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3D Time Dependent Stokes Vector Radiative Transfer in an Atmosphere-Ocean System Including a Stochastic Interface

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LONG-TERM GOALS

The major objective of this proposal is to calculate the 3-D, time dependent radiation field both within the ocean and in the atmosphere in the presence of a stochastically varying interface which may also be perturbed by sea foam, air bubbles, surfactants, rain, etc. This study will serve as the genesis to the future evolution of an inversion algorithm whereby one could reconstruct images that have been distorted by the interface between the atmosphere and the ocean or the ocean itself. This study will rely heavily on both the spectral and polarimetric properties of the radiation field to deduce both the sea state and the perturbations produced on it. A second phase of this study will be to explore the asymptotic polarized light field and to determine how much information can be obtained about the IOP's of the medium by measuring it. The third phase of this proposal will deal with the problem of improving image resolution in the ocean using some novel polarimetric techniques that we are just beginning to explore. Once these studies have been completed using a passive source, it will be rather straightforward to extend them to active sources where we can explore the use of both photo-acoustic and ultrasound-modulated optical tomography to improve image resolution.

OBJECTIVES

The new Navy initiative is focusing on one of the most formidable problems in radiative transfer theory; namely, calculating the full 3D time dependent radiation field (with full Mueller matrix treatment) in a coupled atmosphere-ocean system where the boundary separating the two has both spatial and temporal dependence. Although a great deal of work has been done on obtaining power spectra for ocean waves, I know of no work that has yielded similar results for the radiation field within the ocean. It is clear that as long as the surface has a significant effect on the internal light field, it will leave its signature on the radiation field within the ocean and the relative strength of this field compared to the ambient field will determine the success or failure of inversion algorithms. However, as we go deeper within the ocean we start to enter a region called the asymptotic region where all photons lose memory of their origin and the light field then remains stationary and becomes independent of the azimuthal angle. The depth dependence becomes simply exponential, i.e. $\mathbf{L}(z+h,\theta) = \mathbf{L}(z, \theta) \exp(-kh)$ where k is called the diffusion exponent. It should be noted at this juncture that this asymptotic light field is still polarized which is why we used the bold-faced vector notation. We were the first to compute the degree of polarization for this asymptotic light field for Rayleigh scattering and

were able to obtain an analytic expression for both the polarized radiation field and the diffusion exponent (see ref. 1). In addition, we were also able to set up a numerical scheme to compute the polarized radiation field as well as the diffusion exponent for any single scattering Mueller matrix. The interesting feature about the asymptotic light field is that it depends profoundly on both the single scattering albedo as well as the phase function of the medium. We also found that substantial errors will occur in both the ordinary radiance and the diffusion exponent if they are calculated from scalar rather than vector theory

APPROACH

There are several stages to our approach that we will enumerate. The sine qua non for this entire project will be the development of a fully time dependent 3-D code capable of calculating the complete radiation field, i.e. the complete Mueller or Green matrix at any point within the atmosphere-ocean system. This of course implies that both horizontal as well as vertical IOP's must be accounted for. It should also be noted that the code must be capable of handling internal sources as well in order to explore both fluorescence and bioluminescence. At present there are several 3D codes that are able to compute various radiometric quantities in inhomogeneous media; however, as far as we know, none exists which will couple both atmosphere and ocean with a time dependent stochastic interface. One of the earliest 3D radiative transfer (RT) codes was developed by Stenholm, et. al[2] to model thermal emission from spherical and non-spherical dust clouds. It was based on an implicit discretization of the transfer equation in Cartesian frames. To our knowledge, the first 3D-scalar RT code using discrete ordinates was written by Sánchez[3] et al.; however, it did not make use of spherical harmonics and lacked efficiency and accuracy particularly for small viewing angles. The addition of polarization to the 3D discrete ordinates method was done by Haferman[4] et al. Almost concurrently, a 3D-scalar RT code was written by K. F. Evans[5] which used both spherical harmonics and discrete ordinates. This method uses a spherical harmonic angular representation to reduce memory and CPU time in computing the source function and then the RT equation is integrated along discrete ordinates through a spatial grid to model the radiation streams. We have already obtained this code and will use it for validation of our 3D scalar Monte Carlo code for both the atmosphere and ocean components. Several Monte Carlo codes both scalar and vector have been published for solving specialized problems in atmospheric optics usually dealing with finite clouds[6,7,8,9]. Without exception, these codes are using quite primitive, also called "brute force" , methods. None of them will do what we are proposing in our approach to the fully time dependent 3D solution applicable to both atmosphere and ocean. It should be mentioned that we have already successfully added to our Green matrix Monte Carlo code the capability to handle internal sources such as fluorescence, bioluminescence and even thermal emission.

