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Water Dynamics and Pollution Nearby Leningrad Dam
Hydrodynamique et pollution près du barrage de Léningrad
Wasserbewegung und - verschmutzung in der Nähe des Leningrader Damms

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SUMMARY
This is a brief review of our papers dealing with remote sensing studies of water dynamics and water pollution monitoring in the eastern part of the Gulf of Finland (Baltic Sea). The results are interpreted in the context of a broad public discussion on the possible negative impact of the construction of the dam across the River Neva Mouth on the state of environment in the Leningrad region.

Hydrodynamique et pollution près du barrage de Léningrad

Résumé
L'article traite des mesures à distance de l'hydrodynamique et de la pollution de l'eau dans la partie orientale du golfe de Finlande (Mer Baltique). Les résultats sont interprêtés dans le cadre d'une large discussion publique sur l'influence éventuellement négative de la construction d'un barrage sur le delta de la Neva, à proximité de Léningrad.

Wasserbewegung und -verschmutzung in der Nähe des Leningrader Damms

Zusammenfassung
In einer Zusammenschau unserer Arbeiten wird über Fernerkundung der Strömungsdynamik und Ueberwachung der Wasserverschmutzung im Finnischen Meerbusen der Ostsee berichtet. Ihre Resultate werden im Rahmen einer breiten öffentlichen Diskussion über den möglichen schlechten Einfluss der Dammkonstruktion in der Newamündung auf den Zustand der Umwelt in der Region Leningrad hin interpretiert.

Fig.1. Satellite image of the River Neva Mouth

9 July 1981

Fig.2. Satellite image of the River Neva Mouth
5 July 1989

Fig.3. Satellite image of the River Neva Mouth
8 September 1989

1. BACKGROUND

The River Neva is one of the most full-flowing in Europe. Freshwater surplus from rivers in the drainage area of the Gulf of Finland is as follows [1, p.II-7]:

River	Drainage area, km^2	Discharge, m^3/s
Kymi (Finland)	37235	517
Neva (USSR)	281000	2463
Luga (USSR)	13200	124
Narva (USSR)	56200	437

Nutrient emissions by rivers (tonnes per year) to the Gulf of Finland is [1,p.II-31]:

	Total N	Total P
USSR	52500	3460
Finland	12000	620

These figures give some idea of the River Neva as the source of pollutants. In the River Neva delta the city of Leningrad is situated, with its five million citizens, and great amount of industrial enterprises with inadequate filtering systems. Thus the problem of spread and spatial distribution of the River Neva pollutants in the Gulf of Finland is obvious. This is not a simple scientific problem and it has not yet been solved. The situation became still more critical when in the vicinity of Leningrad in the River Neva Mouth the construction of dam, protecting the city against the floods, was started in the beginning of the 80's. When the dam was almost built the construction was stopped under the pressure of public opinion.
We recognize the fact that all over the world the public opinion and public actions in the field of environment became a powerful driving force and they should not be neglected. The public opinion may be formed by various manipulations with figures, words and images. Two principle questions: "Has the construction of the dam changed the aquatic environment in the River Neva Mouth and the neighbouring aquatoria?" and "Has the dam influenced the state of environment in the Leningrad region?" are under discussion.
In this paper only one aspect of the problem is considered. Remote sensing satellite and airborne data have been used to monitor the spatial distribution of suspended matter in this region for a number of years.

2. DATA SOURCES AND METHODS USED

In our previous papers [2-4] we discussed possibilities of using satellite imagery of small and medium ground resolution in studies of optical inhomogeneties caused by suspended matters along with reliability of the results obtained. At the initial stage since 1980 multispectral data from "Meteor-30" satellite (MSU-S and MSU-M scanners) were analyzed [2,3], later the information of better quality from satellite "Kosmos-1939" became available: since 1988 - data of medium ground-resolution in visible range 175 m x 200 m from scanner MSU-SK [4]; on summer 1989 high resolution images from MSU-E device (30 m x 45 m) where obtained for the River Neva Mouth.
Our paper [4] deals with some problems of environmental satellite monitoring of the Gulf of Finland including the problem of complex studies of water pollution based on satellite imagery in the visible band. We have used satellite images from our database since 1976. Basing on satellite images of the River Neva

Mouth 1980 till 1988, relevant airborne and ship measurements the peculiarities of distribution of suspended matters have been revealed at various hydrometeorological conditions. Our paper [5] deals mainly with analysis of satellite images since July 1988 till September 1989.

In the analysis of satellite imagery we also used the following additional information:

- pilot map of the region,
- mean velocities, general structure and schemes of currents,
- characteristics of suspended matters including size-distribution of suspended particles and sediments,
- data on seston concentration and regression characteristics "transparency-concentration",
- data on the sources of suspended matters,
- historical data on the spatial distribution of suspended matter at various hydrometeorological conditions,
- meteorological situation before, after and at the moment satellite overpass (wind characteristics, atmospheric pressure, horizontal visibility,
- water level position,
- in-situ ground-truth measurements of water transparency, temperature and salinity,
- airborne measurements of sea-surface temperature and optical characteristics of the water upper layer.

The patterns of spread and spatial distribution of suspended matter have been registeredd in satellite imagery of visible and near-IR bands. Suspended particles are used as tracers to visualize flows and currents with their fine structure.

To study the features of fields of suspended matter and the water masses dynamics in the eastern part of the Gulf of Finland satellite images were selected, which fit various hydrological situations, caused by water level changes. We developed a method which enabled us to obtain quantitative estimates of suspended matter concentration limits at each of the zone (cluster) recorded in satellite imagery. (For details see [5]).

Typical values of transparency and concentration of suspended matter for zones determined in satellite imagery of the River Neva Mouth are as follows [5]:

Zone number	Pollution	Transparency, m	Concentration, mg/l
1	"Clean" river water (background level)	>1,0	<10
2	Very small	0.7-1.0	10...15
3	Small	0.5-0.7	15...20
4	Medium	0.4-0.5	20...25
5	High	0.2-0.4	25...60
6	Very high	<0.2	>60

Image processing technique was used to map the distribution of suspended matter with 6-cluster classification with presentation of results in false colors.

3. RESULTS AND DISCUSSION

With respect to characteristics of water level change at least 4 types of hydrological situations can be studied:

- smooth change of level (slow decrease),
- increase of level,
- sharp decrease of level,
- period of change of phase (decrease after durable increase).

For each type of hydrological situation one can see a specific pattern of suspended matter distribution and current field as recorded in satellite imagery. Figs.1-3 show some examples of satellite imagery. In fig.3 the following features can be traced:

- outflow currents in the northern part of the dam,
- quasi-homogenious "mixed" zone at the large area of the mouth to the west of the dam,
- eddy chain along the Morskoj Channel, (the total length of this chain is about 20 km, 10 eddy structures of about 1.5-2.0 km size can be determined),
- reverse currents traced with suspended matter in the northern part of the River Neva Mouth.

