How strong is the wind over the ocean a thousand kilometers away?
Acoustic remote sensing of the wind field

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Introduction

Observations of surface winds over the world's oceans are a long way from providing complete spatial coverage, basically because buoys are expensive and difficult to maintain.

We propose to use relatively inexpensive acoustic techniques to diagnose surface wind speeds. Turbulent wind acts as an inhomogeneous acoustic source at the ocean surface that then propagates underwater. We investigate the feasibility of inverting the signal observed at some range *r* away from this source to diagnose its amplitude, which can then be related to the wind speed. The advantages of this technique, in addition to its lower cost, include the ability to sample surface wind speeds remotely.

The proposed observing system is appropriate for areas of the ocean with a sound speed channel. Minimum sound speed is less than that of the ocean surface, which is less than that at the ocean bottom.

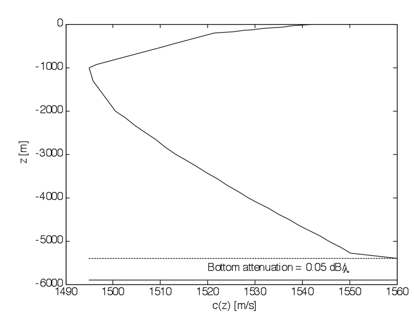
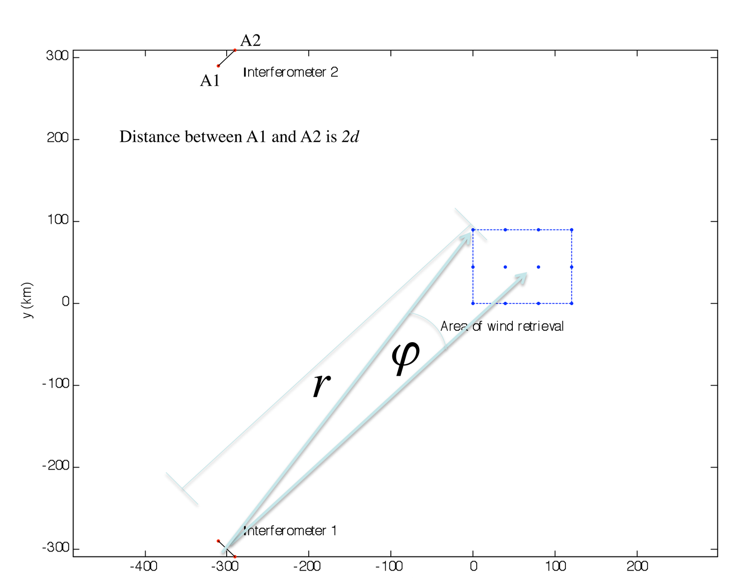


Fig. 1: Sound speed profile in N. Atlantic

This last condition allows probing of the ocean surface by modes that are not heavily attenuated by the bottom. Such profiles are found in the the North Atlantic Ocean.

Fig. 2: ***The Workhorse:*** A pair of interferometers exposing the inhomogeneity from different perspectives.



We envision a pair of dipole interferometers (Fig. 2). Each interferometer consists of a pair of line arrays (A1 and A2) separated by distance *2d* and measures the intensity of an inhomogeneous acoustic source along a path oriented at angle φ to the dipole axis. Using line arrays with hydrophones concentrated near the SOFAR channel permits resolution of the individual acoustic, depth-dependent normal modes necessary for the acoustic inversion. Frequencies between 10 and 30 Hz allow ranges *r* of order 10^3 km. Separation distance *2d* is or order tens of kilometers or smaller.

Theory and Results: How does it work?

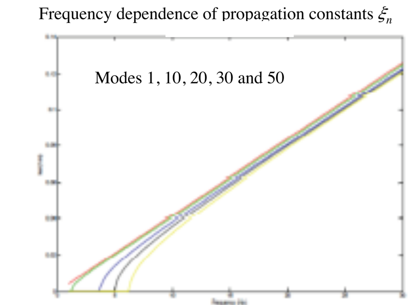
The acoustic pressure field at range $\vec{r}$, depth *z* and time *t* due to underwater sources distributed over a plane near the surface of the ocean is approximately

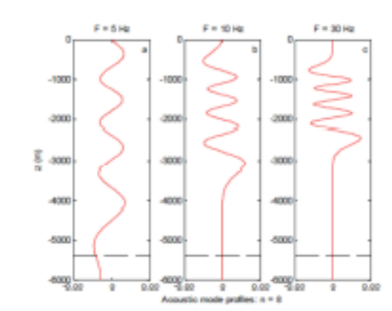
$$p(\vec{r},z,t) = \int d\omega \exp(-i\omega t)\int d\vec{r}\,' a(\vec{r}\,',\omega)\sum_n \left[-\frac{i}{4}H_0^{(1)}(\xi_n(\omega)|\vec{r}-\vec{r}\,'|)\right] u_n(z,\omega)u'_n(0,\omega) \qquad (1)$$

In (1), $a(\vec{r},\omega)$ is a density of sources and ξ_n is the propagation constant given by the boundary problem (2):

