DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

NOAA Technical Memorandum ERL AOML-93

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noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

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Ocean Current Monitoring in the Coastal Zone

Oleg A. Godin, Dmitry Yu. Mikhin, and David R. Palmer

ABSTRACT -- *A new technique has recently been put forward for real-time monitoring of ocean currents in the coastal zone. The acoustic technique, called matched nonreciprocity tomography (MNT), is being developed to extend traditional ocean acoustic tomography to the coastal zone. It should provide maps of the current field extending out tens of kilometers in range and throughout the water column. These maps will have applications to several important scientific problems such as measuring ocean circulation and upwelling and monitoring global climate change. Alternative approaches for monitoring currents in the coastal zone are surveyed and their limitations when compared with the MNT approach are discussed. Nonreciprocity tomography is based on recent progress in the theory of acoustic propagation in moving media and in the use of matched-field processing to solve tomographic inverse problems. The MNT technique can be viewed as an application of matched-field processing to a judiciously selected acoustic observable that is sensitive to flow velocity, but insensitive to sound speed and bathymetric variations, and leads to robust inversions for the depth-dependence of the velocity. The development of nonreciprocity tomography is reviewed in this article in the context of extended opportunities the technique offers in monitoring ocean dynamics in the coastal zone by acoustic means. Applications of the MNT technique to problems not directly related to coastal current monitoring are also noted.*

1. INTRODUCTION

The techniques currently available for measuring currents in coastal regions cannot determine the current field as a function of both the depth and the horizontal coordinates. For example, electromagnetic systems measure only surface currents or, at locations where underwater cables exist, bulk transport. High-frequency acoustic and *in situ* systems can measure vertical profiles at a single location and therefore provide data valid only within the horizontal correlation length of the medium. These, as well as all other existing systems, are inadequate for wide-area, real-time monitoring of the current field in three dimensions.

There are compelling reasons for this type of monitoring. In the coastal zone, just as in the deep ocean, knowledge of the current field contributes to an understanding of the dynamics of ocean circulation and upwelling, and is necessary for estimating vorticity, heat transfer, and other important characteristics of an ocean region. Current monitoring can also serve to verify general circulation models and the assumptions made in their derivation. There are situations where current measurements in the coastal zone can contribute to global climate studies through monitoring of major current systems in narrow coastal straits. An example is estimating the heat flux associated with the Gulf Stream system by monitoring the flow in the Straits of Florida where the system is confined between Florida and the Bahama Banks (e.g. Molinari, 1983; Molinari *et al.*, 1985). A number of societal concerns such as pollution monitoring, fisheries management, and harbor management can also be addressed through coastal current monitoring.

Motivated by the inadequacy of traditional acoustic tomography in the coastal zone, a research group at the P. P. Shirshov Oceanography Institute of the Russian Academy of Sciences proposed a new acoustic tomography technique, matched nonreciprocity tomography (MNT) (Godin *et al.*, 1995, 1996; Godin and Mikhin, 1996b). It has the same advantages and disadvantages compared to point measurements as does traditional tomography but does not suffer from the limitations of traditional tomography when applied to the coastal zone.

In this paper we review the methods that are available for monitoring coastal ocean currents, placing emphasis on matched nonreciprocity tomography (MNT) and traditional ocean acoustic tomography. It is only with tomography systems, that is, low frequency systems, that wide-area monitoring is feasible. We discuss the constraints that the coastal ocean environment places on these systems and discuss why the MNT is not limited by them. We summarize the status of the MNT development effort and indicate that the technique may have application to other oceanographic monitoring problems.

2. LIMITATIONS OF ALTERNATIVE METHODS FOR ACOUSTIC MONITORING OF COASTAL OCEAN CURRENTS

Beside MNT, there are four acoustic methods that have potential for monitoring currents in the coastal zone: traditional tomography, high-frequency methods, modal tomography, and scintillation methods. In addition to these techniques, a number of other inversion schemes for flow velocity remote sensing have been studied theoretically (Norton, 1988 and 1991; Rouseff and Winters, 1994; He and Ström, 1995; Rychagov and Ermert, 1996; Baykov *et al.*, 1996). We will not discuss these studies in this paper. Although they have been insightful in revealing fundamental similarities and differences between inversions for scalar environmental parameters (for example, the sound speed or density), and vector parameters (for example, the flow velocity), they have not lead to a technique that can be directly applied to ocean current tomography. This is because they are based on environmental and propagation models that are too simple to adequately describe underwater sound propagation and/or require an amount of input data that cannot be realistically collected in an at-sea experiment.

2.1 Traditional Ocean Acoustic Tomography

Ocean acoustic tomography is widely recognized as a powerful technique for monitoring the ocean current as well as the ocean temperature field. It averages over the propagation paths effectively suppressing small-scale structure. Tomography can sample remotely across inaccessible areas. Also, the data increase as the square of the number of moorings unlike the linear increase characteristic of direct measurements. Experiments conducted in the last 20 years (Desaubies, 1990; Munk *et al.*, 1995; Send *et al.*, 1997) have determined that both current tomography and temperature tomography are feasible in the deep ocean for propagation paths as great as 1000 km. Attempts to apply ocean acoustic tomography to measure currents in shallow, coastal regions have not been as successful, however. Experiments conducted in the Straits of Florida (DeFerrari and Nguyen, 1986; Chester *et al.*, 1991) have demonstrated that the deep-water tomography approach is not suitable for coastal regions because of an inability to resolve and to identify individual eigenrays. Traditional acoustic tomography is based on inverting ray-path travel times and requires that ray paths be both resolvable and identifiable.