Once we have developed our 3D code to handle both the ocean and atmosphere without the interface included, we will then develop a 3D form of 1D matrix operator theory that we worked out in two seminal papers published in Applied Optics[10,11]. The basic idea of the method is that if one knows the reflection and transmission operators of say two layers, then it is rather straightforward to get the reflection and transmission operators for the combined layer. With this method we can start from an infinitesimal layer and build large and even semi-infinite layers in a rapid way, i.e. if we start with a layer of thickness Δ then in N steps we can reach a thickness of $2^N\Delta$. Another very relevant feature of this method is that it will allow us to add the interface to the "bare" ocean, i.e., one without an interface, to get the combined ocean-interface operator and then add this layer to the atmosphere for the final reflection and transmission operators for the combined system. The question immediately arises is why not solve the entire system at the same time? The answer is that by doing it this way we

only have to use the adding feature to combine the time dependent interface thus avoiding performing the entire calculation at each instant in time. This method has also become known as the adding-doubling method. These operators are effectively the impulse response or Green matrix for the upper and lower boundaries of the medium. Therefore, if we know the external radiance input into both upper and lower layers, we can then obtain the output at both the upper and lower boundaries of the combined system. A pictorial description of the method is shown in Fig. 1. It should be emphasized that this method will also handle internal sources as well such as bioluminescence, fluorescence, and even thermal emission. This method can also handle detectors at any interior point in the medium. Another bonus of matrix operator theory is that one can easily obtain the path radiance between source and detector which is a sine qua non for image analysis.

In order to add a interface which is spatially inhomogeneous in the y direction but homogeneous in the x direction, we will need the reflection (R) and transmission (T) operators for both the atmosphere and ocean now as a function of time t and both z and y; namely $R(y-y_0,z,t,\theta,\phi)$ and similarly for T. It is important to note that we only have to obtain the response of the atmosphere or ocean to a single line source at the point y_0 and then using the translational invariance of the medium in the y-direction will have the reflection and transmission operators at every point in the y-direction. The only method we know to create these 2-D operators is Monte Carlo. Once these are obtained, we can use the output from each layer as the input to the surface boundary whose reflection and transmission properties are either known or calculable. For instance if the surface consists of just capillary or gravity waves, then we just need the Fresnel coefficients to give us the requisite reflection and transmission operators for the interface. Now once these operators are obtained then we can use extended matrix operator theory to get the final time dependent radiation field that a detector will see. Let us consider the simplest case where the surface is 1-D and we know its power spectrum. It should be emphasized at this point that it is not sufficient to have just a wave-slope distribution since it will only give us statistically averaged results for the radiance field. The introduction of the spatial and temporal dependent interface destroys the symmetry and makes all 1-D codes essentially useless in this domain. At each instant in time, the surface will have a distinct shape that will evolve in time. We have developed a method using linear filter theory whereby we can take an ocean power spectrum and using a random number generator crate a realistic surface that will match the original power spectrum and will still exhibit both stationarity and ergodicity. Now the nice feature about what we are proposing is that we can now concentrate on just the effects of the surface on the detectors since as the surface evolves in time so too will the radiance field as recorded by the detectors. Now both the spatial and temporal profiles will be constantly changing; however, we will have created them from a medium which has been assumed stationary and only the interface produces the time dependence and the horizontal spatial inhomogeneities, i.e. the R and T operators for both the atmosphere and ocean need only to be computed **once.** This is clearly a first-order solution to the more complex problem; however, it should tell us a great deal about future complexities of inversion and also the efficacy of pursuing the next level of difficulty. If the surface is perturbed by foam, bubbles, etc. then these can be added and the matrix operator theory will be used to calculate the effective reflection and transmission operators of the perturbed surface. It should also be stated that this project is enormously computationally intensive; however, the type of codes we will produce are ideally suited for large-scale parallel processors, which we do have access to.

