New tools for monitoring the marine environment

New Tools for Monitoring the Marine Environment
Nouveaux instruments pour la surveillance de l'environnement marin
Neue Methoden zur Ueberwachung der Meeresumwelt

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SUMMARY
Increasing concern for environmental issues related to major construction in the marine environment has led to a demand for improved methods of environmental monitoring. New acoustical methods have proven especially effective for this purpose. Water flow measurement is discussed from two complementary viewpoints, together with acoustical monitoring of ocean surface conditions.

Nouveaux instruments pour la surveillance de l'environnement marin

Résumé
Le souci croissant pour les questions de l'environnement, liées aux grands projets en mer, exige de meilleures méthodes de surveillance de l'environnement. De nouvelles méthodes acoustiques se sont avérées particulièrement efficaces dans ce sens. Les mesures de courant d'eau sont présentées selon deux méthodes, prenant en compte la surveillance acoustique de la surface de l'océan.

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Zusammenfassung
Die wachsende Sorge um den Umweltschutz im Zusammenhang mit Grossprojekten auf See forderte verbesserte Methoden der Umweltüberwachung. Neuentwickelte akustische Messmethoden haben sich hierfür als besonders geeignet erwiesen. Die Strömungsmessung wird dazu aus zwei entgegengesetzten Blickwinkeln zusammen mit der akustischen Zustandsüberwachung der Meeresoberflächenbetrachtet.

1. INTRODUCTION

Understanding the marine environment in the neighbourhood of large marine engineering projects is important from various different but often closely related points of view. First, it is necessary to know the circulation, range of sea states and other ocean properties in advance of the engineering design phase, so that the design takes into account the potential impact of the environment on the structure. Second, it is necessary to measure environmental conditions so as to predict the impact of the structure on the environment and to ensure that the design minimises this impact. Thirdly, during construction it is necessary for reasons of safety and efficiency to maintain a comprehensive monitoring program to provide real-time information and preferably to provide input to a short term forecast of conditions. Such monitoring is also necessary to track environmental impacts of construction and, where predictive environmental modelling has been carried out, to verify the accuracy of the modelling as construction proceeds. Finally, monitoring is required after completion of the structure to confirm that its influence on the environment is no greater than predicted.

Monitoring on the scale required for these tasks can present a severe challenge owing to the wide range of spatial and temporal scales of variability encountered, especially in the coastal environment. Efficient design of a monitoring program and effective use of the data requires the implementation of an appropriate model of the local flow. This will normally be a computer model, although analytical calculations and laboratory tests can play an important role. Field measurements can then be used to test the validity of the model and to develop a better understanding of the environment.

In this report a brief account is presented of some new approaches to environmental monitoring that draw on recent advances in the field of Acoustical Oceanography. Acoustical methods are complementary to satellite and airborne remote sensing in that they provide a remote observation beneath the surface. These methods have the additional advantage of providing continuous, real-time output and can often be deployed in such a way that they are relatively immune to the hazards of ship traffic, fishing and related activities.

Acoustical methods are now incorporated in a wide variety of ocean research projects including such diverse topics as the study of ice properties and the monitoring of the ocean response to global climate change. Rather than attempt to survey the full spectrum of potential applications, we briefly comment on two areas of particular relevance to marine engineering projects: Flow Measurement and the monitoring of Ocean Surface Processes.

2. APPLICATIONS

2.1 Flow Measurement

There are two classes of acoustical technology that have been developed for flow measurement: Backscatter Acoustics in which a pulse of sound is reflected back to its source by biological targets or other inhomogeneities in the water, and Forward Scatter Acoustics in which a sound pulse transmitted at one location is detected at another. Backscatter acoustics is relatively short range and best suited to the acquisition of vertical profiles of the current, either from a ship or from the sea-floor. Forward scatter methods have greater range and are suited to a horizontal path, for example between bridge piers, across a harbour entrance or between two moorings.