The reasons that these requirements of tomography cannot be met in the coastal zone are well understood. Ray arrivals are too close together to be resolved with any reasonable bandwidth. If the bandwidth were to be increased there would be new, equally serious, signal-attenuation and coherence-loss problems due to the frequency dependence of acoustic bottom interactions. In the deep ocean, the same narrow bandwidth does not prevent ray paths from being resolved because the paths of interest are refracted and therefore tend to be separated in arrival time to a greater degree than the bottom-reflected ray paths that are characteristic of propagation in the coastal ocean. In addition, the time-of-arrival pattern spreads linearly with the propagation distance and the distances of interest are much greater in the deep ocean than in shallow water.

The interaction of the acoustic ray paths with the ocean bottom results in an identification problem because the paths are sensitive to small-scale bottom roughness (Palmer *et al.*, 1985, 1991). Perturbations in the bottom topography of a few centimeters can significantly alter the ray paths. Without perfect knowledge of the bottom topography one would have no confidence that the identification of the predicted ray paths with peaks in the measured time-of-arrival pattern is meaningful. This inability to identify ray paths results in poor or nonexistent spatial resolution, particularly in the vertical plane.

There is a special case where traditional tomography can be used in coastal regions. In certain situations a surface duct--a near-surface minimum in the sound speed profile--may be present. This duct can support propagation of a few eigenrays that do not interact with the ocean bottom and can be used for traditional tomographic inversions (Monjo and DeFerrari, 1994). Unfortunately, the utility of surface-duct propagation is limited to specific sites and seasons and cannot provide coverage throughout the water column.

2.2 Modal acoustic tomography

Modal acoustic tomography is a form of tomography in which the inversion is based on the characteristics of individual normal modes rather than individual ray paths (Shang, 1989). A tenet of current tomography is that non-reciprocity of the sound field must be exploited (Stallworth, 1973; Worcester, 1977). Otherwise it would be impossible to separate the effects of the current from larger reciprocal effects such as sound speed variations. A system to measure currents based on modal tomography would generally require dense vertical arrays of *transceivers* (that is, transceiver/receiver pairs) so that reciprocal transmissions could be made and so that the individual modes could be extracted from the signal (Baykov *et al.*, 1996). The positions of the individual transceivers would need to be known very precisely. In addition, the versions of modal tomography (Godin *et. al.*, 1990; Elisseeff and Schmidt, 1997) that rely on receiving arrays instead of arrays of transceivers are limited to those situations where mode coupling does not occur (Mikhin and Godin, 1998) and, hence, cannot be applied in coastal ocean. We will have more to say about modal acoustic tomography when we discuss the type of transceiver array needed for the MNT technique.

2.3 Scintillation Methods

Scintillation methods measure path-averaged flow velocity from the rate of passage of sound speed fluctuations across an acoustic path (Farmer and Clifford, 1986; Crawford, Lataitis, and Clifford, 1990; Farmer and Crawford, 1991). The assumptions underlying the technique are not met when the time-dependence of medium inhomogeneities are due to processes other than advection with the mean flow (for instance, due to internal waves). Furthermore, scintillation methods can not be applied (at least, in their present form) when bottom scattering contributes significantly to acoustic scintillations and/or there are unresolved multi-paths propagating through a flow with large-scale spatial inhomogeneities. In particular, unlike the MNT method, the scintillation method cannot determine the vertical structure of the flow velocity profile when acoustic signal consists of unresolved bottom-interacting arrivals.

2.4 High-frequency methods

High frequency systems, for example, acoustic Doppler current profilers (ADCP's), can only provide vertical profiles of the current at a single location. The dependence of signal attenuation on the acoustic frequency reduces useful propagation paths for high-frequency systems to distances of the order of the ocean depth. To provide real-time, three-dimensional current maps, a vast, expensive network of high-frequency systems, all cabled to shore, would be required.

ADCP's are extensively used by oceanographers and are of indisputable value in a number of applications. However, in the current velocity data measured with an ADCP it is difficult, if not impossible, to accurately separate the contributions due to turbulence from those due to processes having larger spatial scales. It is these larger-scale processes that are of primary interest in climate-related research and in ocean circulation and pollutant transport studies. Tomography methods, by their very nature, essentially measure certain path-averages of a quantity of interest, thereby filtering out small-scale processes. For instance, the tomographically-measured current velocity is much more suitable than are ADCP measurements in estimating heat and mass transfer and in providing input data and/or ground truth information for ocean circulation models. Because of their intrinsic path-averaging feature, tomographically-derived current velocity profiles are expected to be readily amenable for assimilation with surface-current data obtained, for example, with emerging high-frequency radar techniques (Prandle, 1991; Chin *et al.,* 1997).

Another important feature of tomography is its remote sensing nature. Currents can be measured tomographically in areas of intensive shipping and fishing without actually placing the measurement devices in those areas thus reducing the risk they could interfere with or be damaged by commercial activities.

Hence, tomography methods, if developed to the stage of commercial availability, will definitely be of value for a number of current monitoring tasks in oceanographic research and coastal management that currently rely, out of necessity, on ADCP's. This fact is the motivation behind the research on extending acoustic tomography of ocean currents to coastal environments.

3. A NEW APPROACH: MATCHED NONRECIPROCITY TOMOGRAPHY

Matched nonreciprocity tomography (Godin *et al.*, 1995, 1996; Godin and Mikhin, 1996b) consists of an innovative molding of traditional ocean current tomography with matched field processing and is based on extensive studies of the effects of ocean currents on acoustic waves in the coastal zone.

