

## **Analysis of the in-Water and Sky Radiance Distribution Data Acquired During the RaDyO Project**

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### **LONG-TERM GOALS**

My work involves experimentally investigating the interrelationships and variability of optical properties in the ocean and atmosphere. My goal is to define the variability of the optical properties, particularly those dealing with light scattering, and to improve the prediction capabilities of image and radiative transfer models used in the ocean. My near term ocean optics objectives have been: 1) to improve the measurement capability of measuring the in-water and above-water spectral radiance distribution and extending this capability to polarization, 2) to investigate the variability of the Point Spread Function (PSF) as it relates to the imaging properties of the ocean, and 3) to improve the characterization of the Bi-directional Reflectance Distribution Function (BRDF) of benthic surfaces in the ocean, and 4) to understand the capabilities and limitations of using radiative transfer to model the BRDF of particulate surfaces.

### **OBJECTIVES**

The major objective of this research is to understand the downwelling spectral polarized radiance distribution, in the near surface of the ocean.

### **APPROACH**

We have built, with ONR support (through the DURIP program) a camera system capable of measuring the polarization state of the downwelling radiance distribution. This instrument follows in the footsteps of other instruments we have developed (Voss and Liu, 1997) and uses a combination of 3-4 images of the radiance distribution to form this polarized radiance distribution. Because the downwelling radiance distribution is very dynamic, we need to have a system that will quickly make these images as matched as possible, so this required a completely new design.

The system we have designed uses 4 fisheye camera lenses with coherent fiber bundles behind each image. Each fisheye will have a polarizer in a different orientation. After the image is in the coherent fiber bundle, these bundles will be brought together and imaged on a CCD array camera, through a filter changer (for spectral information). Thus in a single image we will have 4 separate fisheye images of the scene, each with different polarization information. This instrument was used in the

RaDyO program. The work of this proposal was to analyze the data acquired during the RaDyO program, and prepare articles for publication.

## **WORK COMPLETED**

During the last year we have submitted 3 papers from our own work, and collaborated on an additional 4 papers with RaDyO co-investigators. 3 of these papers have been published, while the remaining papers are accepted and will be published in a JGR special issue including other RaDyO publications. Along with this, the graduate student working on the project finished his Ph.D. thesis and has graduated.

## **RESULTS**

Our measurements found that the polarization behavior of the light field in water near the surface is dominated by the refracted sky light, and depends strongly on the wave-induced curvatures of the water surface. Therefore, near the surface the polarization is predominately inside the Snell's cone. At 1.5 m depth the maximum Degree of Linear Polarization, *DoLP*, for 520 nm, was found to be about 65%, similar to the skylight. Near the surface in clear water this *DoLP* had no clear spectral dependence; however, for more turbid waters, the path radiance from skylight decreases the *DoLP* in proportion to the available skylight. As one progresses in the water column the polarization due to light scattering by the water increases, thereby reducing the effect of refracted sky light. Thus, with the increase of the water depth, the maximum in the polarization moves from the refracted direction of 90° scattering in air, to 90-100 degree scattering angle in water, as expected from the oceanic Mueller matrix [Voss and Fry, 1984]. The peak of the radiance also shifts towards the center (zenith) away from the refracted solar position. This shift is more prominent when the water attenuation coefficient increases, as in coastal waters (SBC). The maximum *DoLP* also decreases with increasing depth. Our data showed that, at a comparable depth, the maximum *DoLP* in clear water is larger than in turbid water. We also found that the pattern of  $\chi$  remains very constant with depth and location, which is interesting, as this is thought to be used by animals for navigation in some cases. This work is detailed in Bhandari et al. [2011].

Our data, for both the sky and in the water, was also used by the two major modeling groups in RaDyO, to successfully validate their radiative transfer models. This work is detailed in the papers by Yu et al. [2011] and Xu et al. [2011]

One very interesting thing that came out of our research over the past year was the observation of off-axis neutral points in the upwelling light field.[Voss et al., 2011] Neutral points in the atmosphere have been studied since the 1800's. They are very sensitive to changes in the atmospheric conditions and are only rarely found off axis. No one had experimentally observed these points off-axis neutral points in the upwelling in-water light field before. We found these in our measurements in the case of very clear water. Our early modeling efforts have indicated that the off-axis position of the neutral points is caused by the addition of the diffused skylight radiance adding to the polarized field of the direct solar radiance. This was a fun, and interesting, offshoot of our polarization measurements.

## **IMPACT/APPLICATIONS**

The goal of the overall RadYO program is to understand how the radiance distribution is modified in the near surface, and what factors are important to this modification. Our work is showing how the

near surface polarized radiance distribution is modified as it is transmitted through the air-sea interface and then into the water column.

## **RELATED PROJECTS**

This project was part of the overall ONR RadYO program. We also have had DURIP support to build the instrument, fundamental to this work. Our work on the polarized radiance distribution is also related to our efforts with NASA funding to look at both the upwelling radiance distribution and the polarized upwelling radiance distribution.

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