectation that under hypothetical conditions with no light scattering in the atmosphere the asymmetry of underwater horizontal radiance would depend mainly on the sun’s position in the sky, with the asymmetry increasing monotonically with solar zenith angle throughout the entire range of sun’s position. This is because with increasing solar zenith angle the direction of refracted solar beam underwater gets closer to the horizontal, and hence the contributions of forward scattering of solar beam into the horizontal direction increase owing to the forward-peaked angular distribution of scattering by seawater.

For the clear sky the asymmetry factor increases with increasing solar zenith angle reaching a maximum value at $\theta \approx 70^\circ$, and then drops distinctly at larger solar zenith angles, particularly within the top 50 m of the water column (Fig. 4.9b, note that these data are also shown in Fig. 4.8e). The decrease in the asymmetry at large solar zenith angles ($\theta > 70^\circ$) supports the significance of variations in the surface irradiance diffuseness with solar zenith angle in driving the changes in the asymmetry of underwater horizontal radiance. Compared to smaller solar zenith angles ($\theta < 70^\circ$), the pathlength of sunlight traveling within the atmosphere to the water surface at very large solar zenith angles is significantly longer. When the sun approaches the horizon the incident irradiance becomes highly diffuse owing to more molecular scattering occurring along this longer pathlength in the atmosphere, resulting in smaller amount of light received underwater by
the $L_{180}(\lambda)$ sensor and therefore a decrease in the asymmetry factor. This increase of the diffuseness of light incident on the sea surface, and hence also entering the water, with increasing solar zenith angle has long been recognized [Jerlov, 1976; Stramski, 1986]. In addition, at larger solar zenith angles a higher proportion of the incoming direct sunlight gets reflected from the sea surface as the Fresnel reflectance increases with an increase in the angle of incidence [Mobley et al., 1993]. This can further increase a proportion of the diffuse skylight which enters the water at large solar zenith angles. However, the latter effect is not strong enough to cause a noticeable reduction of the asymmetry at large solar zenith angles because such reduction is not clearly observed in the simulations for the black sky scenario. Therefore, it appears that the effect associated with the diffuseness of surface irradiance is most important.

When the sky is overcast the light entering the ocean is totally diffuse at all solar zenith angles with no direct solar beam, resulting in the asymmetry values that are near 1 across the entire range of solar zenith angle (Fig. 4.9c). Nevertheless, a relatively broad maximum of the asymmetry factor is still noticeable. The center of this maximum is around $\theta \approx 60^\circ$ within the upper 10 m of the water column, and shifts to smaller solar zenith angles ($\theta \approx 40^\circ$) at large depths of 100 – 150 m. Regardless of the effect of solar zenith angle on the asymmetry of underwater horizontal radiance at any depth within the water column, the values of the asymmetry decrease with increasing depth for all solar zenith angles independent of sky conditions. This is primarily because of scattering of light within the water column and a general trend of underwater radiance field towards symmetrical distribution around the vertical with increasing depth [e.g., Jerlov, 1976].

4.5 Conclusions

To characterize the underwater horizontal radiance field in the photic zone of the ocean, the ratio of the spectral horizontal radiances in two opposite directions (solar and
anti-solar azimuths) within the solar principal plane, $\gamma$, was examined as a measure of asymmetry of horizontal radiance. The spectral range from the near-UV wavelengths (350 nm) to the red portion of the spectrum ($\approx$ 650 nm) was considered in our analysis. We investigated how the spectral asymmetry factor, $\gamma(\lambda)$, varies as a function of solar zenith angle $\theta$ at different depths within the water column down to depths of 100 – 200 m. This analysis was carried out for different sky conditions and inherent optical properties of seawater as parametrized by different concentrations of chlorophyll-a pigment within the water column. We analyzed the asymmetry factor obtained from both field measurements in oceanic waters off the Hawaiian Islands and radiative transfer modeling of underwater light field in optically different water bodies. Our results show generally good agreement between the measured and modeled patterns in the variability of spectral asymmetry factor throughout the water column and as a function of solar zenith angle. Under clear skies, when the solar zenith angle is small, the asymmetry of horizontal radiance is small regardless of depth and light wavelength. Under such conditions the asymmetry factor $\gamma(\lambda)$ is close to 1. Similarly, for overcast skies the asymmetry factor is close to 1. However, when the skies are clear and solar zenith angle is large, the asymmetry factor can be significantly larger than 1 even at depths as large as $\approx$ 100 m. The largest values of asymmetry are observed at shallow depths for the long-wavelength portion of the spectrum, i.e., from the green through the red part of the spectrum. In this case the asymmetry factor typically exceeds 2, and can be higher than 5 in the red portion of the spectrum. In the near-UV part of the spectrum the asymmetry is generally very small.