In general, matched field processing is a method for solving an inverse problem from a set of solutions to the forward problem (see, for example, Tolstoy, 1993; Perkins and Kuperman, 1990). A two-step procedure is followed in applying it. First, one simulates a propagation experiment on a computer a large number of times using different models for the environment. Second, one compares the simulations with the experimental results. The fundamental principle underlying the technique is that the closer the experimental results compare with a particular simulation, the closer the model environment for that simulation agrees with the actual environment.

The construction of the simulations requires a realistic parametric description of the environment and a high-quality solution to the forward problem, that is, the problem of inferring the acoustic field from knowledge of the environment. The MNT technique would not have been possible without the recent progress made in solving the forward problem for acoustic propagation in a moving, inhomogeneous fluid (Brekhovskikh and Godin, 1990, 1992). Previous models for describing acoustic propagation in a moving, inhomogeneous fluid are not adequate for describing all the effects associated with a realistic ocean current field.

The comparison is made using a measure of the quality of the match called a *cost function.* This function depends on the parameters used to describe the model environment as well as on the experimental data. By varying these parameters, one can determine the model ocean for which the cost function is a minimum. This model is then the technique's estimate of the actual ocean.

An example of a cost function is the rms difference between the values of some acoustic field quantity obtained from the simulations and from the experiment (i.e., the rms error). In underwater acoustics the rms value is usually obtained by averaging over water depth. A comparison made at a single depth does not provide enough degrees of freedom to differentiate between the various model oceans. The inversion would also fail if the field quantity were constant or even linear in depth. A successful inversion requires that the depth dependence of the acoustic field quantity have sufficient complexity. The complexity of the sound field in the coastal ocean is a disadvantage for traditional tomography because it results in a large number of unresolvable ray paths, but it is advantage for matched field tomography because it makes it easier to differentiate between similar model oceans. In addition, the NMT technique is not limited to situations where coupling does not occur as is modal acoustic tomography.

A useful cost function must be insensitive to *mismatch* corresponding to noise and unmodeled aspects of the experiment and the environment. Because it is not realistic to consider a cost function defined on a parameter space large enough to completely describe the experiment, mismatch is unavoidable. Therefore, sensitivity studies are required to ensure that a particular cost function does not give spurious results because of mismatch.

3.1 What are the MNT Cost Functions?

It seems certain that all forms of ocean current tomography must rely on reciprocal transmission experiments, that is, experiments in which sound is transmitted reciprocally between two locations separated by a horizontal distance. Because ocean currents are characteristically three to five orders of magnitude smaller than the sound speed, sound-speed variations usually have a far greater effect on the acoustic field than does the current field. However, the current field breaks acoustic reciprocity whereas sound speed variations do not. Simply put, an acoustic wave travels faster with the current than against while sound speed variations produce changes in the wave that are independent of direction of propagation. Reciprocity refers to the symmetry of the acoustic field with respect to interchange of source and receiver positions. By measuring the difference in the values of an acoustic quantity obtained from reciprocal transmissions (the *nonreciprocity* of the acoustic quantity), one can isolate the subtle effects of the current field from the much larger effects of sound-speed variations and also from uncertainties in knowledge of the experimental geometry.

With the exception of ray-path travel time, little was known about the nonreciprocity of acoustic field quantities until recently. Studies (Godin *et al.*, 1995, 1996) have found that nonreciprocity's of various acoustic quantities possess quite different sensitivities to environmental parameters. Cost functions based on these acoustic quantities will therefore have quite different sensitivities to mismatch.

This is easily illustrated by considering the simple example of one-dimensional propagation between the points x_1 and x_2 of two acoustic signals traveling with and against a current. The transmissions are harmonic with angular frequency ω and have unit amplitudes. The wave numbers k^+ and k^- and for the two signals differ slightly due to the current. The nonreciprociy in acoustic pressure is

$$\sin\left(\int_{x_1}^{x_2} k^+ dx - \omega \, t\right) - \sin\left(\int_{x_1}^{x_2} k^- dx - \omega \, t\right) = 2\sin(\delta\phi)\cos\left(\frac{1}{2}\int_{x_1}^{x_2}(k^+ + k^-)dx - \omega \, t\right)$$

(1)

where t is time and

$$\delta\phi = \int_{x_1}^{x_2}(k^+ - k^-)dx \qquad (2)$$

is the phase nonreciprocity. These two nonreciprocity's have quite different sensitivities to sound-speed variations and to uncertainties in source/receiver separation, x_2-x_1, even though they both vanish in the absence of the current. Indeed, the average of the wavenumbers k^+ and k^- is approximately equal to $2\pi/\lambda$, where λ is the acoustic wavelength, whereas the difference of the wavenumbers is of the order of $2\pi M/\lambda$, where M (= 10^{-3} - 10^{-5}) is the ratio of the magnitude of current velocity to sound speed. According to (1), to accurately predict acoustic pressure nonreciprocity, one needs to know the source and receiver positions x_2 and x_1 within a fraction of the wavelength. For the phase nonreciprocity, according to (2), the requirements on the accuracy of source and receiver positioning are M^{-1} times less restrictive. Moreover, to lowest order, variations in sound speed have the same effect on the two wave numbers k^+ and k^-. Therefore, to lowest order, the phase nonreciprocity depends on only the current whereas the pressure nonreciprocity (because of the cosine factor in the right side of (1)) is as sensitive to sound speed variations and source/receiver separation as is the one-way pressure field.