The next level of difficulty is where we will use Monte Carlo methods to compute a full 3-D distribution of the time dependent radiation field, which now may include 3-D inhomogeneities in both the ocean and atmosphere. This will be a computational tour de force requiring a major new computer program that must be capable of placing IOP's of both the atmosphere and ocean at each point in a

large 3-D grid. Matrix operator theory will again be used but it will now be much more complicated since our reflection and transmission operators now become functions of three spatial variables. In fact, the complete solution to this problem could approach the complexity of the general circulation models used in weather forecasting. Due to the large volume of data that will be generated, we will clearly have to develop methods to easily display animated sequences of this time dependence.

There projects were worked on by Dr. Pengwang Zhai, who left for NASA Langley Research Center in August of 2008, and are now being worked on by Dr. Yu You, a postdoctoral research associate.

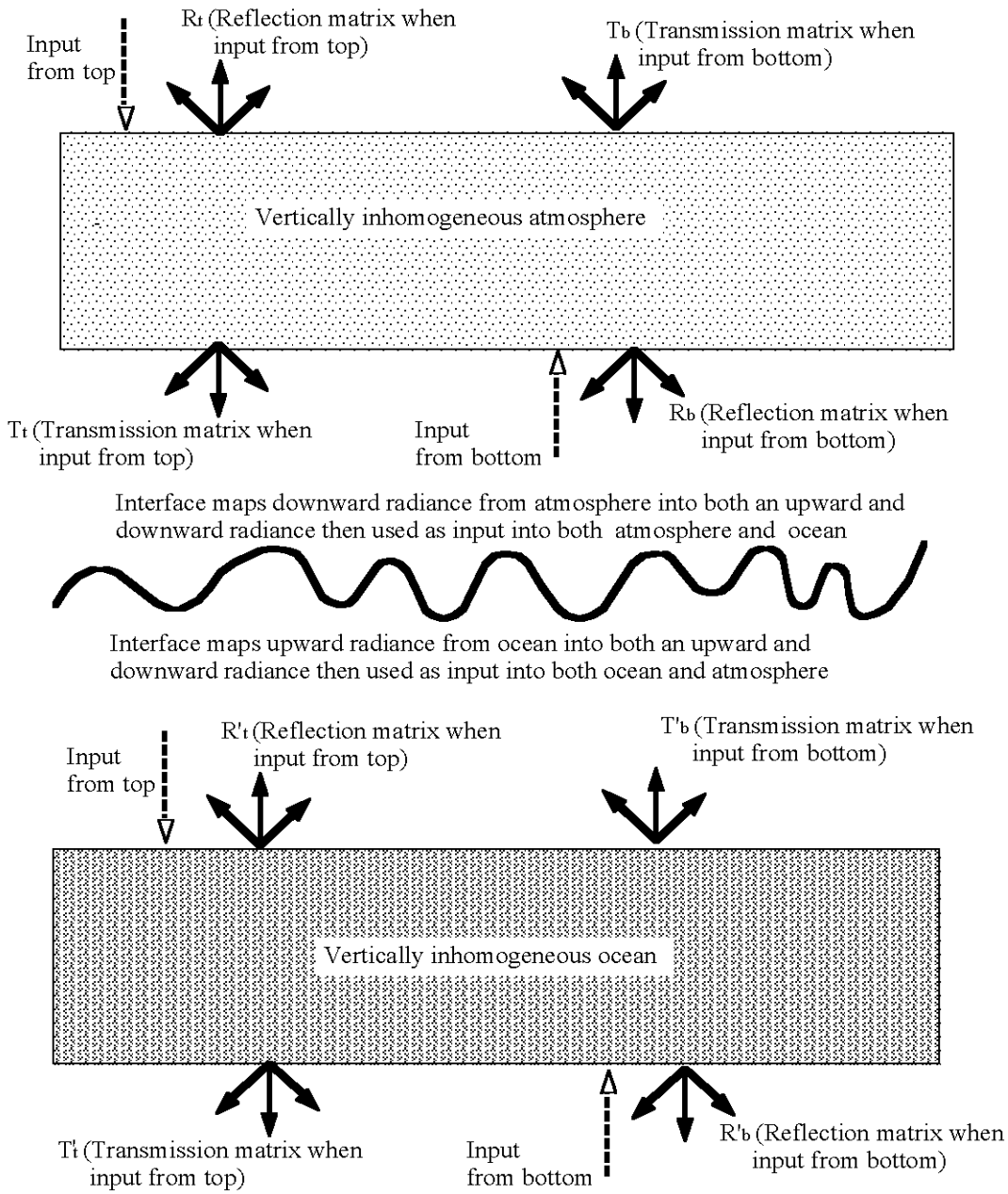

Fig. 1. Schematic representation on the use of matrix operator theory to calculate the time dependent radiation field within the ocean