For details of other types of patterns see [5].

Complex analysis of sets of satellite images of high resolution and in-situ measurements enables to elucidate a lot of fine features at the frontal zones separating different water masses, in the field of currents, in dynamical structures in the River Neva Mouth and the eastern part of the Gulf of Finland.

One can see that there are two zones with increased amount of suspended matter - along the northern and southern coasts of the River Neva Mouth. They had existed long before the start of construction of the dam. It is worthwhile to note that zones with increased amount of suspended matter have been traced in the satellite imagery even at the periods when no dredging or bottom-deepening operations have been performed. This fact shows the great role of processes of bottom sediments mixing in the shallow waters caused by wind and wave turbulization [4].

Analysis of satellite images stored in our database showed that there is a very high variability of feature characteristics of suspended matter patterns at the synoptic scale according to the above mentioned four types of hydrological situations. It means that for a given time interval (for example, month or year) one can find a certain number of images with "dirty" Mouth (large areas with high concentrations of suspended matter) or "clean" Mouth (small areas). Please, keep it in mind for the future discussion!

As for the seasonal variability, there is a tendency that the total area of zones of suspended matter increases from spring to the end of autumn. One of the reasons may be the increasing activity of dredging and other operations in the summer period plus seasonal grouth of wind and wave activity.

It is difficult to show any tendency in annual variability, no reliable remote sensing data exist which could show changing in general patterns of suspended matter fields before and after the construction of the dam.

Those are the conclusions we came to after having analyzed and thoroughly studied more then 100 of remote sensing images from our database.

Unfortunately the sore subject of dam construction gave rise to some sweeping statements made as a rule by non-professional opponents of the dam and based on no scientific data. They

agitated the public anxiety appealing not to reason but to emotions. Thus people having no idea of the peculiarities of hydrological regime of the aquatoria using a few random remote sensing images tried to present to the public the "awful" picture of the dam impact on the aquatoria. The images they showed were ones taken at different hydrometeorological situations, different seasons, and with different number and location of dredging and bottom-deepening machines. More often than not those ignorent "experts" have a very vague idea of what is recorded in remote sensing images of different spectral bands; all the optical non-homogeneties in their interpretation are called "mud". We shall discuss this situation later.
The results obtained have once more proved the validity of operative (transmitte via radio links) satellite data in regional ecosystem studies and the hard necessity of development of these studies according to suggestions listed in [4]. The gained experience can be used also in the analysis of photographic satellite data [5].

4. THE DAM LESSONS

4.1. Some lessons in the field of scientific research.

- adequate observation of the aquatoria requires regular satellite monitoring providing high-resolution images once in 3-4 days and medium-resolution images - daily,
- specific spectrometric remote sensing measurements should be performed along with the existing broad band satellite images,
- location of regular in-situ observation stations must be specified in accordance with current system and spatial distribution of suspended matter,
- prior to construction of Major Engineering Structures (MES) and in the process of it storage of homogenious time-series of remote-sensing and relevant in-situ data is necessary,
- those data should be accumulated in integrated Geographical Information Systems (GIS) of the type suggested in [6],
- further analysis of satellite imagery demands the efforts of specialists in hydrodynamical modelling who could use satellite data to obtain the new or to specify the already known initial and boundary conditions and some parameters in numerical models. These models for the River Neva Mouth should account for 2-dimensional sources of pollution,
- "zero-solution approach" suggested for the Great Belt Link is a good example to follow in future MES projects.

4.2. Some lessons in the field of public relations.

- for MES that could possibly affect a great number of citizens or a large aquatoria, or cause trans-generational effects international examination of the project is recommended,
- scientists should not ignore public discussions. Sometimes scientists simply ignore non-specialists opinions. Very soon a large amount of non-professional opinions expressed in letters, published in news-papers or appeared in TV-programmes becomes so large that it is almost impossible to dissuade the public,
- try to avoid manipulating with terms: pollution, mud, clean, dirty, - all these terms should be defined strictly before you start discussion with lay men,

- it should be clarified that two environmental events occuring at the same time interval or one after another might not necessarily be caused by one another. Even this very simple thought has to be explained to many people over and over again,
- experts in public relations in the field of environment should have good knowledge of modern sociology, psychology, mass-media, communicative theory, etc.,
- first ideas of ecology and environment must come to people at a very early age, may be, in their childhood (see my concept of ECOLOGIUM in [6]).

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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.

Neue Methoden zur Ueberwachung der Meeresumwelt

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).

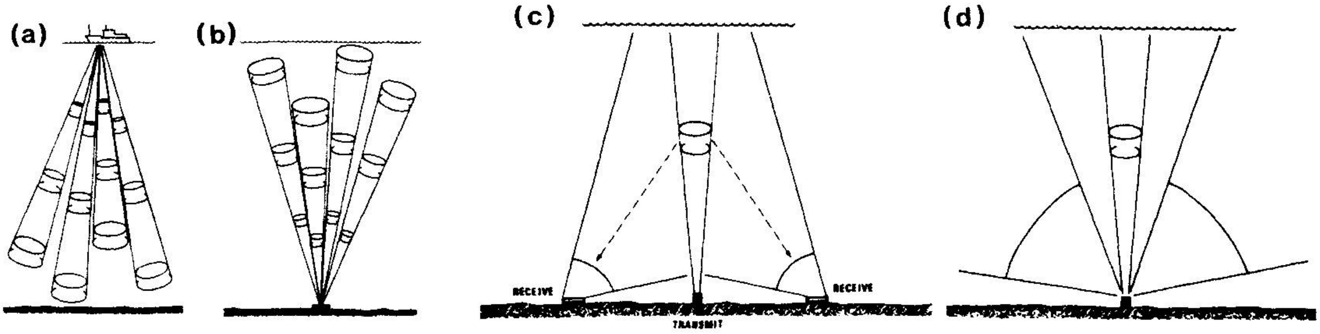

Figure 1. (a) Ship based. (b) Bottom mounted Doppler profiler. (c) Bistatic Doppler. (d) Doppler sidescans, narrow beam vertical sonars and broadband hydrophone for monitoring waves and near surface circulation.

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:

$$\omega_0 = K_0 V(x_0). \quad (5)$$

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.