2.2.1. Backscatter

Various backscatter techniques have been demonstrated. Most of these exploit the Doppler shift of sound scattered by small, naturally occurring targets in the water such as zooplankton or sharp temperature gradients [1]. The incoherent pulsed Doppler is the most widely used and is commercially available both for self-recording deployment and ship-mounting. Four narrow beam transducers are used to project acoustic pulses into the water at a frequency (ω) typically in the range 75 kHz to 1.2 MHz.

In the usual configuration, the Doppler system measures the flow separately along four beams deployed as shown in Figure 1a. Since the flow measurement is resolved along each beam axis, the final determination of the current is based on the assumption that there is no vertical component and that at each depth the four beams are sensing the same current field. Alternatively the Doppler can be mounted on the sea-floor looking upwards, with data either stored internally or transmitted back by cable (Figure 1b).

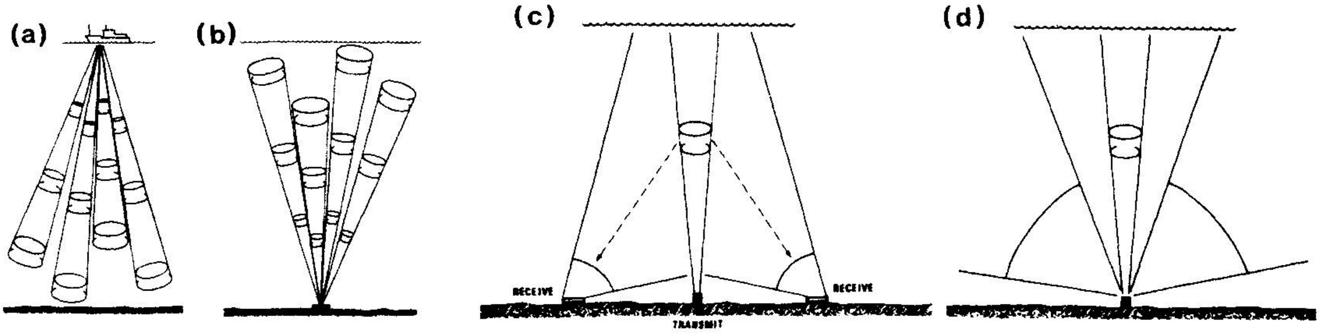

Figure 1. (a) Ship based. (b) Bottom mounted Doppler profiler. (c) Bistatic Doppler. (d) Doppler sidescans, narrow beam vertical sonars and broadband hydrophone for monitoring waves and near surface circulation.

The Doppler shift $\Delta\omega$ of the backscattered signal detected at each transducer is proportional to the velocity component V resolved along the beam axis:

$$\Delta\omega = -\omega V/(C-V) \tag{1}$$

where V is measured positively away from the transducer, and C is the local sound speed at the transducer. The range resolution Δr along a beam, for a given pulse length τ is

$$\Delta r = C\tau/2. \tag{2}$$

The speed measurement uncertainty σ, for a given pulse is [2]

$$\sigma = C/4\pi\tau\omega. \tag{3}$$

It is clear from (1)–(3) that a compromise must be struck between range resolution and speed uncertainty. In general the shortness of the pulse length τ is limited by the transducer bandwidth BW (i.e. $\tau_{min} \approx 1/BW$), but the bandwidth increases, and thus the range resolution improves with increasing frequency. Similarly, the speed measurement uncertainly σ decreases with increasing frequency. However acoustical absorption increases with frequency so that operation at 1.2 MHz, for example, is limited to about 30m.

Even at lower frequencies the range is limited to 200-300m since only a very small fraction of acoustic energy is scattered back to the transducer. These ranges are nevertheless fully adequate for acquiring vertical profiles of the current in the coastal environment.