WORK COMPLETED

a) We have applied the previously developed hybrid matrix operator–Monte Carlo (HMOMC) method to simulations of time series of polarized light fields under dynamic surface waves, as well as time series of the underwater image of an object above the ocean surface. A paper on this work has been published in Applied Optics, 48, pp. 3019-3029 (2009).

b) We have completed simulations of the color ratio associated with the backscattering of radiation by ice crystals at 0.532 and 1.064-μm wavelengths. A paper on this work has been published in J. Geophys. Res., 114, D00H08, (2009).

c) We have investigated the influence of the assumed ice particle microphysical and optical model on inferring ice cloud optical thickness from satellite measurements of the Earth's reflected shortwave radiance. A paper on this work has been published in Atmos. Chem. Phys., 9, pp. 7115-7129, (2009).

d) We have studied the relationship between the asymptotic far field and the near field in the Lorenz-Mie theory and the T-matrix formulation through the Kirchhoff surface integral. A paper on this work has been published in J. Quant. Spectrosc. Radiat. Transfer, 11, pp. 515-518, (2010).

e) We have explored the use of nonsymmetric geometries to simulate the single-scattering properties of airborne dust particles with complicated hexahedral particles. A paper on this work has been published in Appl. Opt., 49, pp. 334-342, (2010).

f) We have examined the equivalent absorption path length in an integrating cavity. A paper on this work has been published in Appl. Optics, 49, 575-577, (2010).

g) We have developed a user-friendly database software package of the single-scattering properties of individual dust-like aerosol particles for application to radiative transfer calculations in the spectral region from ultraviolet to far-infrared. A paper on this work has been published in J. of Aerosol Science, 41, pp. 501-512, (2010).

h) We have developed a fast radiative transfer model for simulating the temporal fluctuations of the underwater downward irradiance in shallow waters due to the focusing effect of surface waves. We have applied this model to simulations of irradiance in water bodies with the same IOPs as those measured during the Santa Barbara Channel cruise, and have achieved impressive consistency between the model-simulated and measured temporal variance and flash statistics in the downward irradiance. A paper on this work have been published in Applied Optics, 49, pp. 1041-1053, (2010).

i) We have applied a backward Monte Carlo model to the prediction of variations in the underwater visibility due to measured optical variabilities, and found that the model predicted visibilities are greater than, but the visibility differences are consistent with those predicted by a first-order extinction model. A paper on this work has been published in Appl. Opt., 49, 2784-2796, (2010).

j) We have investigated the extinction efficiency factor associated with the scattering of a plane wave on a basal face of a dielectric disk or a cylindrical particle using the physical-geometric optics hybrid method and the discrete-dipole approximation method. A paper on this work has been published in Applied Optics, 49, 4641-4646, (2010).

k) We have assessed the numerical accuracy in conjunction with the application of four "equivalent" spherical approximations in the computation of the optical properties of small aggregate soot particles. A paper on this work has been published in J. Quant. Spectrosc. Radiat. Transfer, 2127-2132, (2010).

l) We have compared three approximate methods, the surface-integral method, the volume-integral method, and the diffraction plus reflection pattern from ray optics method, that compute scattering of light by dielectric faceted particles. A paper on this work has been accepted for publication in J. Quant. Spectrosc. Radiat. Transfer.

m) We have investigated the use of scattering properties of ice particle aggregates for the remote sensing of ice clouds. A paper on this work has been accepted for publication in Applied Optics.