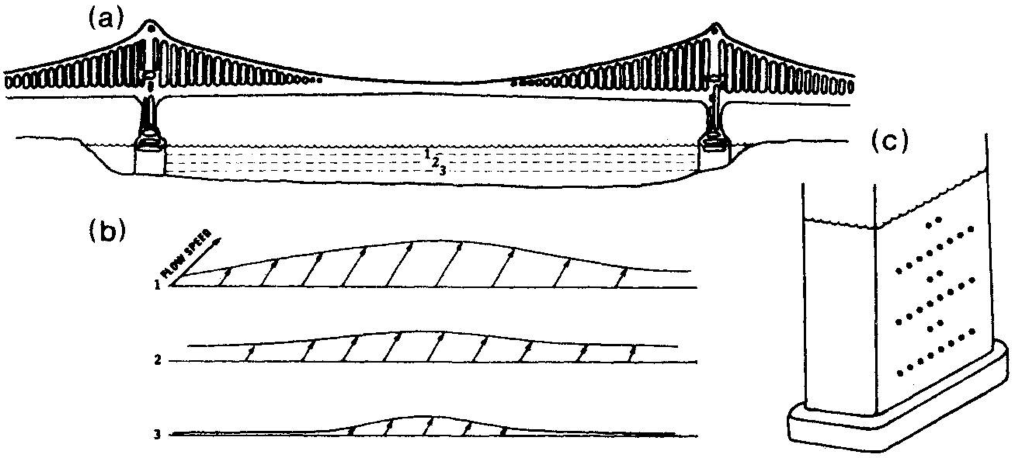

Figure 2. (a) Spatial aperture acoustic scintillation system mounted at different depths on bridge piers. (b) Typical measured profile at 3 depths. (c) Transducer configuration.

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:

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

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

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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Current Acoustic Velocity Profiler for Coastal Monitoring
Surveillance de la côte au moyen d'un procédé acoustique
Küstenüberwachung mittels einer akustischen Methode

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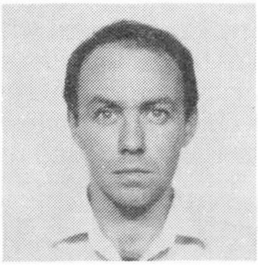

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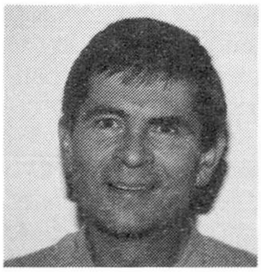

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SUMMARY

A coherent backscatter velocity profiling sonar is described which uses pseudo random tone modulation and pulse pair processing to extend the range velocity ambiguity product. The consequences of pseudo random tone modulation and detection on the range resolution and the coherence time of the backscattered signal is presented with practical results obtained from laboratory tests. The functional implementation of the instrument and its novel signal generation technique is described with emphasis placed on the system reconfigurability under software control. Practical results obtained with the instrument in field trials are presented. The role of the instrument in coastal monitoring and the management of water resources and future multi-dimensional implementations of the instrument outlined.

Surveillance de la côte au moyen d'un procédé acoustique

Résumé

L'article présente une technique et un instrument de surveillance de la côte basée sur un principe acoustique. Des détails techniques sont donnés. Le rôle de cet instrument, ses applications futures possibles et la gestion des ressources en eau dans les zones côtière sont présentés.

Küstenüberwachung mittels einer akustischen Methode

Zusammenfassung

Der Artikel präsentiert eine Technik und ein Instrumentarium der Küstenüberwachung, das auf einem akustischen Prinzip basiert. Technische Einzelheiten werden gegeben. Seine zukünftigen möglichen Anwendungen für die Rolle dieses Instrumentariums und die Verwaltung der Gewässerresourcen in den Küstenzonen werden dargestellt.

ABSTRACT

A coherent backscatter velocity profiling sonar is described which uses pseudo random tone modulation and pulse pair processing to extend the range velocity ambiguity product. The consequences of pseudo random tone modulation and detection on the range resolution and the coherence time of the backscattered signal is presented with practical results obtained from laboratory tests. The functional implementation of the instrument and its novel signal generation technique is described with emphasis placed on the system reconfigurability under software control. Practical results obtained with the instrument in field trials are presented. The role of the instrument in coastal monitoring and the management of water resources and future multi-dimensional implementations of the instrument outlined.

INTRODUCTION

The Acoustic Doppler Current Meter (ADCM) is a backscatter coherent Doppler sonar used to derive water velocities as a function of depth in rivers and coastal waters. The instrument also incorporates a conventional echo ranging function allowing the instrument to monitor water depth or bottom profile as a function of time. The instrument was developed in response to specific requirements :

(i) provide a low cost, accurate method of estimating water velocity as a function of depth

(ii) provide a reliable method of estimating the bed/water/surface interface so as to monitor depth/scour in rivers and around structures.

The development commenced in February 1989 as a two stage, two year project. Stage one would deal with the preliminary research and lead to the construction of a laboratory prototype while stage two would then build on that work and develop a field prototype. Stage one was successful in demonstrating the principles involves and stage two is now nearly complete with the instrument currently undergoing field trials.

The instruments requirements can be summarised as

(i) able to resolve velocities up to a velocity range ambiguity limit of 25 $m^2 s^{-1}$

(ii) a velocity resolution of 5 mm s^{-1}

(iii) a spatial resolution of 20 mm

(iv) able to simultaneously detect the surface/water/bed interface with a spatial resolution of 10 mm

Figure 1 shows a typical deployment application of the ADCM.

BACKGROUND

The interrelationships of the different types of sonars and the ADCM is shown in Fig. 2. Backscatter Doppler sonars all operate on the principle of echoes from suspended particles and density discontinuities in the acoustic path being reflected back to the source. The principle is shown diagrammatically in Fig. 3 where echoes from a transmitted pulse (starting at t = 0) are reflected from an ensonified bin and then received at time t_e (travel time to and from the ensonification). The Doppler shift, caused by the motion of particles in the bin is then derived by observing the phase shifts between adjacent echoes relative to the phase coherent interrogating pulses. The velocity of the particles in the bin and hence the accompanying water can then be derived.

Coherent Doppler sonar are subject to performance limitations caused principally by (i) a finite propagation speed for acoustic energy and (ii) Nyquists criteria for sampled waveforms. Together they form what are known as the range-velocity ambiguity equations [7] for r_m, the maximum resolvable range, and v_m, the maximum resolvable velocity.

$$f_d = \frac{2 . v_r . f_c}{c} \qquad (1)$$

the Doppler shift, f_d, from a radial velocity v_r, given a carrier frequency f_c and the speed of sound, c.

$$r_m = \frac{c}{2.PRF}$$

a pulse cannot be transmitted before the previous echo has arrived limiting the maximum resolvable range with the pulse repetition frequency, PRF. (2)

$$v_m = \frac{c.PRF}{4.f_c}$$

the resulting Doppler frequency must not exceed a phase shift greater than π radians between adjacent interrogating pulses (Nyquists criteria) otherwise a velocity ambiquity will result. (3)

or combining (2) and (3)

$$v_m\, r_m = \frac{c^2}{8\, f_c} \qquad (4)$$

Additionally when considering the performance of coherent Doppler sonars the range resolution must be considered. The range resolution or bin size, r_e, is shown in Fig. 3 and defined [1] as

$$r_e = c.\, t_w$$

where t_w is the temporal width of the transmitted pulse. (5)

Upon consideration of the above equations it can be seen that the above objectives are particularly stringent in relation to the instrument requirements. The acoustic beam can be directed at an angle of 45 ° relative to the bed giving a $1/\sqrt{2}$ reduction in the maximum unambiguous velocity, however, the unambiguous range velocity product is still

$$v_m . r_m = \frac{5.5}{\sqrt{2}} = 17.67$$

which, upon substituting into (4) gives a carrier frequency of 15.9 kHz. Such a low carrier frequency is impractical because of (i) the resulting low spatial resolution and (ii) the required transducer diameter for an adequately small beamwidth. The spatial resolution would be determined by the period of 15.9 kHz in a (say) ten cycle burst of 15.9 kHz i.e. 610uS corresponding to a spatial resolution of 943 mm. Similarly the beamwidth for a piston transducer is given by

$$BW = \frac{91440}{(fc.d)}$$

where BW is the beamwidth in degress and d is the transducer diameter (6)

implying a diameter of 575 mm for a 10° beamwidth (ignoring the near/far field of such a large transducer). The low carrier frequency is obviously impractical.