Much effort has been spent attempting to optimise the choice of pulse length and frequency, and in trying to overcome some of the limitations of the resulting compromise. If a range of just 10–12m is sufficient, very high range and velocity resolution can be achieved by using the coherent Doppler approach [3]. Short pulses (i.e. high range resolution) are transmitted in relatively rapid sequence or in closely spaced pairs. If the scattered signal from one pulse is coherent with that from its successor the effective integration time is the time delay between pulses rather than the much shorter pulse length. The velocity uncertainty is reduced proportionately. The penalty that must be paid is in the form of ambiguity in both range and speed. Range ambiguity arises from the fact that scatter from pulses at two ranges is received simultaneously; speed ambiguity arises from the potential for aliassing of the Doppler signal sampled at the pulse separation period. Effort is now being focussed on overcoming these ambiguities using randomly fluctuating pulse separation and various signal processing schemes. Modified pulse transmission techniques are also being applied to incoherent Doppler so as to increase the effective integration time and bandwidth, thus reducing the uncertainty in velocity measurement. Different 'bistatic' transducer configurations (Figure 1c) allow measurement over much smaller sample volumes than the traditional Doppler configuration.

The importance of these developments to environmental monitoring lies in the increasing range resolution and accuracy of velocity measurement available. Detailed observations of flow around obstacles such as bridge piers or jetties can now be obtained from a small vessel equipped with an acoustic Doppler velocity profiler and an accurate positioning system. Such observations allow close comparison with numerical or laboratory simulations and are useful for investigation of flow distortion, scouring and other environmental impacts. Vertically oriented, bottom mounted Doppler sonars can provide excellent vertical resolution of the current shear, and are therefore ideal for use in strongly density stratified environments such as estuaries and channels having significant vertical salinity gradients.

The backscatter sonar signal also has other important applications besides velocity measurement. The signal intensity can be used to provide an effective flow visualisation, especially for density stratified flows. Density plumes of suspended sediment, an important aspect of environmental concern during marine construction, can often be effectively mapped with backscatter sonar. Such measurements can both guide water sampling strategies and, when used together with Doppler velocity profiles, aid in the validation of sediment dispersion models.

2.2.2. Forward Scatter:

Measurements are often needed of the currents over horizontal scales much greater than the water depth. In principle ship mounted Doppler profilers can be used to traverse different areas of interest. However time series measurements over extended periods are important, both in the examination of seasonal variations in the oceanographic environment and for providing real time current information during construction. Forward scatter techniques are especially appropriate for this purpose, particularly in channels that are relatively well stirred by tidal or other currents.

The operational principle [4] is straightforward. Sound pulses transmitted at one location travel nearly horizontally through the water until detected by two or more horizontally spaced hydrophones at another location. As each pulse travels this path it is distorted by small temperature inhomogeneities in the water. At the receiving hydrophones these distortions appear as a spatial scintillation pattern. Successive pulses show the horizontal displacement of this pattern as the temperature variability is carried through the acoustic path by the background current flow. This displacement, and hence the averaged flow speed perpendicular to the acoustical path, can then be found from the cross-correlation between the signals from each hydrophone.

Most of the fluctuations in signal intensity detected at the hydrophone arise from temperature variability having the dimensions of the Fresnel scale, i.e. $\sqrt{\lambda L}$, where λ is the acoustical wavelength and L the path length. Surprisingly, these temperature or sound speed fluctuations are invariably present in natural flows so that even in water that is very well mixed a useful signal can be obtained. If a single acoustical projector is used, the contribution to the velocity measurement varies along the path in a way that depends upon the separation of the two hydrophones [5]. For example, if the hydrophones are separated by one third of a Fresnel scale then the contributions are weighted towards the middle of the path. If two sources and two hydrophones are positioned such that the two acoustical paths are parallel, the weighting will be nearly uniform.

The path averaging characteristic of this implementation is useful if one requires average flow speeds, for example the discharge of a river or transport through a channel, and by setting up several paths at different depths an averaged vertical profile of current speed can be obtained. However it can also be important to determine the profile of flow speed at different points along the acoustical path. The scintillation scheme has recently been extended to allow for this, by exploiting the concept of a spatial aperture filter [6,7].