RESULTS

a) We have used high resolution wave slope measurements and water inherent optical properties (IOPs) measurements as input to our hybrid radiative transfer model, in an effort to reconstruct the highly dynamic polarized radiance field in shallow waters. Figure 2 shows snapshots of wave elevation fields reconstructed from measured wave slope components using a Fourier Transform approach (wave slopes from Chris Zappa, reconstruction algorithm from Howard Schultz). The wave slope measurements were made in the Santa Barbara Channel experiment, with a spatial resolution of roughly 1.3 mm × 1.7 mm and a frame rate of 60 Hz. However, these high resolution measurements cover only a 1 m × 1 m surface patch, which is not adequate for purposes of radiative transfer modeling. We had to extend this surface patch to a 3 m × 3 m one using periodic boundary conditions, such that a detector depth of 1 meter is possible (i.e., the footprint of the Snell cone – the region that the sky radiance can reach – viewed at that depth is within the computational domain).

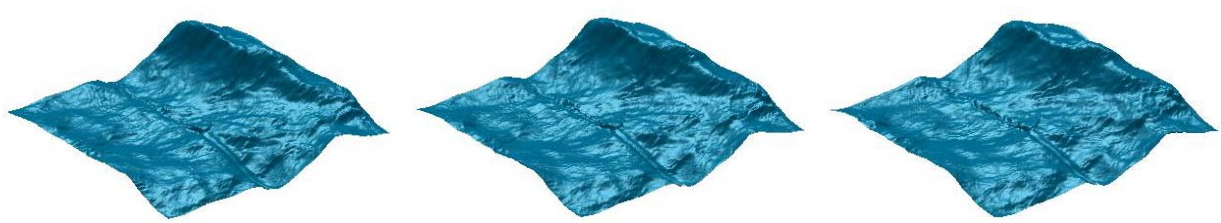

Fig. 2. Snapshots of a dynamic wave elevation field reconstructed from wave slope component measurements in the Santa Barbara Channel (wind speed 5.1 m/s). The spatial resolution is roughly 1.3 mm × 1.7 mm, and the frame rate is 60 Hz. Shown here are 1 m × 1 m wave patches. They are extended to 3 m × 3 m and used as input to the hybrid radiative transfer model.

Furthermore, we have obtained relevant ocean IOPs from RaDyO collaborators. Field data used in the model simulation include ocean particulate extinction (c_w), single scattering albedo (ω_p) and backscatter factor (b_{back}). The aerosol optical thickness (AOT) is also used. A summary of properties in the simulated atmosphere–surface–ocean system can be found in Table 1.

Table 1. Summary of properties in the simulated ASO system. Entries with an asteroid use field data from RaDyO Santa Barbara Channel experiment. A wavelength of 532 nm was assumed.

Light source	Solar zenith angle	30°
	Solar irradiance	Top-of-atmosphere solar radiation spectrum
Atmosphere	Molecular scattering	Rayleigh phase matrix
	Optical thickness	0.112
	Single scattering albedo	1
	Aerosol scattering	Oceanic aerosols
	Optical thickness*	0.15
Air-sea interface	Wave slopes*	Field data under wind speed 5.1 m/s (extended to 3 m × 3 m)
Ocean	Molecular scattering	Rayleigh phase matrix with depolarization ratio 0.047
	Extinction and albedo	$c_w = 0.046$ m^{-1}, $\omega_w = 0.0457$
	Hydrosol scattering*	Fournier–Forand phase function, where b_{back} is from field data, combined with reduced Rayleigh phase matrix with depolarization ratio 0.1
	Extinction and albedo*	$c_p = 0.6522$ m^{-1}, $\omega_p = 0.9314$
	Physical depth	10 m
Bottom	Lambertian surface	Surface albedo A = 0

To resolve the fine angular distributions when real wave slopes are present, we further improved the hybrid model by treating the direct light part (sun light getting into the ocean without atmospheric scattering, and then multiply-scattered in the ocean) separately. A rather fine angular resolution (1° × 2° in the results shown below) can be achieved in this part. The low-resolution diffuse part (sun light multiply-scattering in the atmosphere and enters the ocean) is then interpolated and added to the direct part. The total radiance field will have the same angular resolution as the direct part, which is necessary to resolve the fine structures in the angular distribution of dynamic radiance fields.