A more attractive carrier frequency in terms of the beamwidth, spatial resolution, propagation loss and transducer availability would be 300 kHz. A 30 mm transducer would then have a beamwidth of 10° and a ten cycle burst at 300 kHz would exhibit a spatial resolution of 50 mm. Unfortunately, the range velocity product would then be only 0.9375. A factor of 19 below the specified.

Therefore, although coherent backscatter sonars initially seem applicable, it is not possible to simultaneously retain a sufficiently high range velocity ambiguity product, narrow beamwidth, and high spatial resolution to meet the design parameters. Modifications to the basic system were necessary to ensure a practical instrument.

ACOUSTIC DOPPLER CURRENT METER

To enhance the applicability of the coherent Doppler sonar, two methods of extending v_m and r_m are utilised in the ADCM.

(i) Independent pulses
The range ambiguity restriction is based on the premise of a single pulse traversing the acoustic path between the transducer and the target volume at any one time. This is valid if consecutive pulses are identical because echoes from following transmitted pulses would interfere with echoes from the specified volume. If, however, the pulses were coded and the received "matched" to a specified pulse it would be possible to discriminate between echoes. The ADCM uses transmitted pulses composed of independent m-sequences phase modulating the carrier [3]. M-sequences have a number of desirable properties for the ADCM including ease of implementation, however, other possible coding schemes do exist, Barker [10], Golay [4] and complementary [8].

M-sequence possess (i) good cross correlation properties between sequences [9] and (ii) optimal autocorrelation properties. The first property determines the degree of relation between successive pulses and therefore the signal to noise ratio at the matched received whilst the second has the effect of redefining the range resolution. The autocorrelation of a non-circular m-sequence [2] can be shown to be maximal at zero shift i.e. R(0) with maximal sidelobes of $1/\sqrt{N}$ where N is the length of the sequence. The range resolution and range ambiguity for a sonar using m-sequences as the transmitted pulses can be redefined as

$$r_e = c \,.\, t_c \qquad \text{where } t_c \text{ is the chip length} \tag{7}$$

and $t_w = n \,.\, t_c$ i.e. n is the number of chips in the sequence

$$r_m = \frac{m.c}{2.PRF} \qquad \text{where m is the pulse multiplicity i.e. the number of pulses traversing the path simultaneously} \tag{8}$$

(ii) Frequency pair processing
The velocity ambiguity restriction is based on a finite pulse repetition frequency when interrogating a volume. If a velocity greater than the ambiguity limit is encountered then the resultant measured velocity $v_{measured}$ will "wrap around" or be aliased modulo v_m. The number of times a velocity has wrapped over the v_m limit is termed the aliasing order. The apparent velocity is then

$$v_{measured} = v_{actual} \text{ modulo } v_m$$

or

$$v_{actual} = k \,.\, v_m + v_{measured} \tag{9}$$

where k is the aliasing order.

The v_m limit is determined by both the carrier and pulse repetition frequency. It is possible, with certain constraints, to combine two uniquely aliased estimates to unwrap or dealias the measured velocity to its true magnitude. The aliased estimates may be obtained by interrogating the same volume and varying either the pulse repetition or carrier frequency. Varying or staggering the PRF is frequently used [6], however, we chose to vary the carrier frequency. Varying the carrier frequency [1] has implementation advantages in terms of system complexity, however, it also allows the PRF to be retained as a maximum (see later consequences of independent pulses) over the two successive interrogations. If the two interrogations occur with consecutive high and low carrier frequency we have

$$v_{ml} = \frac{c.PRF}{4\, f_{cl}} \qquad v_{mh} = \frac{c.PRF}{4\, f_{ch}} \tag{10}$$

where v_{ml}, v_{mh} are the maximum unambiguous velocities for the two carrier frequencies f_{cl} and f_{ch}

$$v_{actual} = k_1 v_{ml} + v_{measuredlow}$$

$$v_{actual} = k_2 v_{mh} + v_{measuredhigh}$$

If we now introduce the constraint that

$$\frac{f_{cl}}{f_{ch}} = \frac{j}{j+1} \quad (11)$$

for j any positive non-zero integer then

$$v_{md} = \frac{j.c.PRF}{4.f_{cl}}$$

or

$$v_{md} = \frac{(j+1).c.PRF}{4.fch} \quad (12)$$

where v_{md}, is the new dealiased, ambiguity limit

The ratio $^{j}/_{j} + 1$ can be chosen as low as the frequency resolution in determining $v_{measured}$ will allow. However, small errors in measuring $v_{measured}$ may result in dramatic errors after dealiasing. In the ADCM a (2, 3) frequency pair are the default frequency pair i.e. 250 kHz, 375 kHz, however, a (3, 4) or (4, 5) pair can be nominated.

Consequences of independent pulses

As stated in (6) a system using m-sequence pulses exhibits a modified spatial resolution. For the ADCM using an 8uS chip length (2 cycles of 250 kHz) the spatial resolution is 12 mm. While allowing more accurate velocity profiling the reduced bin size has the disadvantage that particles will be ensonified for shorter periods of time. Defining the coherence period as the time for which a single particle is resident the PRF must therefore exceed the coherence period for pulse to pulse coherence. A 12 mm bin at the specified maximum velocity $^{5}/_{\sqrt{2}}$ ms^{-1} would require a PRF of at least 290 Hz to meet the pulse to pulse coherence criteria. In practice, to ensure maximum pulse to pulse coherence, the PRF must be as high as possible.

The echo ranging function

As discussed earlier, it is necessary to provide an echo ranging function within the instrument to detect the surface/water/bed interface. This facility is provided by reconfiguring the instrument to generate sinusoidal tone bursts as transmitted pulses. The receiver then heterodynes the received echoes down to baseband and, after edge enhancement, detects the rising edge of the received pulse. The transmitted pulse is ten cycles of 375 kHz giving a spatial resolution of 40 mm. Since we detect the rising edge of the received pulse and not the envelope, somewhat better resolution can be expected.