Under clear skies the asymmetry factor $\gamma$ exhibits a distinctive pattern of variation as a function of solar zenith angle $\theta$. When the sun position is near zenith (i.e., $\theta \approx 0^\circ$), the horizontal radiance field is approximately symmetric (i.e., $\gamma \approx 1$). The asymmetry increases with increasing $\theta$ until it reaches a maximum which typically occurs around $\theta \approx 60^\circ – 70^\circ$ at shallow depths. Then, with further increase in $\theta$ when the sun approaches
the horizon, the asymmetry decreases. This pattern is more pronounced at shallow depths than deeper in the water column. As depth increases the asymmetry tends to decrease and the solar zenith angle at which maximum asymmetry occurs also tends to decrease. The initial increase of $\gamma$ with increasing $\theta$ is associated with the geometry of illumination of the sea surface and the greater magnitude of forward scattering than backward scattering of light underwater. The presence of the maximum of $\gamma$ followed by a decrease in $\gamma$ at very large solar zenith angles ($\theta > 70^\circ$) is caused primarily by a dramatic increase in the diffuseness of irradiance incident on the sea surface at large solar zenith angles. This result is remarkable in a sense that this signature of maximum in the horizontal radiance asymmetry as a function of solar zenith angle is very well pronounced at near-surface depths where the effects of water optical properties on the asymmetry are not yet significant, so the primary cause factor for such signature of underwater light field is the behavior of diffuseness of surface irradiance associated with light scattering in the atmosphere. Our results also suggest that this imprint of atmospheric effect on the dependence of $\gamma$ on $\theta$ persists throughout the water column of the upper ocean layer, although the role of inherent optical properties of seawater naturally increases with depth. In addition, we found that the asymmetry of horizontal radiance at shallow depths tends to be higher in waters with higher chlorophyll concentrations. As our results contribute insights into the understanding of the horizontal radiance field including variations in its spectral asymmetry within the upper ocean as a function of solar zenith angle in optically different water bodies under different sky conditions, they can aid in better understanding of optical environment experienced by aquatic organisms with implications to animal camouflage and vision.
4.6 Acknowledgments

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Chapter 4, in full, is in revision for publication of the material in Gassmann, E., Stramski, D., Reynolds, R., Johnsen, S., The asymmetry of the underwater horizontal radiance around the vertical axis within solar principal plane. *Applied Optics*. The dissertation author was the primary investigator and author of this paper.
Table 4.1. Parameters of the five stations where the horizontal radiance measurements were conducted. Direct sun during measurements is indicated by '*'.