In the simulations, a virtual detector was put at two depths, 0.2 meters and 1 meter. Figure 3 shows the simulated angular distribution of downwelling radiance field viewed at 0.2 meters (upper panel) and 1 meter (lower panel). The frames are 1/60 seconds apart from each other. It is obvious from Fig. 3 that there are plenty of variations within this extremely short duration. The variations are most appreciable at the boundary of the Snell cone where the impact from the wavy surface is substantial. As expected, the structures in the angular distribution due to the wavy surface is even finer as the detector moves further away from the surface.

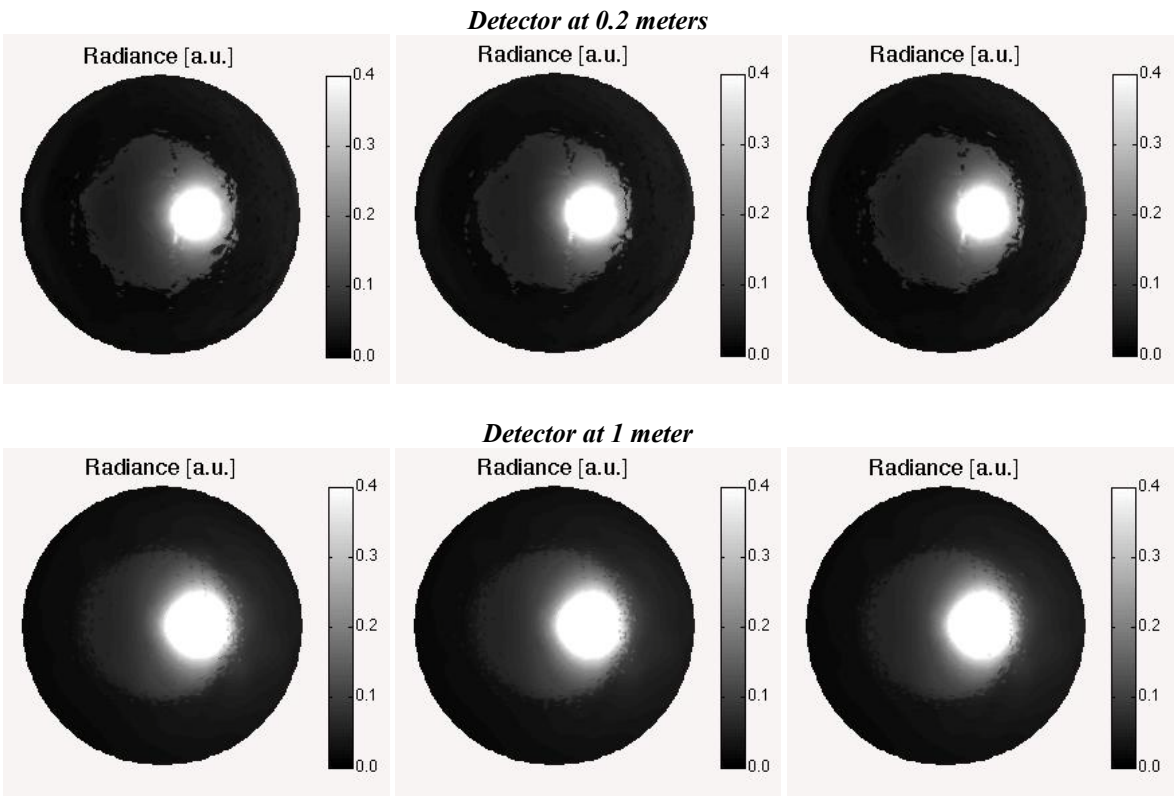

Fig. 3. Simulated downwelling angular distribution of radiance at 0.2 meters (upper panel) and 1 meter (lower panel) in the low-sea condition. Frames are 1/60 seconds apart from each other.

Figure 4 shows the simulated degree of polarization (DoP, left panel) and plane of polarization (PoP, right panel) viewed at 0.2 meters. Unlike the radiance pattern, these patterns (especially the PoP pattern) are highly dynamic outside the Snell cone, since the polarization states are largely determined by multiple scattering in the ocean.