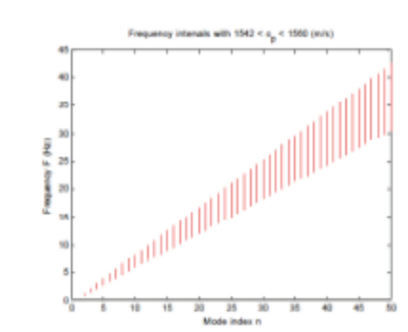
$$\frac{d}{dz}\left(\frac{1}{\rho_o(z)}\frac{du_n(z)}{dz}\right)+\frac{1}{\rho_o(z)}\left(\frac{\omega^2}{c^2(z)}-\xi_n^2\right)u_n(z)=0, \qquad u_n(0)=\frac{du_n(z=-H_{hb})}{dz}=0. \qquad (2)$$

For the sound speed profile shown in Fig. (1), the propagation constants $\{\xi_n(\omega)\}$ and normal modes $\{u_n(z)\}$ vary with frequency as follows:





Frequency intervals within which modes interact with the surface but not the bottom.



We estimate the co-spectrum $C_{a\alpha,b\beta}(\omega)$ of the acoustic field measured at two hydrophones having coordinates $(\vec{r}_a,z_\alpha)$ and $(\vec{r}_b,z_\beta)$ and use a least squares technique to estimate the covariance matrix of the sources. That is, we assume that $< a(\vec{r},\omega)a^*(\vec{r}\,',\omega) >= A(\vec{r})\omega^{-\gamma}\delta(\vec{r}-\vec{r}\,')\delta(\omega-\omega')$ and expand the density of stochastic sources as a superposition of basis functions $\{\varphi_k(\vec{r})\}$:

$$A(\vec{r}) = \sum_k A_k\varphi_k(\vec{r}) \qquad (3)$$

In this feasibility study, $\{\varphi_k(\vec{r})\}$ were simple products of sinusoids in Cartesian coordinates. However, the basis can be chosen as appropriate for the study at hand. For example, one might choose the Empirical Orthogonal Functions from an ensemble of hurricane structures.

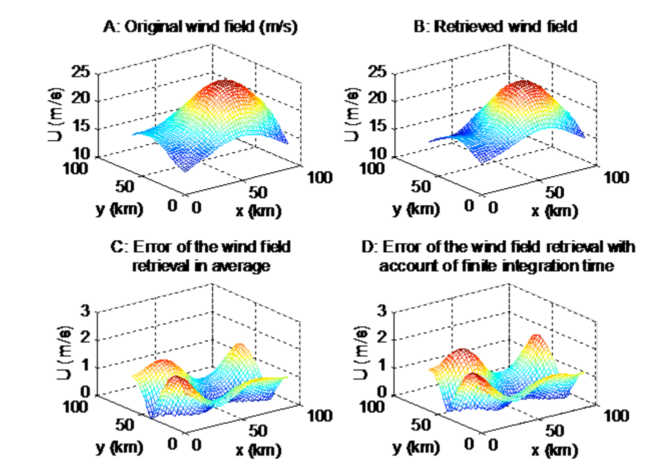
When the noise is the signal, what's the noise in the noise?

The uncertainty in $A(\vec{r})$ is proportional to $10^5/T\Delta F$, where *T* is the integration time and ΔF is the frequency bandwidth. For a nominal wind speed of about 5m/s, a signal-to-noise ratio less than one can be obtained with *T* about 3 hours. For strong winds, the contribution of errors to the finite integration time is relatively small.

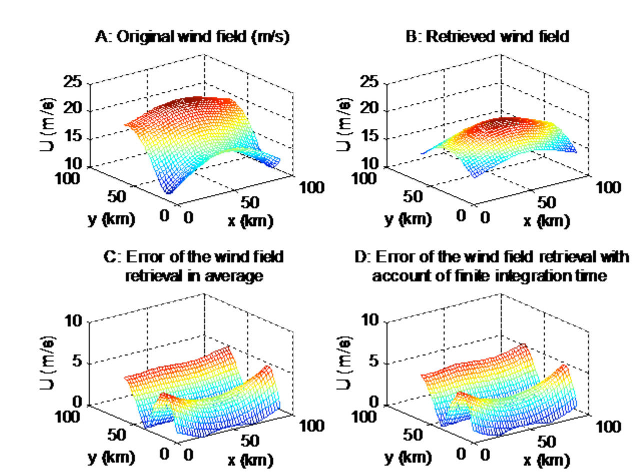
How well does it work?

Details: Consider an oceanic environment with a sound speed profile as in Fig.1. The bottom sediment is a single layer 500m deep, having a density 1.4g/cm^3 and attenuation 0.05 db/λ. The interferometer set-up is shown in Fig. 2.

Case 1: Wind field projects well onto basis functions



Case 2: An arbitrary wind field



Conclusions

- Mapping a surface wind field over areas O(10^3km) appears feasible using acoustic correlation techniques.
- Range information is gathered using a pair of dipole interferometers.
- Each dipole interferometer consists of a pair of receivers separated by ~10km.
- The signal to noise ratio increases as $\sqrt{T}$, where *T* is the integration time. Reasonable results can be obtained with integration times on the order of a few hours.

References

Wilson, J. D., and N. C. Makris, 2006: Ocean acoustic hurricane classification. *J. Acoust. Soc. Am.*, **119**, 168.

Voronovich, A. G., and C. Penland, 2010: Mapping of the ocean surface wind by ocean acoustic interferometers. *J. Acoust. Soc. Am.*, submitted.