Wave-Driven Marine Boundary Layers: Implications for Atmospheric Electromagnetics and Ocean Acoustics

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LONG-TERM GOALS

The description of electromagnetic propagation through the marine atmospheric boundary layer is considerably more complex than through the terrestrial boundary layer. Contributing to the complexity are refractive ducts as well as the moving wave-roughened sea surface. A significant issue for propagation in marine environment is the reproducible tendency of models to overestimate the signal's intensity at the receiver (Barrios and Patterson (2002)). Such discrepancy, in turn, leads to a uncertainty in estimating a number of variables with practical importance, among them being the distance to an object detected by radar and its velocity. This error is likely due to ignoring or incorrectly describing the physical mechanisms responsible for signal degradation. The long-term goal of this effort is to advance our quantitative understanding of the physical factors influencing the signal propagation in the marine environment, essential for detection, tracking, communication and guidance applications.

A major part of the effort within the Rough Evaporation Duct (RED) project (Anderson *et al.*, (2004)) has been focused on the vertical structure of the refractive duct, exploring the hypothesis that a weaker duct is allowing the signal to diffuse out of the marine atmospheric boundary layer (MABL). However, two other physical factors, namely the fluctuating refractivity in the boundary layer and the scattering by the ocean surface are generally ignored. In this context, a goal of this work is to explore the influence on signals of factors and processes in the marine boundary layer that have so far been ignored, such as micrometeorological fields. A special attention is given to the multifaceted role of surface waves, one distinct element of the marine environment.

OBJECTIVES

The surface waves induce fluctuations of velocity, pressure and passive scalars in the atmospheric boundary layer. In low-wind conditions, often encountered over the ocean, this wave modulation is the dominant motion in the boundary layer, clearly noticeable in measured unprocessed data (Figure 1). In any conditions that modulation, along with the turbulence, contributes to scintillation, which affects the accuracy of detecting objects by radar, sonar or lidar. While the role of the turbulence has been studied extensively through observations as well as analytically and numerically, the role of the wave effects is largely unknown. The objective of this effort is to obtain a statistical description that is useful in modeling, for the wave-induced modulation of the atmospheric motion and its influence on the scintillation patterns. Physical similarities between the electromagnetic waves over the ocean and the sound signals in the water allow to extend the application of our results to the case of acoustic propagation under the sea surface.

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14. ABSTRACT
The description of electromagnetic propagation through the marine atmospheric boundary layer is considerably more complex than through the terrestrial boundary layer. Contributing to the complexity are refractive ducts as well as the moving wave-roughened sea surface. A significant issue for propagation in marine environment is the reproducible tendency of models to overestimate the signal’s intensity at the receiver (Barrios and Patterson (2002)). Such discrepancy, in turn, leads to a uncertainty in estimating a number of variables with practical importance, among them being the distance to an object detected by radar and its velocity. This error is likely due to ignoring or incorrectly describing the physical mechanisms responsible for signal degradation. The long-term goal of this effort is to advance our quantitative understanding of the physical factors influencing the signal propagation in the marine environment, essential for detection, tracking, communication and guidance applications.