The actual situation is, of course, much more complicated than this example. However, extensive analysis has shown that nonreciprociy in the acoustic phase, as opposed to nonreciprocity in the acoustic pressure itself, does not depend to lowest order on variations in sound speed, mass density, ocean bottom topography, and horizontal source/receiver separation. Moreover, unlike the nonreciprocity in the pressure amplitude, nonreciprocity in the acoustic phase is sensitive to the vertical distribution of the current field. These characteristics form the physical basis for the MNT technique. The MNT cost functions that have been proposed (Godin *et al.*, 1995, 1996; Godin and Mikhin 1996a) are based on phase nonreciprocity and differ from one another in essentially two ways: how the relative signal strengths at the individual transceivers are used in the inversions and how the fact that phase can only be measured modulo 2π is taken into account. In the first case weighting is given in the cost function to the individual phase nonreciprocity's calculated from the signals recorded on any pair of transceivers according to their relative strength. In the second case cost functions are constructed not from the phase nonrecriprocity's themselves but rather from sine and cosine functions of them.

3.2 Insights Gained from Numerical Experiments

Extensive numerical experiments have provided useful insights into the capabilities of MNT and into the stability and sensitivity of MNT inversions to current variations and various types of mismatch e.g., (Godin *et al.*, 1996). In these experiments the forward problem was solved for sound propagation between a single moored transceiver (combined source/receiver unit) and a vertical transceiver array. Transceivers are needed for the required reciprocal transmissions, and a vertical transceiver array is needed so that the depth dependence of the phase nonreciprocity can provide the needed degrees of freedom for the matched-field procedure. These experiments addressed the effect on the inversion process of mismatch in horizontal transceiver separation, array tilt, bottom geoacoustic parameters, bathymetry, sound speed, and acoustic noise.

A numerical experiment using a model ocean resembling summer conditions in the Straits of Florida is provided as an illustration. Simulations were made of harmonic, 100-Hz sound propagating between the single transceiver and the (near) vertical transceiver array located at a horizontal distance of 20 km. The ocean depth was taken to be 400 m over the propagation path. The transceiver was positioned 40 m above the bottom, and the depth, length, and number of elements in the array were varied. Range-independent profiles of sound speed and the current component in the vertical plane of the transceivers are shown in Figs. 1a and 1b, respectively. The phase non-reciprocity calculated as a function of depth for the current profile in Fig. 1b, represented the "experimental" data. The "simulated" data were calculated for a two-parameter model of the current where the parameters were the amplitudes of the components of the baroclinic current and the barotropic current. The baroclinic current was assumed to be linear in depth. The experimental and simulated data were compared using an MNT cost function. The current for the parameters that minimized the cost function was the MNT estimate of the "true" current plotted in Fig. 1b.

Figure 2a shows the inverse of the cost function for the ideal case where no mismatch is present and the transceiver array consists of 161 elements equally spaced from the surface to the bottom. The minimum in the cost function in the two-dimensional parameter space is sharply defined and has a location corresponding to the true current profile. Figure 2b shows the cumulative effect of a signal-to-noise ratio of 10 dB; of mismatches in range of 50 m, in array inclination to the vertical of 10° degrees, and in amplitudes of systematic and quasi-random fluctuations in sound speed of 0.25 and 0.5 m s^{-1}, respectively; and of a 16-element array extending from 250 to 400 m in depth.