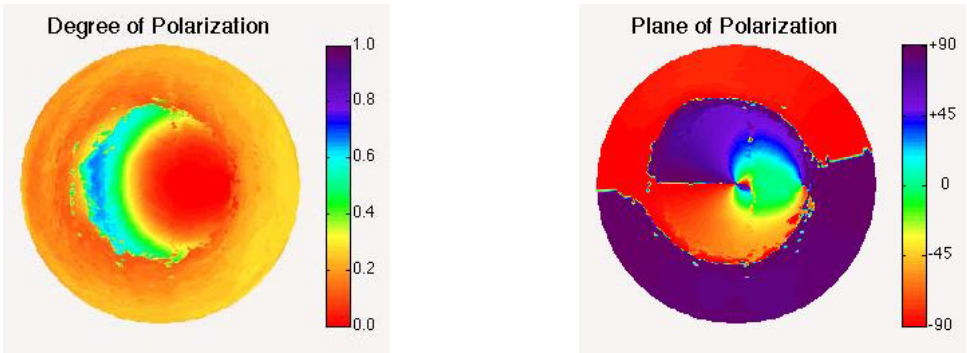

Fig. 4. Simulated downwelling angular distribution of degree of polarization (left) and plane of polarization (right) at 0.2 meters.

In Fig. 5 we show comparisons between measured and model simulated underwater angular distributions of radiance, degree of polarization and plane of polarization. The measurements were made by RaDyO researcher Ken Voss in the Santa Barbara Channel experiment, with a solar position at about 30° zenith and 248° azimuth, a very clear sky, a surface wind speed of about 6.2 m/s, and a detector depth of 1 meter. In the simulation, we used parameters as close as we can get, and averaged the resultant radiance field over every 0.1 seconds (6 frames) to match up with the integration time associated with the measurements. Although it is unlikely that the instantaneous wave patch is the same (as one can tell from the boundary of the Snell cone), the overall consistencies in all three patterns are surprisingly encouraging. The model simulations failed to reproduce some of the noises in the measured DoP and PoP patterns, which are likely from both instrumentation noises and wave disturbances. This could be partly attributed to the neglect of wave elevations in the model.

A comparison between the model simulated radiance fields (Fig. 3, lower panel) and the averaged or temporally-integrated ones (Fig. 5, lower panel) also reveals that, some of the fast varying features in the dynamic radiance field can be lost in measurement even with an integration time as short as 0.1 seconds.

b) In a collaboration with RaDyO researcher Grace Chang, we used a backward Monte Carlo model to predict the platform effects on the optical variability and predicted underwater visibility. Field measurements of ocean IOPs off the two RaDyO platforms, the R/P FLoating Instrument Platform (FLIP) and the R/V Kilo Moana (KM), are usually different. Among other important results, it is found that the variations are greater during low wind conditions, as a high wind tends to mix the water body and decrease the spatial inhomogeneity of water properties.

To understand how much this variation in water properties will impact the predicted underwater visibility, we simulated the horizontal visibility, y, of submerged black targets using the measured IOPs as input. A comparison between the simulated horizontal visibilities using IOPs measured from FLIP and KM are shown in Fig. 6. Crosses represent visiblities corresponding to measurements during high wind conditions, while triangles represent visibilities during low wind conditions. The Monte Carlo predicted percentage difference is found to be up to 15% in high wind conditions and up to 45% in low wind conditions. These are consistent with results from a first-order extinction model, although the Monte Carlo predicted visibilities themselves are greater. Furthermore, Monte Carlo results indicate that the visibility increases as the size of the target increases, while the first-order extinction model is target-size-independent.