Composite signal structure

Independent m-sequence pulses, phase shift keyed onto the lower of the two carrier frequency pairs, are used to gain a velocity estimate of an ensonified volume at a specified range. The same volume is then ensonified with the upper of the two carrier frequency pairs. The two estimates (possibly aliased) are then used to form an unaliased estimate. The new range velocity ambiguity equation is defined as

$$v_m . r_m = \frac{m.(j+1).c^2}{8 f_{ch}} \quad (13)$$

or
$$= \frac{m.j.c^2}{8.f_{cl}}$$

A (250 kHz, 375 kHz) frequency pair i.e. (2, 3) and a pulse multiplicity factor of 6 [11] therefore gives a $v_m r_m$ of 13.5 which, while not exceeding the required 17.6 ($^{25}/_{\sqrt{2}}$), will demonstrate the validity of the system.

System structure

A block diagram of the system is shown in Fig. 4. Since substantial development was to take place on the system, emphasis was placed on flexibility and replacement of hardware with software where possible. This approach has proven to be invaluable throughout the project.

(i) Signal storage and generation
Real time generation of the transmitted and reference signals is not feasible with current microprocessors, however, the complexity of the signals precludes a hard wired solution. A compromise was arrived at with a temporary storage area of 64 kB static RAM shared between a microprocessor and a sequential counter. In operation, the signals are generated by the microprocessor, written into the RAM, and then sequentially read out by the counter in real time. With a 64 kB RAM and a counter clock of 3 MHz, signals can be generated with delays sufficient to ensonify a volume at a range of 16 meters. The flexibility inherent in this system has allowed us to provide an echo ranging facility as well as a backscatter Doppler sonar in the same instrument.

(ii) Signal processing
Signal processing comprises two sections (a) analogue correlators and (b) the digital spectral transform.

(a) Analogue correlators are provided by multipliers and integrators with integrate and dump facilities. It is important to realise that this configuration does not allow continuous time correlation but only correlation at a defined temporal point. The substantial added complexity of a continuous time correlator was not necessary for this instrument. Analogue correlators were chosen over digital implementations due to their low cost, low power consumption and improved performance.

(b) The digital spectral transform of the output of the correlators is provided by an ADSP-2100 signal processor and analogue to digital convertors. The processor transforms the time domain Doppler signal to the frequency domain and derives the first moment of the resulting spectra. The ADSP-2100 operates at 12.5 MIP's and is capable of real time operation on the received Doppler signals.

(iii) System controller
Overall system control is provided by an Intel 80C196 embedded controller. The system controller generates the transmitted and reference signals in non real time and translates the spectral estimates from the ADSP-2100 into dealiased velocity estimates. It also provides a serial interface to the surface data acquisition system and a real time clock facility.

(iv) Surface data acquisition
The surface data acquisition system is a laptop PC running an instrument configuration and data capture and display programme. Options for instrument configuration are provided with a window based selection procedure and transmitted to the instrument by the serial link. Subsequent data from the instrument is then received and displayed in a graphical format by the PC, a logging facility whereby data is written to disc for later analysis is provided.

Field results

Field testing of the instrument is still in progress at the time of writing, however, preliminary results appear very promising. Figures 5 to 8 show some data obtained from a recent test at the Water Authority of Western Australia, waste water treatment plant in Shenton Park, Perth. The plant provides a number of conveniently located channels of moving water with a relatively constant velocity and variable suspended particle densities. During the tests, the instrument was mounted at the bottom of a 750 mm channel giving the acoustic path a 45° elevation towards the surface.

(i) Figure 5 shows an echo ranging profile obtained by averaging 256 consecutive pings. The two peaks shown are the backscattered reflections from the water surface and the bed of the channel. From the figure it can be seen that the echoes from the surface and the bed can be easily discriminated from other echoes.
(ii) Figure 6 shows the displacement of the backscattered spectra when the carrier frequency is varied. The dependence of the Doppler frequency on the carrier underlies the dealiasing concept.
(iii) Figure 7 shows a time series of velocity estimates for a single bin. The low variance of the estimates is obvious and compares well with the velocimeter readings (propeller type).
(iv) Figure 8 shows a velocity profile as a function of range. The lower velocities encountered near the surface can be seen. The outlier at a range of 600 mm's is due to sidelobe reflections from the surface and has been described by other researchers [5]. Surface reflections occur with zero Doppler shift and it should therefore be possible to discriminate reflections from stationary objects. Field tests to confirm this are currently in preparation.

Wider applications

In the wider context, the instrument will be used in coastal circulation investigations (range 20 m, velocity range 1.25 ms^{-1}), estuarine research projects (range 5 m, velocity range 5 ms^{-1}) and in the study of lake hydrodynamics (range 50 m, velocity range 0.5 ms^{-1}). By extending the range ambiguity it has been possible to construct an extremely versatile, highly accurate instrument. Under optimum conditions it will be possible to measure the velocity field with a spatial resolution down to the Kolmogorov scale (for a dissipation of turbulent kinetic energy dissipation of 10^{-7} m^2 s^{-3}) which will enable the resolution of the turbulent field. Thus, the instrument will not only find application in circulation studies, but also in the study of turbulent dispersion.

Further development

Further development of the principles developed for the ADCM are planned. A four axis instrument for the three dimensional resolution of bin velocities will be developed. A continuous time correlator will be developed for this instrument to decrease profile acquisition time.

Work is also planned for the optimisation of the code sequences and specifically for the suppression of the spreading code sidelobes by the use of artificial guard sequences.

At the conclusion of the field tests a commercialisation of the ADCM will be undertaken. The cost of the instrument will be minimised and the packaging optimised for end user requirements. Additionally, the software package will be modified so as to remove its developmental aspects and build a useful customer interface.

CONCLUSIONS

Conventional coherent Doppler backscatter sonars, although ideally suited to the measurement of water velocities, are limited by the range velocity ambiguity equations. This limitation restricts their use at higher water velocities or at longer ranges. The ADCM enhances the basic backscatter system by using noise based pulses and a velocity dealiasing method using two carrier frequencies. These modifications allow the ADCM to be applied to a practical situation where conventional techniques would fail. Preliminary data from field tests has been presented demonstrating the performance of the instrument in deployment conditions.