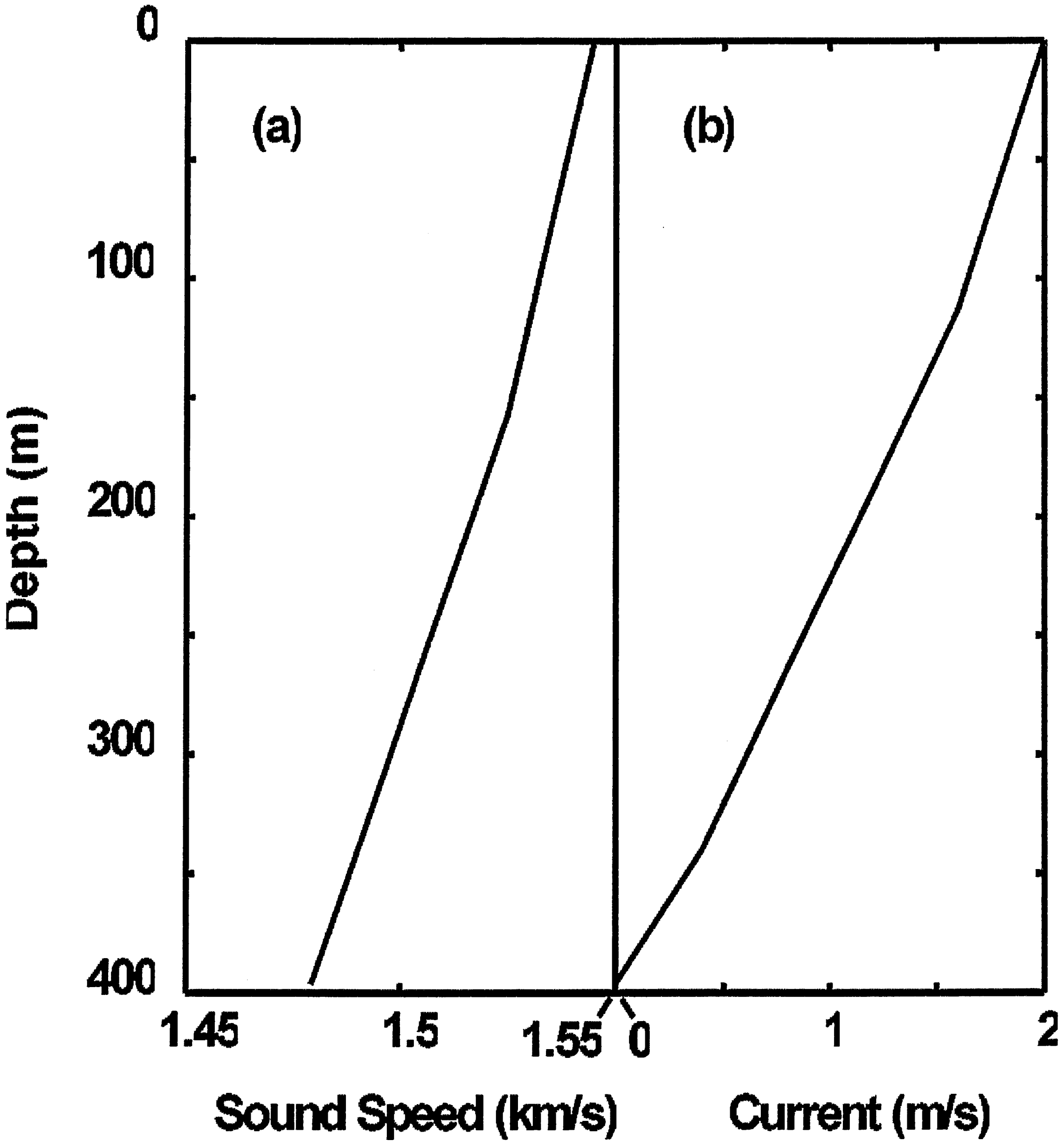

Fig. 1. *Vertical profiles of (a) sound speed and (b) current representative of conditions in the Straits of Florida in summer. The current data represent the "true" current in the numerical simulations and were compared with the numerical estimate of the current obtained using the MNT technique.*

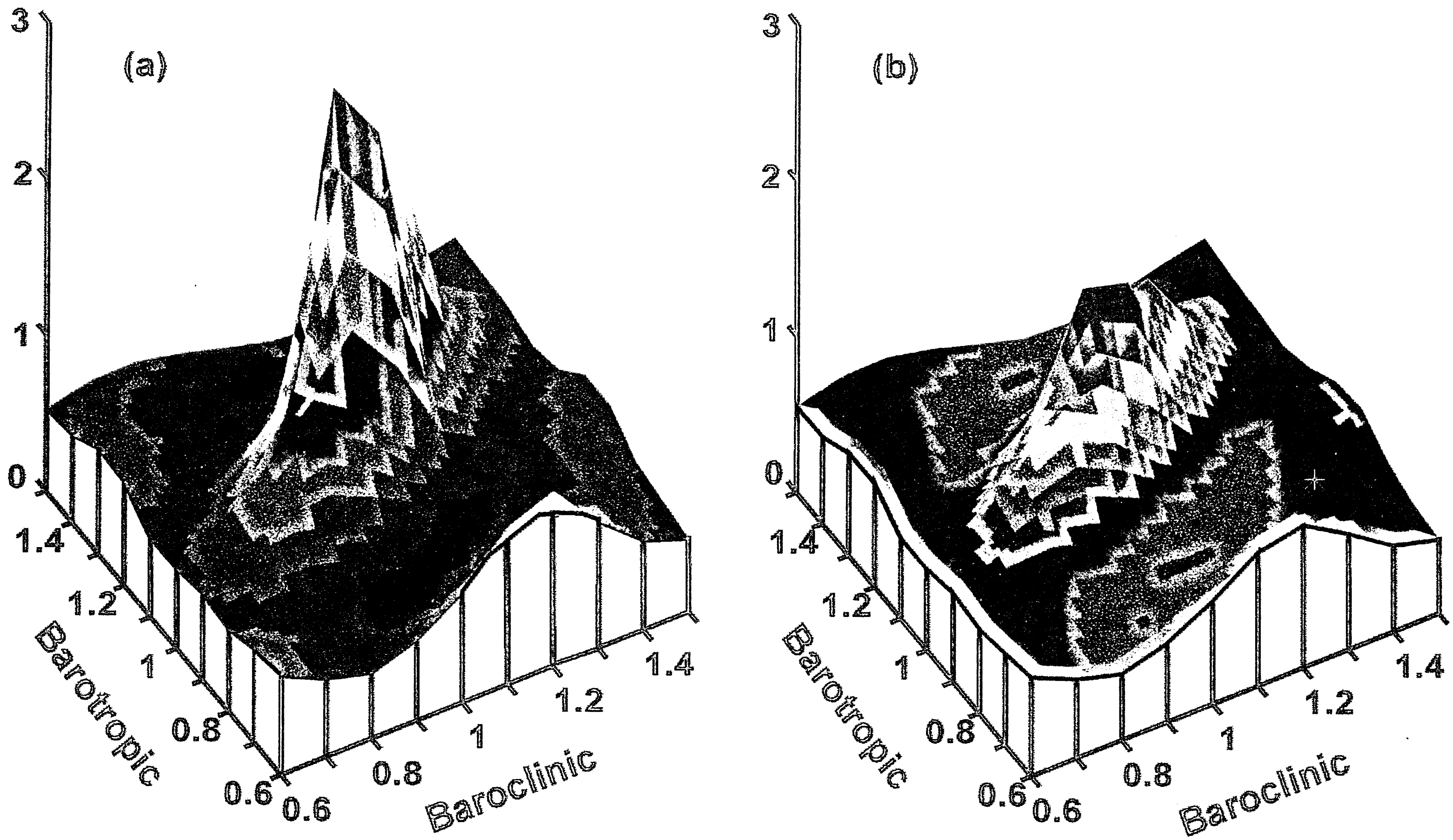

Fig. 2. *Plots of the inverse of the (dimensionless) cost function obtained from the numerical simulations. The inverse is plotted as a function of the two dimensionless parameters that represent the amplitudes of the barotropic and baroclinic current components in the ocean model. The current in Figure 1b corresponds to values of 1.1 and 1.0 for these parameters. Plot (a) is for the ideal case where no sources of error (mismatch) are present. Plot (b) is similar to (a) except six different potential sources of error were assumed to be present in (b): a signal-to-noise ratio of 10 dB; a reduction in the number of elements in the transceiver array from 161 to 16; and mismatches in range of 50 m, in array inclination of 10°, and in the amplitudes of the systematic and quasi-random fluctuations in the sound speed of 0.25* $m\,s^{-1}$ *and 0.5* $m\,s^{-1}$*, respectively.*