<table>
<thead>
<tr>
<th>Station</th>
<th>Station #4 (noon)</th>
<th>Station #5 (morning)</th>
<th>Station #5 (afternoon)</th>
<th>Station #6 (sunrise)</th>
<th>Station #6 (morning)</th>
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<td>Time (local)</td>
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<td>08:50-09:04 AM</td>
<td>01:49-02:05 PM</td>
<td>06:29-06:46 AM</td>
<td>07:55-08:08 AM</td>
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<tr>
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<td>49.7°-46.5°</td>
<td>20.1°-23.8°</td>
<td>81.2°-77.7°</td>
<td>62.3°-59.3°</td>
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<tr>
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<td>≈ 3.3 ms⁻¹</td>
<td>≈ 4.9 ms⁻¹</td>
<td>≈ 1.2 ms⁻¹</td>
<td>≈ 1.4 ms⁻¹</td>
</tr>
<tr>
<td>Sky conditions</td>
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<td>partly cloudy*</td>
<td>partly cloudy*</td>
<td>clear</td>
<td>clear</td>
</tr>
<tr>
<td>Surface Chl</td>
<td>0.1 mg m⁻³</td>
<td>0.1 mg m⁻³</td>
<td>0.1 mg m⁻³</td>
<td>0.08 mg m⁻³</td>
<td>0.08 mg m⁻³</td>
</tr>
</tbody>
</table>
Figure 4.1. The radiometer used for underwater horizontal radiance measurements during a deployment. The object hanging below the instrument is a weight to help the instrument maintain a vertical orientation. The two lines on the sides of the instrument were used to help ensure that the instrument maintained a constant azimuth.
Figure 4.2. Results from measurements at the noon station (solar zenith angle $\theta = 3.4^\circ - 3.5^\circ$): (a) Depth profiles of horizontal radiances, $L_{180}(\lambda)$ and $L_0(\lambda)$, for three light wavelengths of $\lambda = 410$, 480, and 550 nm. (b) Downward plane irradiance measured just above the sea surface ($E_s$) during acquisition of the vertical profile data throughout the water column. (c) and (d) Spectra of $L_{180}(\lambda)$ and $L_0(\lambda)$ at selected depths, respectively.
Figure 4.3. Results from measurements at the sunrise station (solar zenith angle $\theta = 77.7^\circ - 81.2^\circ$): (a) Depth profiles of horizontal radiances, $L_{180}(\lambda)$ and $L_0(\lambda)$, for three light wavelengths of $\lambda = 410, 480, \text{ and } 550 \text{ nm}$. (b) Downward plane irradiance measured just above the sea surface ($E_s$) during acquisition of the vertical profile data throughout the water column. (c) and (d) Spectra of $L_{180}(\lambda)$ and $L_0(\lambda)$ at selected depths, respectively.
**Figure 4.4.** Depth profiles of the asymmetry factor, $\gamma$, for three light wavelengths of $\lambda = 410$, 480, and 550 nm and spectra of $\gamma$ at selected depths for the noon (a) and (b), and sunrise (c) and (d) stations, respectively.
Figure 4.5. The asymmetry factor, $\gamma$, as a function of solar zenith angle, $\theta$, at three selected depths for light wavelength of $\lambda = 480$ nm for measured (solid circles connected by a dotted line) and modeled (solid lines) results. Modeled results were obtained from radiative transfer simulations with inherent optical properties of seawater derived from depth profile of chlorophyll-a concentration, $Chl$, measured at station #4. Chl values ranged from 0.1 mg m$^{-3}$ at near-surface depths to 0.3 mg m$^{-3}$ at the chlorophyll-a maximum around 140 m.
Figure 4.6. The asymmetry factor, $\gamma$, as a function of solar zenith angle, $\theta$, at selected depths obtained from radiative transfer simulations for four light wavelengths of $\lambda = 350$, 480, 550, and 650 nm (panels a, b, c, d, respectively). Modeled data were obtained with the same input to the simulations as in Fig. 4.5.
Figure 4.7. Diffuseness of downwelling plane irradiance incident on the sea surface, $d_E$, as a function of solar zenith angle, $\theta$, obtained from radiative transfer model for four light wavelengths of $\lambda = 350, 480, 550$ and 650 nm. Modeled data were obtained from the same simulations as presented in Figs. 4.5 and 4.6.
Figure 4.8. The asymmetry factor, $\gamma$, as a function of solar zenith angle, $\theta$, at selected depths obtained from radiative transfer simulations for four light wavelengths of $\lambda = 350 \text{ nm}$ (a, b, c), $\lambda = 480 \text{ nm}$ (d, e, f), $\lambda = 550 \text{ nm}$ (g, h, i) and $\lambda = 650 \text{ nm}$ (j, k, l) and three selected chlorophyll-a concentrations, $Chl = 0.02$, 0.2, and $2 \text{ mg m}^{-3}$.
Figure 4.9. The asymmetry factor, $\gamma$, as a function of solar zenith angle, $\theta$, at selected depths obtained from radiative transfer simulations for light wavelength of $\lambda = 480 nm$ and $Chl = 0.2 mg m^{-3}$ for three different sky conditions; black sky (a), clear sky (b), and overcast sky (c). Note different scale of $y$ axis in different panels.
4.7 References


Chapter 5

Conclusions

The major contributions of this PhD dissertation advance our understanding of two distinctive features of underwater light field: (i) the surface induced by surface waves high-frequency light fluctuations within the near-surface layer, and, (ii) the asymmetry of horizontal radiance within the photic layer of the ocean.