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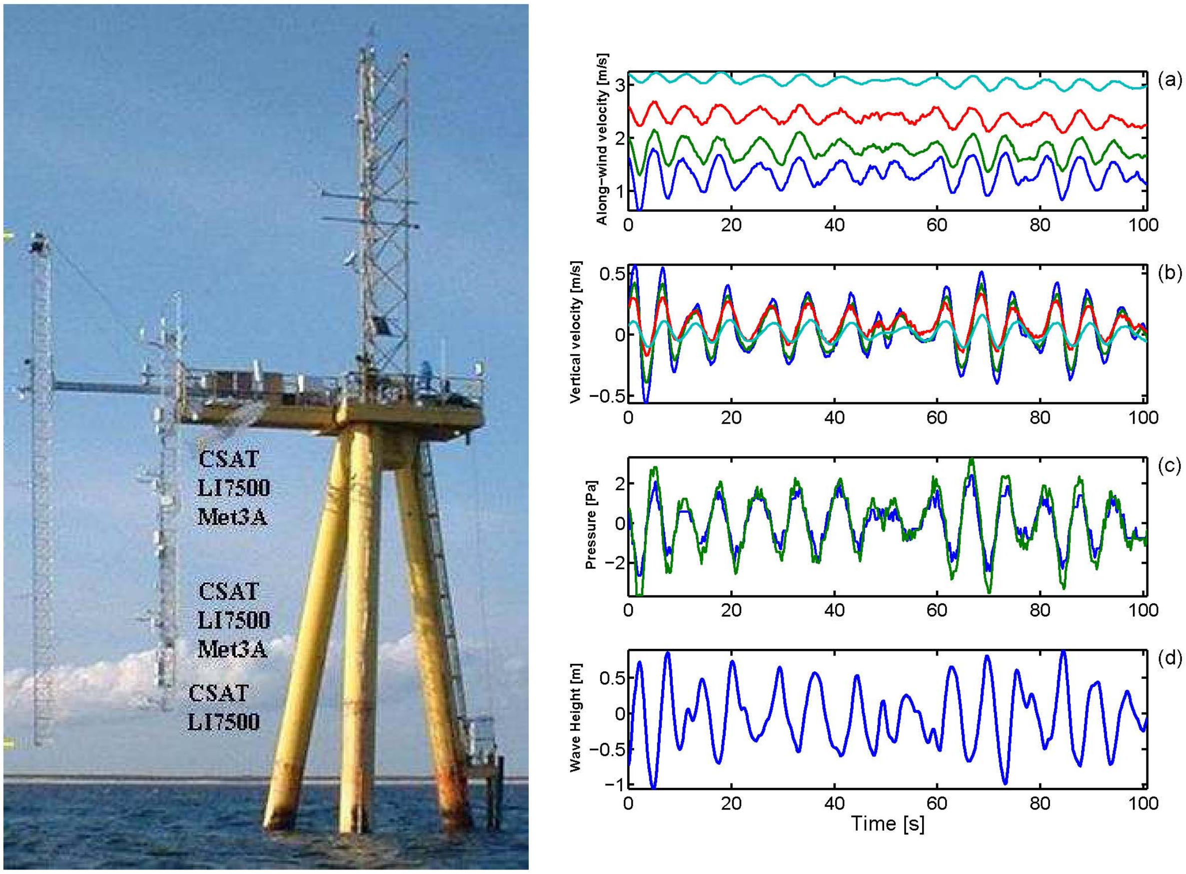

Figure 1. Left, the instruments deployed on the Air-sea interaction tower during the CBLAST experiment; photograph courtesy of Dr. Jim Edson, University of Connecticut. Quantities being measured included wind velocity, atmospheric temperature and humidity, pressure fluctuations, and surface elevation. Right, the plots show 100s of the measured (not processed) signals at low-wind conditions: (a) along-wind velocity at 4 levels from the surface (colors indicating the height of the instrument from the surface in the order blue -lowest, green, red, cyan - highest), (b) vertical wind velocity (same color-height correspondence), (c) atmospheric pressure fluctuations (green-lower, blue-higher instrument), and (d)surface elevation.

APPROACH

The semi-empirical similarity-based theory of Wyngaard *et al.*, (1971), proposed for a refractive-index-structure parameter in the terrestrial atmospheric boundary layer, inspired a number of observational studies that have sought a verification of that theory for the marine atmospheric boundary layer (Friehe *et al.*, (1975); Friehe, (1977); Davidson *et al.*, (1978)) using only micrometeorological measurements. However, experiments combining both meteorological and propagation measurements (Frederickson *et al.*, (2000)) have found a discrepancy between meteorological and propagation estimates of the refractive structure parameter C_n^2. An attempt to attribute the discrepancy on atmospheric stability was supported by data collected in the EOPACE experiment over the San Diego Bay, but contradicted data collected on the East Coast. No surface wave measurements have been carried out to explore any possible surface wave influence on the propagation pattern. Assuming that the observed discrepancy between theory and observations has a statistical nature, Potvin *et al.,* (2008) have explored the potential of Bayesian regression methods for explaining and reconciling that difference.