Although the minimum is not as sharp as in the ideal case, it is sufficiently defined to be able to infer the correct current profile to within a grid spacing (10 cm s^{-1} or 5% of the value of the current at the surface).

These results, together with those from more complex numerical experiments (Godin and Mikhin, 1996a, 1996b; Mikhin and Godin, 1998) involving a range-dependent ocean model and a parametric space of higher dimensionality, indicate the MNT technique gives good results in spite of significant uncertainty in knowledge of system and environmental parameters and at considerable noise levels.

3.3 Exploiting Multifrequency Signals

We have emphasized the importance of using a cost function that is an average over depth. A cost function constructed from data collected at one depth would not provide much resolution. The collection of depth data requires a vertical array of transceivers. This array might be a physical one or even a synthetic aperture array. The use of a synthetic aperture array is possible because of the insensitivity of the MNT technique to uncertainties in transceiver positions. It could be formed by varying the depth of a single transceiver suspended from a ship or moored from a bottom-mounted underwater winch. In any event, MNT, as originally conceived, requires more specialized hardware than is used for traditional tomography.

Initial studies of MNT assumed the signals transmitted by the transceivers consisted of a single carrier frequency with an attendant bandwidth. Because the phase nonreciprocity depends not only on the current and on the depth but also on the acoustic frequency, the question rises whether this frequency dependence can be exploited by transmitting several narrow band frequencies to reduce or eliminate the need for the depth data collected with a vertical array (Godin and Mikhin, 1996a, 1996b). In investigating this question, one must first consider whether the frequency dependence of the phase nonreciprocity is nontrivial. Figure 3 is a plot of the phase nonreciprocity as a function of frequency and depth for conditions representative of the Straits of Florida. The phase nonreciprocity is a distinct and nondegenerate function of frequency, suggesting depth data and frequency data can be efficiently combined in the MNT current inversion procedure.

A number of numerical simulations of the inversion process were carried out to determine the significance of the frequency dependence of the phase nonreciprocity. These simulations consisted of modeling sound propagation between a moored transceiver and a vertical transceiver array for several experiment scenarios and environmental models appropriate for the Straits of Florida. The ocean bottom was assumed to be a fluid half-space completely characterized by a sound speed and a specific density. Three types of mismatch were considered: discrepancies in horizontal separation of the transceivers, in the bottom characteristics, due to additive acoustic noise.

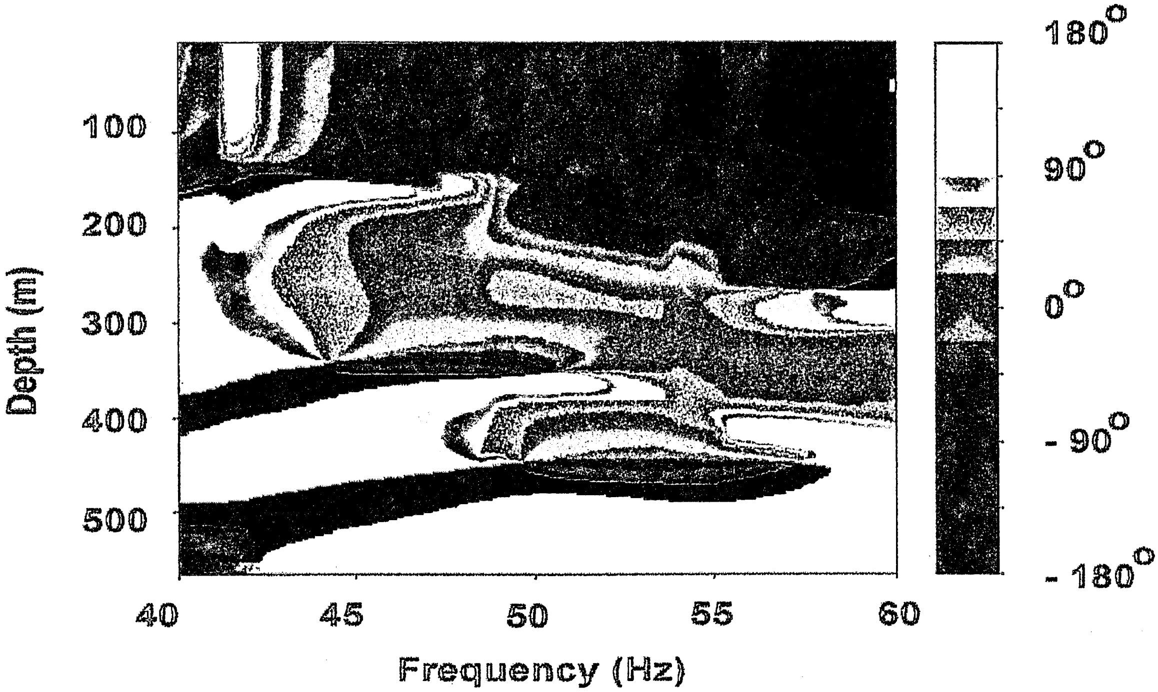

Fig. 3. *Simulated phase nonreciprocity (the difference in acoustic phases obtained from reciprocal transmissions) in degrees as a function of acoustic frequency and transceiver depth for conditions representative of the Straits of Florida in summer. The two transceivers were separated by 36 km. The stationary one was located at a depth of 530 m or 40 m above the bottom. The complexity of the phase nonreciprocity is an indication that depth data and frequency data can be successfully combined in an MNT current inversion procedure.*