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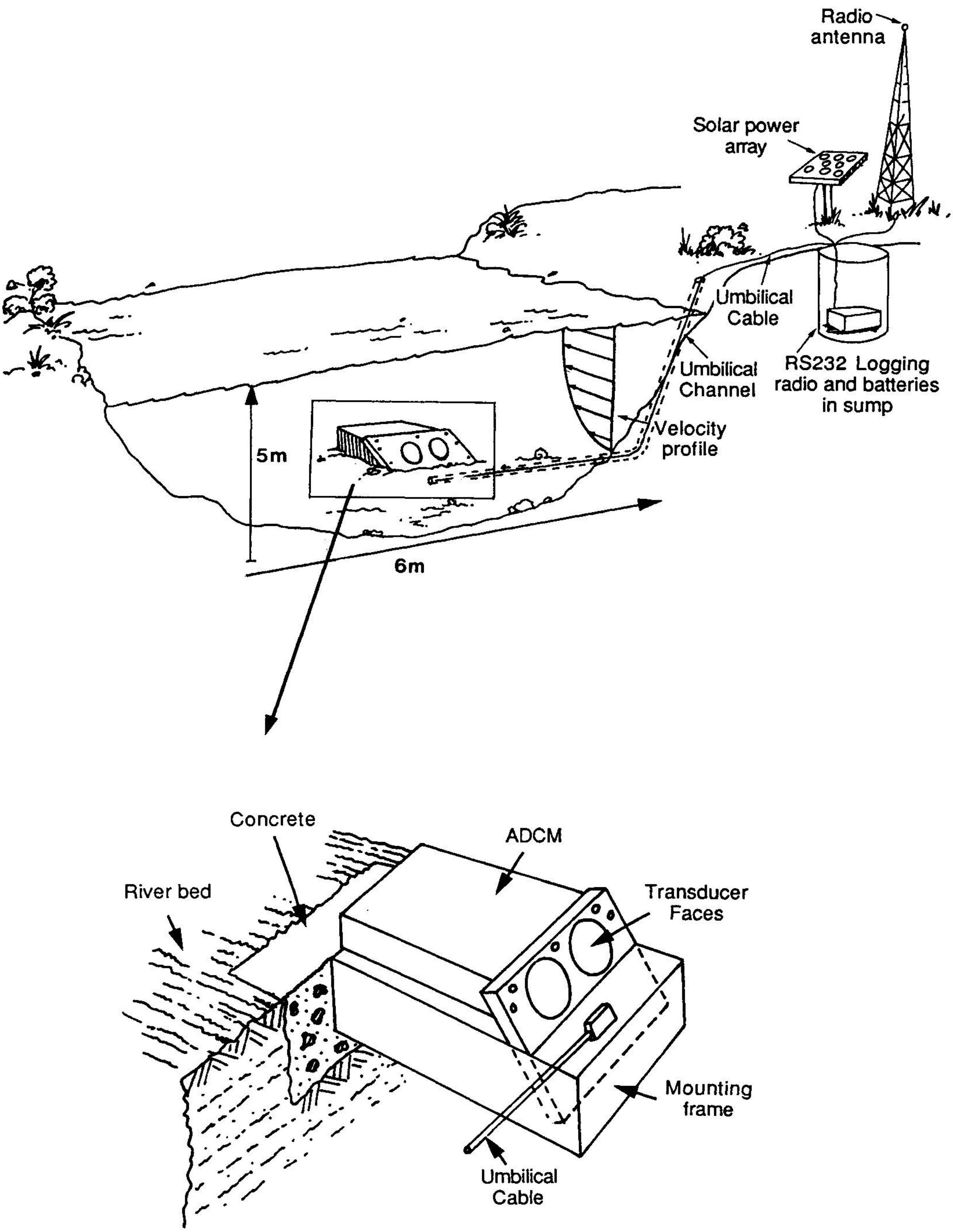