The present effort included a review of the approach used in these works to study scintillation over the ocean. The alternative employed here is the broad premise that the cause for theory-experiment discrepancy is physical rather than statistical, i.e. that physical processes of significance are left out of the analysis, with specific focus is on the wave modulation of the boundary layer. Given a stratified atmospheric refractivity, commonly observed over the ocean, we propose a mechanism for the wave-induced fluctuations of atmospheric refractivity. In that mechanism the waves vertically displace the column of air, thus bringing higher refractivity from below (when displacement is upwards) and lower refractivity from above (when displacement is downwards). Assuming the wave slope to be limited by breaking, i.e. small slope waves ($ak << 1$), we rely on a linear theory (Hristov *et al.* (2003)) to describe the distortion of the air flow streamlines caused by the waves and the concomitant column of air displacement. This physical picture will be the basis of our approach to describing the structure of the boundary layer motion and the influence of the wave modulation on the signal propagation pattern.

WORK COMPLETED

The scintillation analysis of Frederickson *et al.,* (2000), builds on Tatarskii's, (1971) results, assuming that homogeneous isotropic turbulence approximates well the atmospheric motion over the sea. In such motion the refractivity structure, function scales as $D(r) = C_n^2 r^{2/3}$ in the inertial sub-range $l < r < L$ and the key parameter determining the scintillation pattern is the structure constant C_n^2. It implicitly assumes that any processes specific for marine atmospheric boundary layer (MABL) (e.g. influence of the surface waves) can be accounted for by re-parameterizing the structure constant C_n^2. The latter, in turn, means that all these MABL-specific processes are homogeneous, isotropic and obey the scaling $r^{2/3}$, thus contrasting the results from our analysis here.

The analysis conducted within this effort assumed that the wave-induced and turbulent fluctuations are uncorrelated and arrived formally to an expression for the refractivity structure function $D_n(\vec{r}_1,\vec{r}_2) = \left\langle \left[n(\vec{r}_1) - n(\vec{r}_2)\right]^2 \right\rangle$ that describes both the turbulent $D_n^{turb}(\vec{r}_1,\vec{r}_2)$ and wave effects $\tilde{D}_n(\vec{r}_1,\vec{r}_2)$:

$$D_n(\vec{r}_1,\vec{r}_2) = D_n^{turb}(\vec{r}_1,\vec{r}_2) + \tilde{D}_n(\vec{r}_1,\vec{r}_2)\ .$$

The structure function associated wave-induced motion is expressed as

$$\tilde{D}_n(\vec{r}_1,\vec{r}_2) = 2\left\langle \left(\tilde{n}(\vec{R}_1,Z_1)\right)^2 \right\rangle - 2\left\langle \tilde{n}(\vec{R}_1,Z_1)\,\tilde{n}(\vec{R}_2,Z_2) \right\rangle$$

where

$$\left\langle \tilde{n}(\vec{R}_1,Z_1)\tilde{n}(\vec{R}_2,Z_2) \right\rangle = \int e^{i\vec{k}\cdot(\vec{R}_1-\vec{R}_2)}\,\mathrm{T}(Z_1,\vec{k})\,\mathrm{T}^*(Z_2,\vec{k})\,S_{\eta\eta}(\vec{k})\,d\vec{k}\ ,$$

$S_{\eta\eta}(\vec{k})$ being the surface wave spectrum and $\mathrm{T}(Z,\vec{k})$ is the transfer function relating the surface elevation and the wave-induced fluctuations of refractivity.

To compare these results with the turbulent scaling of $r^{2/3}$ let us first observe that clearly the wave-induced structure function is not isotropic. In a horizontal plane, anisotropy is introduced by the surface wave spectrum, commonly exhibiting one or a small number of dominant wave directions. The wave effects generally decay with height and thus the dependence on the vertical coordinate qualitatively differs from the dependence on the two horizontal coordinates. Consequently, the wave effects entirely lack the spatial rotational symmetry (i.e. the isotropy) of the isotropic turbulence as well as its homogeneity (translational symmetry) in the vertical direction, which makes it impossible that the wave effects could possibly follow the $r^{2/3}$ spatial behavior.