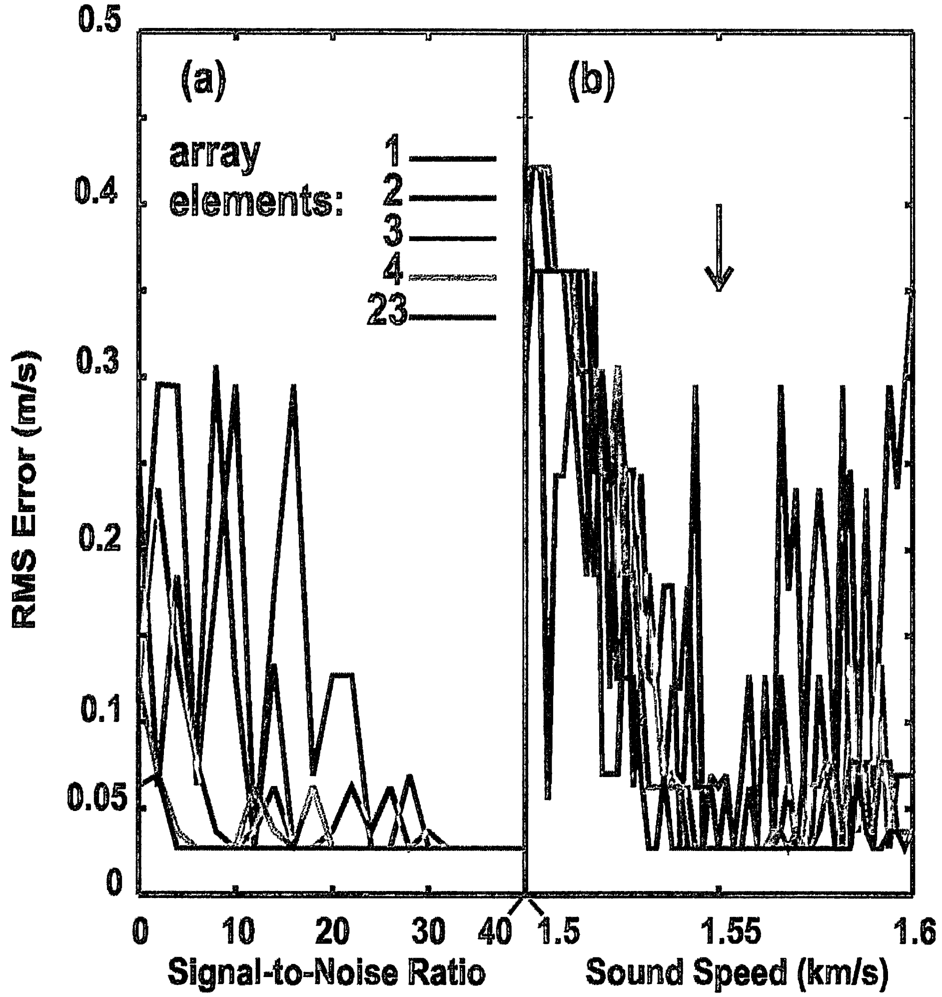

Fig. 4. *The rms error in the current field inversion as a function of (a) signal-to-noise ratio and (b) mismatch in the ocean bottom sound speed. The color coding corresponds to the number of elements in the transceiver array. For both plots additional mismatches of 9% difference in the bottom density and 50-m error in the horizontal separation of the transceivers were assumed. In (a) a 10 m* s^{-1} *mismatch was assumed in the ocean bottom sound speed and in (b) a signal-to-noise level of 20 dB was assumed. In (b) the location of the actual bottom sound speed of 1.55 km* s^{-1} *is indicated by the arrow. Data at 11 equally spaced frequencies between 40 and 60 Hz were used in the inversions. These results indicate that an array consisting of only three or four elements can provide quality inversions if the information obtained from transmitting several frequencies is exploited.*

In one study, input data at 11 different equally spaced frequencies between 40 and 60 Hz were processed incoherently by averaging the cost function over frequency. Five transceiver arrays were considered, consisting of one element (510 m in depth), two elements (560 and 360 m), three elements (560, 360, and 160 m), four elements (560 to 110 m in 150-m steps), and 23 elements (560 to 10 m in 25-m steps). Figure 4 shows plots of the rms difference between the true current profile and the inversion for the five array types as a function of (a) signal-to-noise ratio and (b) mismatch in ocean bottom sound speed. For both plots mismatches in horizontal separation of 50 m and in bottom density of 9% were assumed. In addition, in Fig. 4a a mismatch of 10 m s^{-1} was assumed, and in Fig. 4b the signal-to-noise ratio was taken to be 20 dB.

One sees from Fig. 4a, a signal-to-noise ratio of about 16 dB or greater for an array of only two elements resulted in an rms error of at most about 10 cm s^{-1}, or 5% of the surface value of the current. Figure 4b indicates a mismatch of 30 m s^{-1} in the bottom sound speed has no appreciable effect on the inversion for an array consisting of only two or three elements. These studies demonstrate that depth- and frequency-dependence of the phase nonreciprocity can be beneficially combined for current inversions, thus reducing or eliminating the need for specialized hardware.