A spatial aperture filter makes use of an array of several projectors and several hydrophones. The signal from each possible path between a projector and a hydrophone is assigned a numerical weight. Adjustment of these weights controls the focus on a position x_o and a wavenumber K_o. The transmitting array and receiving array each have effective wavenumbers K_t and K_r respectively, determined by the choice of weights assigned to each transducer. The focus of the array in then given by

$$x_o = L \frac{K_r}{K_t + K_r} \tag{4}$$

and $K_o = K_t + K_r$. In effect the array is tuned to respond to temperature (or sound speed) fluctuations of wavenumber K_o at position x_o. Other fluctuations at other locations also contribute, and form sidelobes of sensitivity both in position and wavenumber, but in general these sidelobes can be made small if the array is large enough and if the filter weights are chosen appropriately.

An alteration of the filter weights leads to a different focus point. Thus several different focus locations can be derived simultaneously by processing the signal with different choices of filter weight so as to form a profile of the current at different points along the path. For each set of weights, the flow speed $V(x_o)$ is determined from the frequency ω_o of the resulting signal fluctuations:

$$\omega_0 = K_0 V(x_0). \tag{5}$$

Unlike the Doppler measurement discussed earlier, this frequency is unrelated to the acoustical frequency, which is chosen on the basis of path length, array dimensions and practical convenience.

A vertical array of spatial aperture scintillation filters thus offers the opportunity of measuring the horizontal profile at different depths. Figure 2 illustrates a possible deployment arrangement. Horizontal arrays are mounted at several depths on the sides of two bridge piers. Real time processing gives the horizontal current profile at each depth.

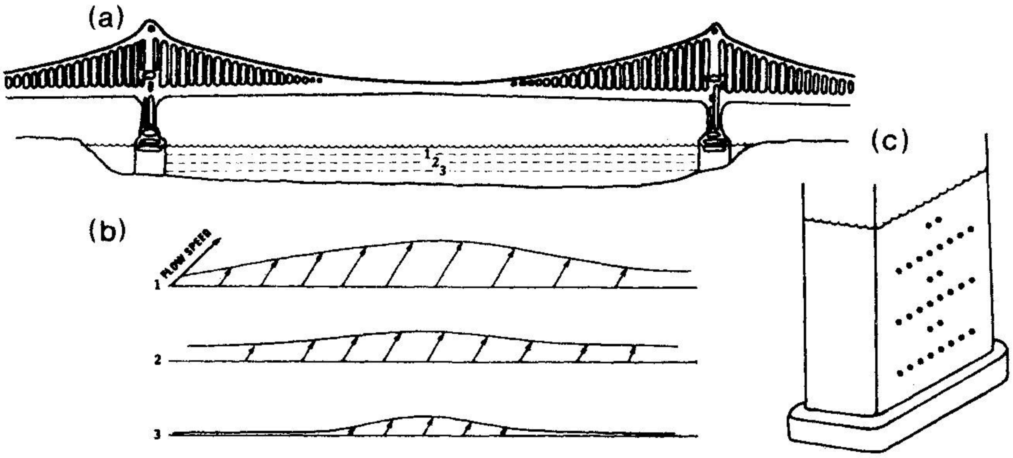

Figure 2. (a) Spatial aperture acoustic scintillation system mounted at different depths on bridge piers. (b) Typical measured profile at 3 depths. (c) Transducer configuration.

Forward scatter measurement along the lines illustrated here can be carried out over horizontal paths of several kilometres. The path length is limited by the need to be able separately to resolve the direct signal from the path that is reflected by the surface or the sea-floor. This path discrimination is more easily achieved as the vertical distance between the direct path and the surface (or bottom) increases. Coding techniques can be used to optimise the time resolution of the signal detection, with the limit being imposed by the transducer bandwidth. Because forward scatter is much more efficient than backscatter, comparable frequencies can be used over much greater distances than for Doppler. (The author has experience with a 70 kHz system operating over a 2.6 km path.) Significant sound speed gradients in the water column will cause refraction of the acoustical paths which must be taken into account in any particular installation. Vertical and horizontal integration gives the water transport. Other properties can also be monitored. For example, if the acoustic travel time is monitored in both directions (i.e. t^+, t^-), the transverse velocity component V_y along the acoustical path and the mean sound speed $\bar{c}$ can be found:

$$\bar{c} = \tfrac{1}{2}L(t^+ + t^-)/t^+t^-, \tag{6}$$

$$V_y = \tfrac{1}{2}L(t^+ - t^-)/t^+t^-. \tag{7}$$

Since temperature is easily measured, the value of $\bar{c}$ at each depth can be expressed as a salinity. In coastal or estuarine environments, the salinity profile may be recovered in this way.