One more distinction between the turbulence and the wave effects can be found in their spatial structure, as indicated by the relationship between the structure function $D_n(\vec{\rho})$ and the correlation function $B_n(\vec{\rho})$ of the atmospheric refractivity, $D_n(\vec{\rho}) = 2B_n(\vec{0}) - 2B_n(\vec{\rho})$. Generally, the correlation function of the turbulence $B_n(\vec{\rho})$ vanishes at distances of the order of the integral scale L an there the structure function $D_n(\vec{\rho})$ saturates. For the wave effects, the scale over which the correlation function vanishes is known as a correlation distance L_η of the surface wave field, which is related to the width of the wave spectrum, yet it is entirely independent of the turbulent integral scale in the air L.

Each of these two observations alone, i.e. absent spatial symmetries of the wave effects and difference in spatial extents of the turbulence and wave effects, is sufficient to reject the possibility that the wave effects could be incorporated by re-parameterizing the structure constant C_n^2, (Frederickson *et al.,* (2000); Potvin *et al.,* (2008)).

Further, we explored the scaling behavior of the structure function of the wave-induced refractivity using a relationship between the structure function of a random field $\tilde{D}_n(x)$ and its spectral density $P_n(k)$ (Ishimaru (1978)):

$$\tilde{D}_n(x;z) = 2\int_0^\infty [1-\cos(kx)]P_n(k;z)dk$$

We consider a simplification in which the spectrum of the wave-induced atmospheric refractivity at a height z, $P_n(k;z)$ is related to spectrum of the surface waves $S_\eta(k)$ as $P_n(k;z) = e^{-2kz}S_\eta(k)$. To proceed we need a parameterization of the wave spectrum. A spectrum parameterization proposed by Phillips, (1977) from theoretical considerations is $S_\eta(k) \propto k^{-3}$, while a spectrum more closely agreeing with observations is $S_\eta(k) \propto k^{-5/2}$. Taking the general form $S_\eta(k) \propto k^{-\alpha}$, $(5/2) < \alpha < 3$, for the range within the correlation distance of the surface waves $x < L_\eta$, we obtain

$$\tilde{D}_n(x;z) = -2^{\alpha-1}z^{\alpha-1}\Gamma(1-\alpha)\left\{-1+\left[1+\frac{x^2}{4z^2}\right]^{(\alpha-1)/2}\cos\left[(\alpha-1)\arctan\left(\frac{|x|}{2z}\right)\right]\right\}.$$

For the observed spectrum of $S_\eta(k) \propto k^{-5/2}$ the structure, function scales as $\tilde{D}_n(x;z) \propto |x|^{3/2}$ and saturates for $x > L_\eta$.

The relationship $\tilde{D}_n(x;z) = 2\int_0^\infty [1-\cos(kx)]P_n(k;z)dk$ also indicates that the structure function is additive with respect of the surface waves spectrum, i.e. the structure function can be viewed as a superposition of the structure functions corresponding to individual spectral modes or to finite spectral ranges. Therefore, studying the structure function of individual modes can be informative and those results can be extended to wave fields with finite-width spectra. Considering a monochromatic surface wave $\eta = Ae^{i\vec{k}\cdot\vec{R}}$ and two points separated horizontally by distance $\vec{R} = \vec{r}_1 - \vec{r}_2$ and vertically at heights $z - \delta z$ and $z + \delta z$, we obtained the structure function of the refractivity:

$$\tilde{D}_n(\vec{R}; z-\delta z, z+\delta z) = A^2\left(\frac{dN}{dz}\right)^2 e^{-2kz}\left[e^{2k\delta z} + e^{-2k\delta z} - 2e^{-2i\vec{k}\cdot\vec{R}}\right]$$

When averaged over all directions the periodic non-local term $2e^{-2i\vec{k}\cdot\vec{R}}$ vanishes for a monochromatic wave, similarly to the case of finite spectrum where it vanishes over separations exceeding the surface waves correlation distance:

$$\left\langle \tilde{D}_n(\vec{R}; z-\delta z, z+\delta z)\right\rangle_{\vec{R}} = A^2\left(\frac{dN}{dz}\right)^2 e^{-2kz}\left[e^{2k\delta z} + e^{-2k\delta z}\right].$$

For two points separated only vertically the structure function takes the form

$$\tilde{D}_n(\vec{0}; z-\delta z, z+\delta z) = 4A^2\left(\frac{dN}{dz}\right)^2 e^{-2kz}\left[\sinh(k\delta z)\right]^2$$

where $N(z)$ is the atmospheric refractivity profile.