The transceiver arrays needed for MNT can be compared with those needed for the use of modal acoustic tomography to monitor currents. The modal tomography arrays would need to be much denser to resolve the individual normal modes. Modal tomography would require far more sophisticated equipment than MNT.

3.4 Complementary Sea Trials

Sea trials have been planned that will address the issues of resolution and robustness of MNT and will determine the appropriate engineering parameters for long-term monitoring. The preferred site is at 27°N in the Straits of Florida. This site is within a region that has been extensively studied by physical oceanographers during the STACS Program (Molinari, 1983; Molinari *et al.*, 1985) and is the location of studies that demonstrated traditional acoustic tomography is not appropriate for monitoring currents in coastal regions (e.g. Chester *et al.*, 1991).

This ocean region is characterized by a highly-variable, complicated structure in both the vertical and horizontal planes. Significant, large-scale variability can occur in a period of a several days. The oceanography in the Straits is interesting in all seasons but it is in the summer, when propagation conditions in the Straits are particularly simple, that we would prefer to conduct tests. During the winter months a sub-surface duct forms with the result that both ducted and bottom-limited propagation can occur. It is best to avoid this complication in initial tests.

The most likely experimental arrangement consists of a sparse transceiver array and a number of point transceivers. With a single array and a single point transducer or even two arrays, only the in-plane component of the current can be measured. However, with a single array and a pair of horizontally separated point transceivers, the vector current field can, in principle, be retrieved. It should be noted in this regard that for a MNT system consisting of one or two vertical arrays and point transceivers, the amount of data does not increase as the square of the number of transceivers. It increases as the product of the number of arrays by the sum of the number of arrays plus the number of point transceivers.

In support of these trials, theoretical and numerical studies are now under way to develop an efficient, full-field mathematical model of sound propagation in coastal environments and an optimum inversion scheme for constructing maps of the current field. While the propagation models that have been used in the numerical experiments are quite advanced, they are not adequate for modeling the many time-varying processes that exist in the ocean and can contribute to the phase nonreciprocity nor can they account for all the effects associated with a variable bottom topography.

4. APPLICATION OF MNT TO OTHER SCIENTIFIC PROBLEMS

The long-term objective of the MNT research effort is the development of a monitoring system that will provide real-time maps of the ocean current field in any coastal region of interest. It will be an alternative to techniques that provide point measurements. The effort may also have application to problems not directly related to this objective. We briefly describe here some possibilities.

Unlike traditional tomography the MNT technique can utilize bottom-interacting acoustic energy to measure ocean currents. This feature provides an opportunity to use the technique to measure near-bottom currents not only in shallow-water regions but also in deep-water regions of particular interest. An MNT acoustic system might be used for monitoring the Gibraltar Straits heat and salt transfer to the North and South Atlantic from the Mediterranean Sea. A similar acoustic system deployed in the Kerch Straits for monitoring water inflow from the Black Sea could contribute to the conservation of the unique environment of the Azov Sea. Studies of coastal erosion due to sediment transfer by near-bottom currents might benefit from MNT-based current measurements. Estimation of contaminant fluxes from radioactive or chemical pollutant sources on the ocean bottom is another problem that could be addressed with the MNT technique.

One possible application is the study of the formation of inter-thermocline eddies of Mediterranean water (meddies) by observing the dynamics of currents in the vicinity of seamounts in the Iberian basin and on the continental slope of Portugal. Meddies are the prominent means of salt transfer to the Atlantic Ocean and are supposed, by many researchers, to result from the flow of Mediterranean water interacting with large-scale bathymetric features in the Iberian basin (McDowell and Rossby, 1978; Käse and Zenk, 1996).

An optimum inversion scheme will lead to an improved methodology for separating the contributions to the acoustic phase from the various contributing nonreciprocal processes, including internal waves. This methodology could provide a new technique for measuring the frequency spectrum of internal waves in shallow water.

5. CONCLUDING REMARKS

Three-dimensional, real-time monitoring of coastal currents represents an important, long-recognized problem in ocean remote sensing. A purpose in writing this brief review is to point out how previously developed methods for current monitoring cannot provide a solution to this problem because of the constraints imposed by the coastal ocean environment and how these constraints can be overcome by a proper accounting of the physics of low-frequency acoustic wave propagation in a moving fluid. Extensive theoretical and numerical analyses indicate the MNT technique is a promising solution to the problem. These analyses do not account for all the scales of variability that are present in the coastal ocean, however. Our present knowledge is too limited to be able to construct a compete model of the variability. Sea trials are needed to extend and complement the theoretical and numerical studies. If future sea trials confirm the predicted properties of the MNT technique, a basis will exist for the construction of an operational system for real-time, long term monitoring of ocean currents in the coastal zone. We anticipate the technique will also provide data of interest to researchers in a number of oceanographic disciplines.

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ACKNOWLEDGMENTS

It was through the efforts of N. A. Ostenso, former Assistant Administrator, NOAA's Office for Oceanic and Atmospheric Research (OAR), that a MNT research and development effort was established within the United States. This paper is dedicated to his memory. We are also very grateful to L. M. Brekhovskikh, P.P. Shirshov Oceanography Institute of the Russian Academy of Sciences, for his encouragement and support. The research described in this publication was made possible in part by Award No. RG1-190 of the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union (CRDF). Additional funding has been provided by the Russian Basic Research Foundation, Project RBRF-96-02-18538, the U.S. Office of Naval Research, and NOAA's OAR.