Figure 1. Typical Deployment of ADCM

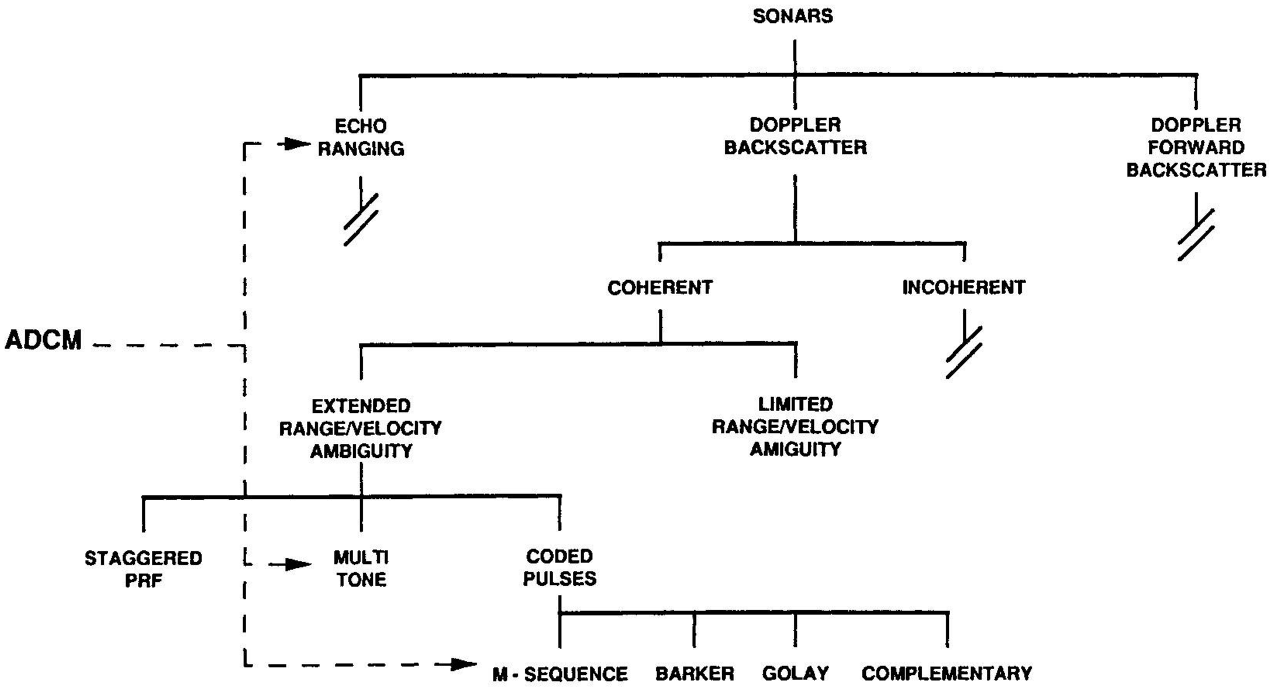


Figure 2. Relationship of ADCM to other sonar systems

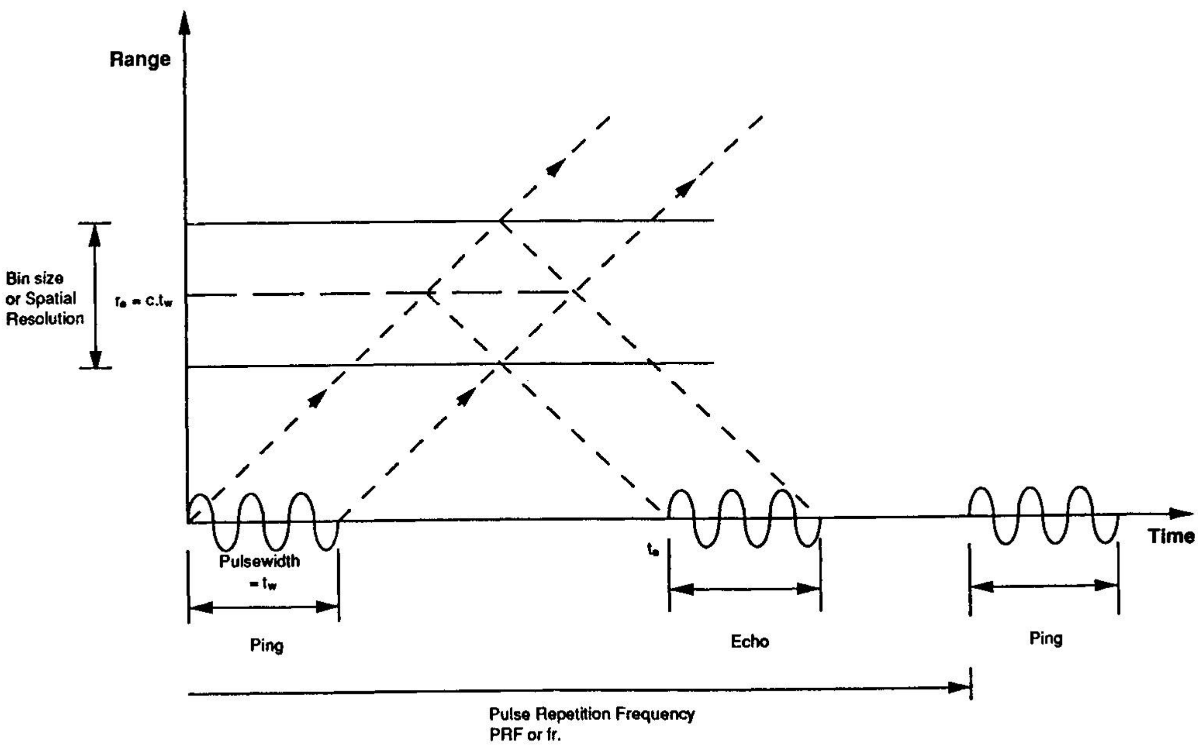


Figure 3. Time/Space diagram for a transmitted pulse

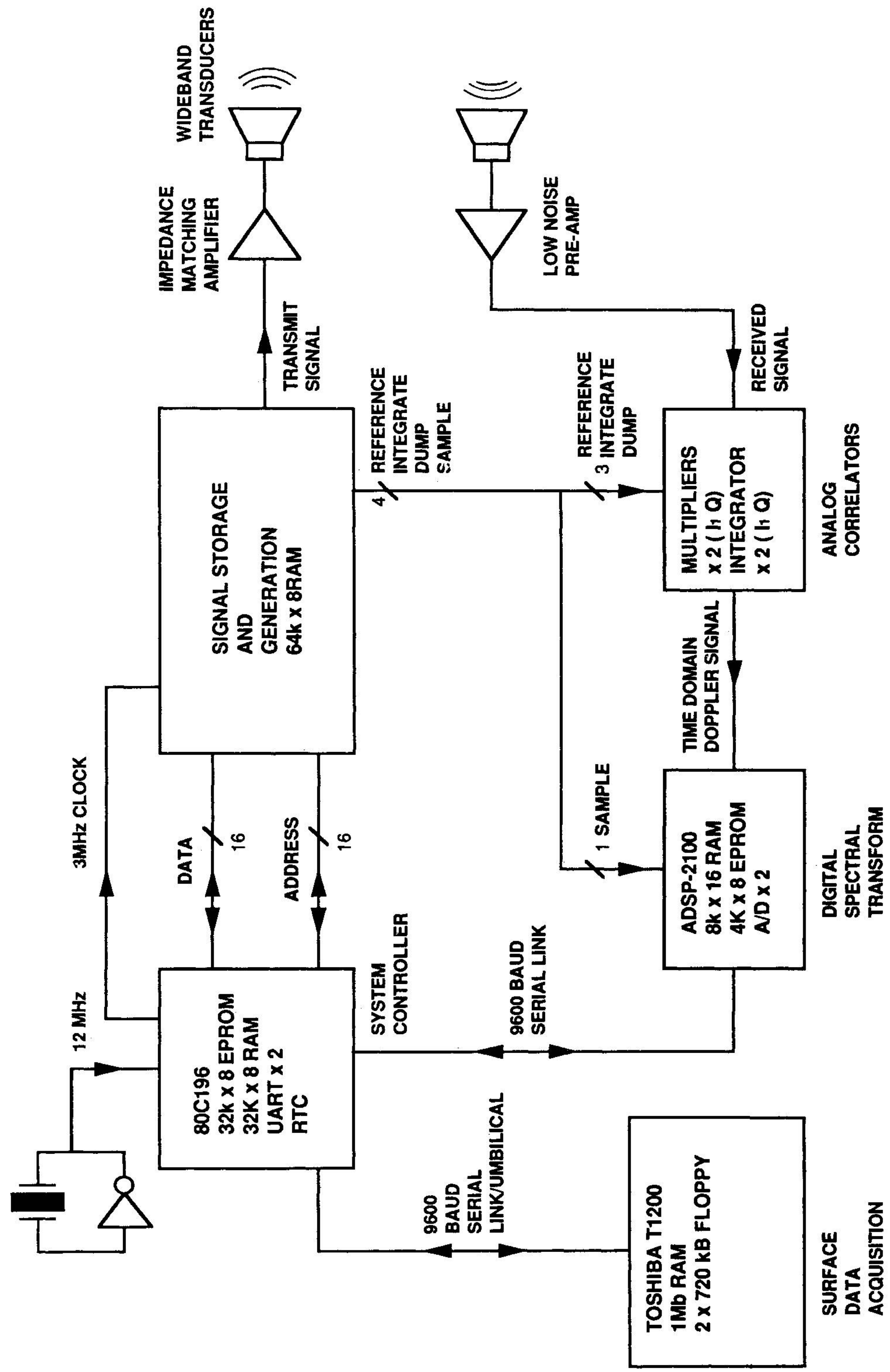
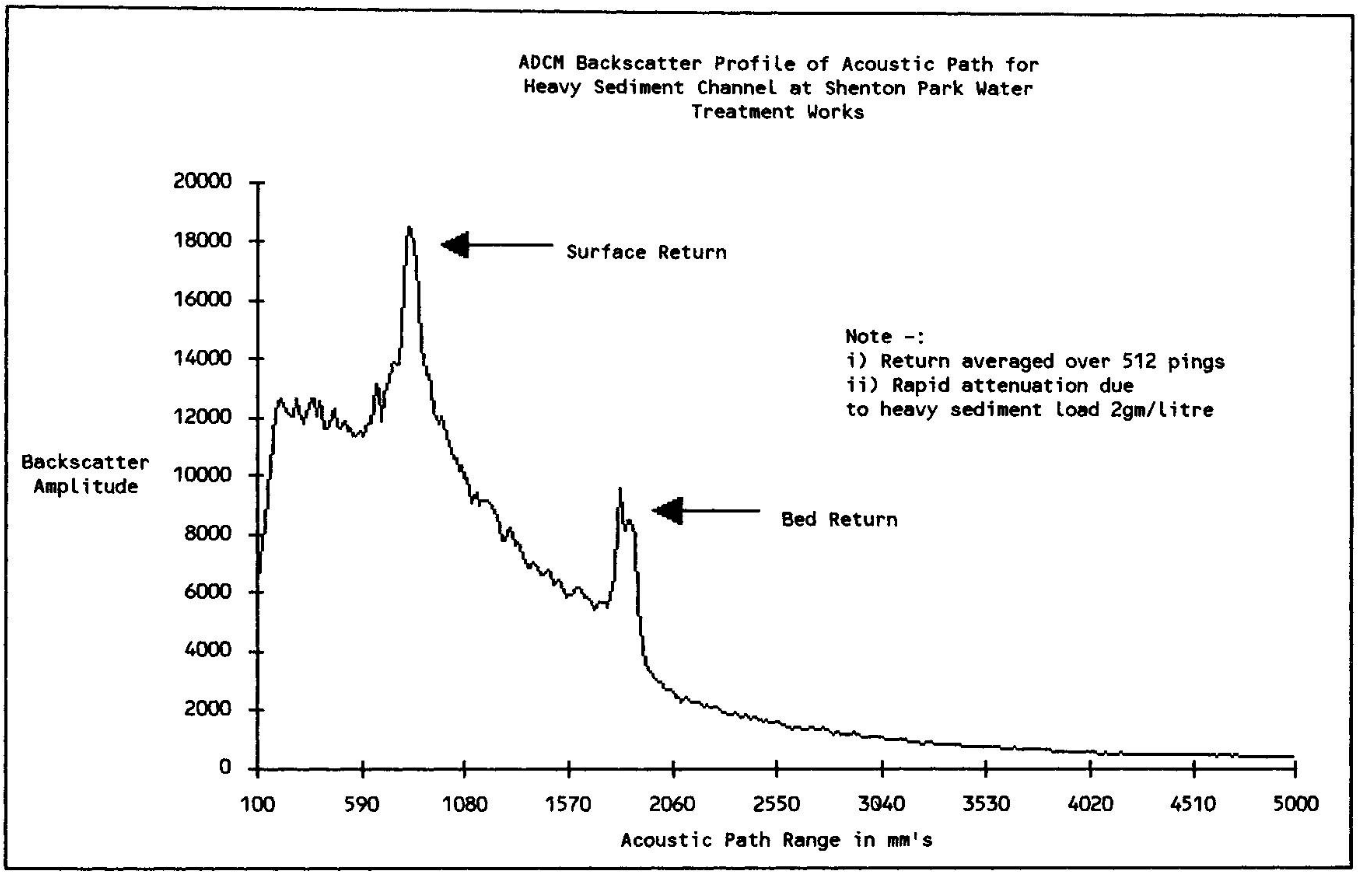