For the first time the spatiotemporal statistical properties of wave-induced light fluctuations were measured and characterized very close to the surface at depths < 0.5 m where the fluctuations are strongest (chapter 2 and chapter 3). The fluctuations at near-surface depths were resolved at spatial and temporal scales down to 1 cm and 1 ms in both the open ocean and near-shore environments using two novel specially developed instruments, the Porcupine Underwater Radiometer System and the SeQuence of Underwater Irradiance Detectors (SQUID). The Porcupine was developed to measure temporal characteristics of fluctuations at a point in space and SQUID to measure both the temporal and spatial characteristics of fluctuations. Both instruments were equipped with sensors to measure the spectral downward plane irradiance (within the visible portion of the spectrum) with sampling frequency of 1 kHz and the size of light collector of 2.5 mm. These features are important to adequately resolve the short time scales and small spatial scales of wave focusing events at near surface depths. The measurements were taken between ≈ 0.5 m and 10 m depth during the open ocean experiments and between
10 cm and 3 m during the near-shore experiment, both under sunny sky conditions at different solar zenith angles and weak to moderate wind speeds. It was found that that the maximum intensity of light fluctuations occurs at depths as shallow as 20 cm (not at ≈ 1 m as previously reported) under the most favorable conditions for wave focusing, which correspond to high sun in a clear sky with weak wind. The strong frequency dependence of the dynamic near-surface underwater light field indicates dominant frequency range of 1–3 Hz under favorable conditions that shifts toward lower frequencies with increasing depth. The spatial autocorrelation length of light fluctuations at near-surface depths was found to vary from a few cm up to 10–20 cm. For example, the underwater light field within the top 50 cm was found to be spatially correlated over horizontal distances of 1–2 cm, whereas at a depth of 1.05 m over horizontal distances up to 12 cm for ≥ 8 ms⁻¹ wind speeds and ≥ 56° solar zenith angles. Also, an entirely novel insight gained from the frequency analysis concerns the frequencies at which the light field is coherent in space. The maximum coherence lengths of spatial light fluctuations (from a few cm up to 20 cm) were found at dominant frequencies of 1–3 Hz, below a depth of 0.5 m for weak to moderate wind speeds (1.8–8 ms⁻¹) and moderate solar zenith angles (38.4° and 66.1°). Both the spatial autocorrelation length and distance of coherence tend to increase with increasing depth, solar zenith angle, and wind speed. The observed variations in spatiotemporal statistical properties of underwater light fluctuations with depth and environmental conditions are driven largely by weakening of sunlight focusing which is associated with light scattering in the atmosphere, at the air-sea interface, and within the water column.

Another major contribution of this dissertation stems from the investigation of the horizontal radiance field in the photic zone of the ocean. For the first time comprehensive analysis of variations in the asymmetry of horizontal radiance within the solar principal plane for different solar zenith angles, depths, inherent optical properties of seawater, and
different light wavelengths ranging from near-UV through the visible spectral range was made. This analysis is based on both the measurements of spectral horizontal radiance and modeling of radiative transfer in the ocean (chapter 4). The asymmetry of horizontal radiance was found to increase with increasing solar zenith angle, reaching a maximum at angles of $60^\circ – 80^\circ$ (and not when the sun is near the horizon) under clear skies at shallow depths. At larger depths the maximum of the asymmetry occurs at smaller solar zenith angles. Also, the asymmetry showed a significant spectral variation with the highest values in the red spectral regions and lowest in blue and ultraviolet (UV). An important novelty of evaluating the spectral asymmetry is the UV part of radiance field that has not been previously reported. The results from radiative transfer simulations of the underwater radiance field confirmed the experimental observations and revealed a greater asymmetry in waters with higher chlorophyll concentrations at shallow depths. Modelling different sky conditions (including the hypothetical black sky) examined the sky effect on the horizontal radiance and provided evidence that variations in the asymmetry with solar zenith angle are driven largely by the diffuseness of light incident upon the sea surface and the geometry of illumination of the sea surface, both associated with changing position of the sun.

In addition to contributions to the field of ocean optics itself, the findings of this dissertation have relevance for ocean biology and photochemistry. For example, our findings related to variations in the asymmetry of horizontal radiance within the photic layer have significance for behavior, vision, and camouflage responses of many aquatic animals. The problem of mirror-based crypsis of silvery-sided pelagic fish under specific viewing geometries determined by the asymmetry of the horizontal light field was described in the recent collaborative study [Johnsen et al. 2014], which is not included in this dissertation. The insight of the horizontal radiance asymmetry at UV wavelengths can contribute to better understanding of the behavioral responses to light of the near-surface...
species, given the prevalence of ultraviolet vision and high intensity of UV radiation in clear, shallow oceanic waters. The wave-induced near-surface light fluctuations presented here have also implications for animal behavior and camouflage. The spatiotemporal scales of these fluctuations can provide insights for better understanding the stimulatory fields faced by a wide spectrum of aquatic animals, but also are likely significant to camouflaging animals of comparable sizes. In addition, the results are encouraging for further investigations with the potential of advancing ocean sea-surface studies as the strong frequency-dependence of the coherence length of light fluctuations is presumably related to the ocean surface waves that induced the irradiance fluctuations. Besides, the phenomenon of those light fluctuations is certainly important for photosynthesis and other photochemical processes within the near-surface ocean, although potential implications have been poorly investigated and are not well understood. The results from this study can aid in further research in this direction.