Following the semi-quantitative approach of Tatarskii, (1992) we evaluate the fractional variance of the intensity fluctuations $\sigma_I^2 \equiv \left\langle (\Delta I)^2\right\rangle / I^2$. Consider interference of two beams vertically separated by a distance of the size of the first Fresnel zone $\sqrt{\lambda L}$, where $\lambda \equiv 2\pi / K$ is the signal's wavelength. The number of refractive inhomogeneities encountered by the beams over a distance L will be of the order of kL. Taking k as a representative wavenumber for the surface waves, σ_η^2, the surface wave variance as a representative wave amplitude, and applying Tatarskii's, (1992) arguments we arrive to

$$\sigma_I^2 = \tilde{D}(\sqrt{\lambda L})(Lk)^3 = 4\sigma_\eta^2\left(\frac{dN}{dz}\right)^2 e^{-2kz}(k^2\lambda L)(Lk)^3 \propto \sigma_\eta^2\left(\frac{dN}{dz}\right)^2 e^{-2kz}k^5K^{-1}L^4.$$

RESULTS

A work under this grant conclusively established (Hristov *et al.*, 2008) that a surface scattering model (Miller et al., (1984)) that according to Levy, (2000) “is the one generally used by radiowave propagation modelers” is systematically yet unphysically overestimating the intensity of the scattered signal and thus is responsible for the discrepancy between propagation model predictions and observational results. A statistically correct alternative to the Miller-Brown-Vegh model, accounting for deviations of the sea surface from Gaussianity, was proposed under this grant. The new scattering model also predicts new effects, not described in any older models, such as spatial shift of the locations of blind spots over the ocean, i.e. of the locations where an object could be temporarily "invisible" for the radar. The new scattering model has been incorporated into the Advanced Propagation Model (APL) (SPAWAR Systems Center, San Diego). Test runs of APL have shown that the new scattering model essentially eliminates the discrepancy between propagation model predictions and observations for some frequency bands (e.g. X-band) and reduces the discrepancy in other bands (Ku-band).

The work on the grant also explored the influence of the surface waves on atmospheric scintillation. Analysis of the spatial symmetries of the surface waves signature on the atmospheric refractivity determined that wave effects cannot be incorporated by re-parameterizing the structure constant C_n^2. The work on the grant proposed explicit forms of the wave-induced structure function of the atmospheric refractivity, the characteristic function of the wave-induced wind velocity and characteristic function of the two-point differences of the wave-induced wind velocity. Furthermore, our analysis determined the statistical distributions of second order moments of wave induced fields, necessary in calculating the characteristic functions. All these quantities commonly occur in estimates of phase fluctuations or intensity fluctuations variance. The wave effects in the atmosphere are the primary cause for scintillation in low-wind conditions, often encountered over the tropical ocean.

IMPACT/APPLICATIONS

Numerical models for propagation in ducting conditions have shown a persistent tendency to overestimate the intensity at the receiver (Barrios and Patterson (2002)), thus leading to overestimation of the distance to the object producing the radar return as well as to overestimation of the available response time. We reviewed the possible mechanisms for signal degradation, potentially responsible for this deficiency in propagation models. The analysis outlined above has identified both physical and statistical causes for discrepancy between propagation model results and observations. The statistically correct alternative to Miller *et al.* (1984) for surface scattering, proposed under this grant (Hristov *et al.*, 2008), and the analysis of the surface waves influence on the atmospheric refraction, are expected to improve the performance of models for signal propagation over the ocean. Although the strong modulation of atmospheric motion has been observed over the mid-latitude Atlantic, it is likely that the phenomenon would be both more prevalent and more pronounced over the tropical ocean, where low wind conditions are often encountered and where dry air from the surrounding deserts can move over the ocean and cause strong refractive ducts. Because of the profound physical similarities between atmospheric electromagnetics and underwater acoustics, the application of these results can be extended to sound signals in the ocean.

RELATED PROJECTS

The PI is unaware of any related ONR sponsored projects.

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