Other interesting and potentially useful properties recoverable from this type of monitoring system include turbulence characteristics and a measure of suspended sediment. The turbulent refractive index variability is related to the variance of the detected signal [5], whereas the suspended sediment results in absorption and scattering of the sound pulse leading to a diminution of the detected sound level. In contrast to the other measurements derived from this instrument, the estimate of sediment load would have to be based on empirically determined calibrations.

In summary, a forward scatter array can provide a wealth of environmental data including two components of the current vector as a function of depth and time, with the potential for flow profiles along the acoustical path using spatial aperture filtering. Turbulence, sound speed or salinity profiles and an integral measure of suspended sediment can also be obtained. The measurement technique can be set up so as to exploit the acoustical phase, providing extraordinary sensitivity; for example an achievable resolution of 1% in acoustical phase using a centimetre wavelength over a kilometre path length corresponds to a pulse travel time precision of one part in 10 million. It seems likely that the full potential of this approach to environmental monitoring has yet to be developed.

2.3.1 The Ocean Surface

Many important environmental issues relate to processes occurring at or close to the ocean surface. Ocean surface processes have recently received increasing attention from acoustical oceanographers and some of the methods that have been developed may prove useful for monitoring the environment in areas of concern near major marine construction works. Two approaches have been used. First, the natural sound of the sea, for example that caused by the effects of wind, provide a very simple means of acquiring important environmental information. Second, active sonars such as the backscatter concept discussed above, can be used to monitor currents, waves and other properties of the sea surface.

Figure 1d illustrates the basic concept. An acoustical instrument deployed on the sea floor in shallow water, or suspended at intermediate depth in deeper water can both listen to the natural sound and use active sonars to probe the surface. It will be obvious from Figure 1b, that these measurements can be combined with Doppler velocity profiles of the flow speed within the water column. Data can be transferred along a cable to shore, to a radio or telephone link. The simplest and one of the most useful observations is made with a broad-band hydrophone. There is a robust relationship between the sound pressure level and the local wind speed [8] which allows useful wind measurement from the sea-floor, with an accuracy of about 0.5 ms^{-1}. The acoustic spectrum of wind is distinctive and contamination by passing ships or by precipitation can be readily identified. (Although the sound made by rainfall is also distinctive, there is at present no reliable algorithm for extraction of accurate rainfall rates from the sound signal.)

Narrow beam sonars can easily resolve the sea-surface displacement due to waves. Thus a single sonar can be used to detect the one-dimensional surface wave field. Sidescan sonars can be used to detect near surface circulation patterns [9], and when operated in Doppler mode can accumulate information from which the directional wave spectrum can be derived [10]. Multiple frequency sonars have been used to monitor wave-breaking and near surface bubble clouds. In combination these new approaches can provide a comprehensive local observation of ocean surface conditions relevant to the needs of construction and of environmental monitoring.

3. SUMMARY

There are many practical requirements for environmental monitoring in areas of proposed or ongoing marine engineering construction. Relatively simple acoustical instruments can meet many of these monitoring requirements from the comparative safety of the sea-floor, or with transducers built into the structure itself. A distinctive feature of the acoustical approach is that by using different processing techniques, data obtained from the same set of transducers can provide a variety of different measurements. Thus forward scatter sonars can provide profiles of currents, sound speed and hence salinity profiles, and measures of turbulence and suspended particulates. Backscatter sonars can provide velocity profiles, flow visualisation, surface wave fields, bubble clouds and near surface circulation. Real-time monitoring with these techniques will become an increasingly prominent component of environmental programs associated with major engineering construction projects.

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