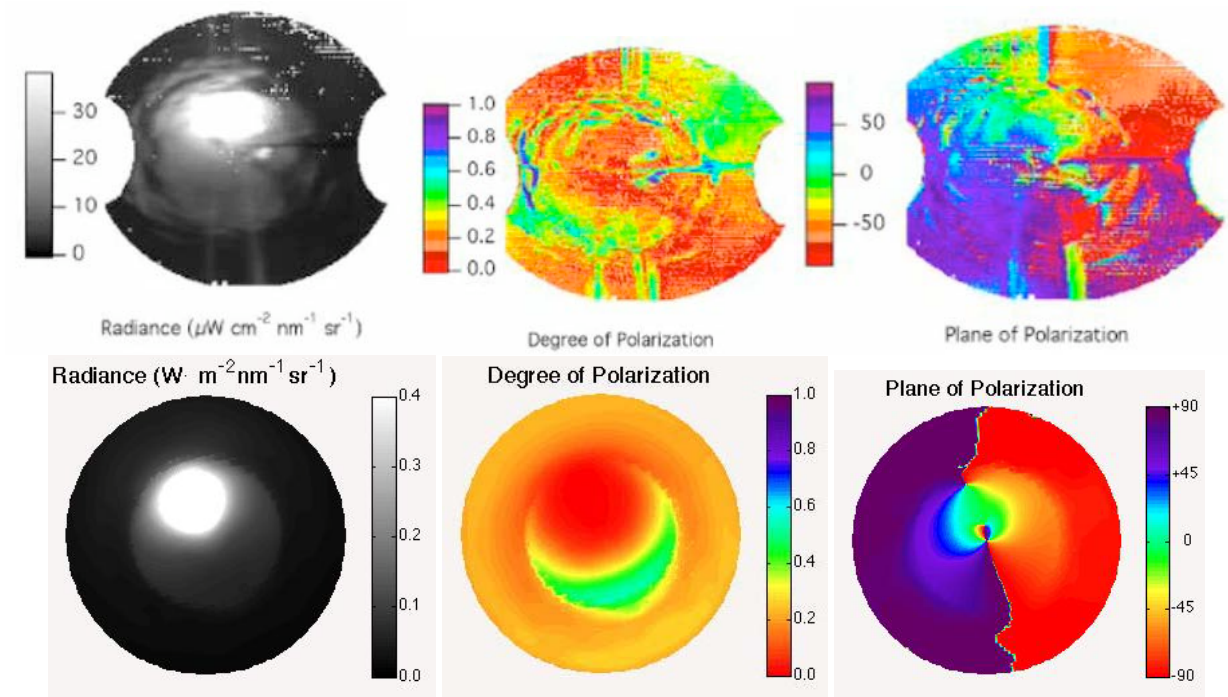

Fig. 5. Comparisons of measured (upper panel, from Ken Voss) and model simulated (lower panel) downwelling angular distributions of radiance, degree of polarization, and plane of polarization at 1 meter. Sun is at a zenith angle of about 30° and an azimuth angle of about 248°; the sky is clear; and the surface wave speed is about 5 m/s.

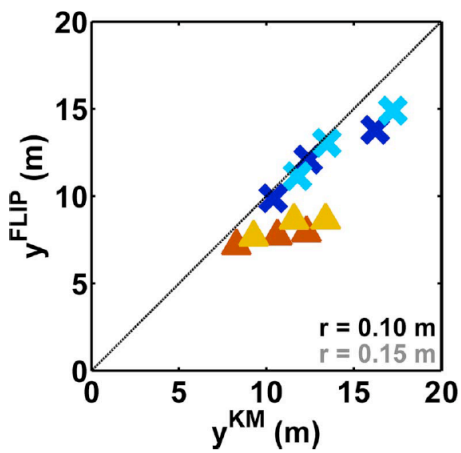

Fig. 6. Comparisons of Monte Carlo predicted horizontal visibility using FLIP and KM measured water inherent optical properties (IOPs) as input. Greater percentage differences are found for measurements during low wind conditions (triangles, strong mixing) than those during high wind conditions (crosses, weak mixing); larger visibilities are predicted by the Monte Carlo model for larger targets (light colors) than for smaller targets (dark colors).

IMPACT/APPLICATION

The HMOMC code and the fast irradiance code will become powerful tools to investigate the effects of a dynamic wave profile on the radiance field, especially on the polarization states and fast fluctuations of the light field. The fast irradiance code will also be helpful in understanding the fast-varying environment surrounding ocean creatures, which is part of an ONR funded MURI project on underwater camouflage.

TRANSITIONS

Due to the efficiency and versatility of this new code, it will be directly applicable to understanding one of the most formidable problems in global warming, i.e. the effect of broken clouds on the reflectivity of the atmosphere. My colleague, Dr. Ping Yang in the Department of Atmospheric Sciences at TAMU, will use it to interpret the measurements of the satellites, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), Moderate Resolution Imaging Spectroradiometer (MODIS), and Polarization and Directionality of the Earth's Reflectances (POLDER). This code can also be used in biomedical studies, such as numerical simulations of the light propagation in skin tissue.

RELATED PROJECTS

We use the results from our other ONR Grant to use as input to our codes in the RaDyO study.

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