Figure 4. ADCM system diagram



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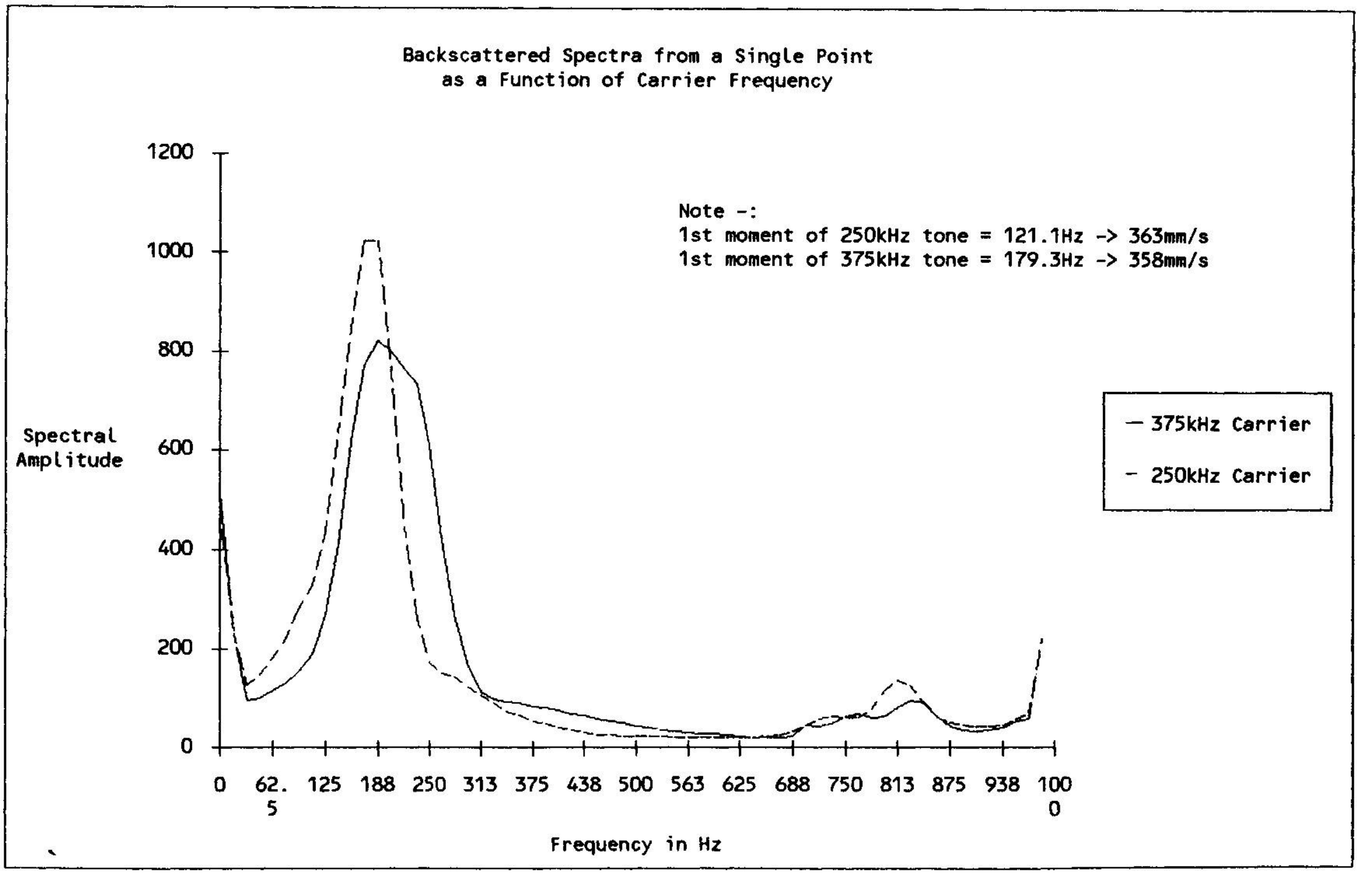

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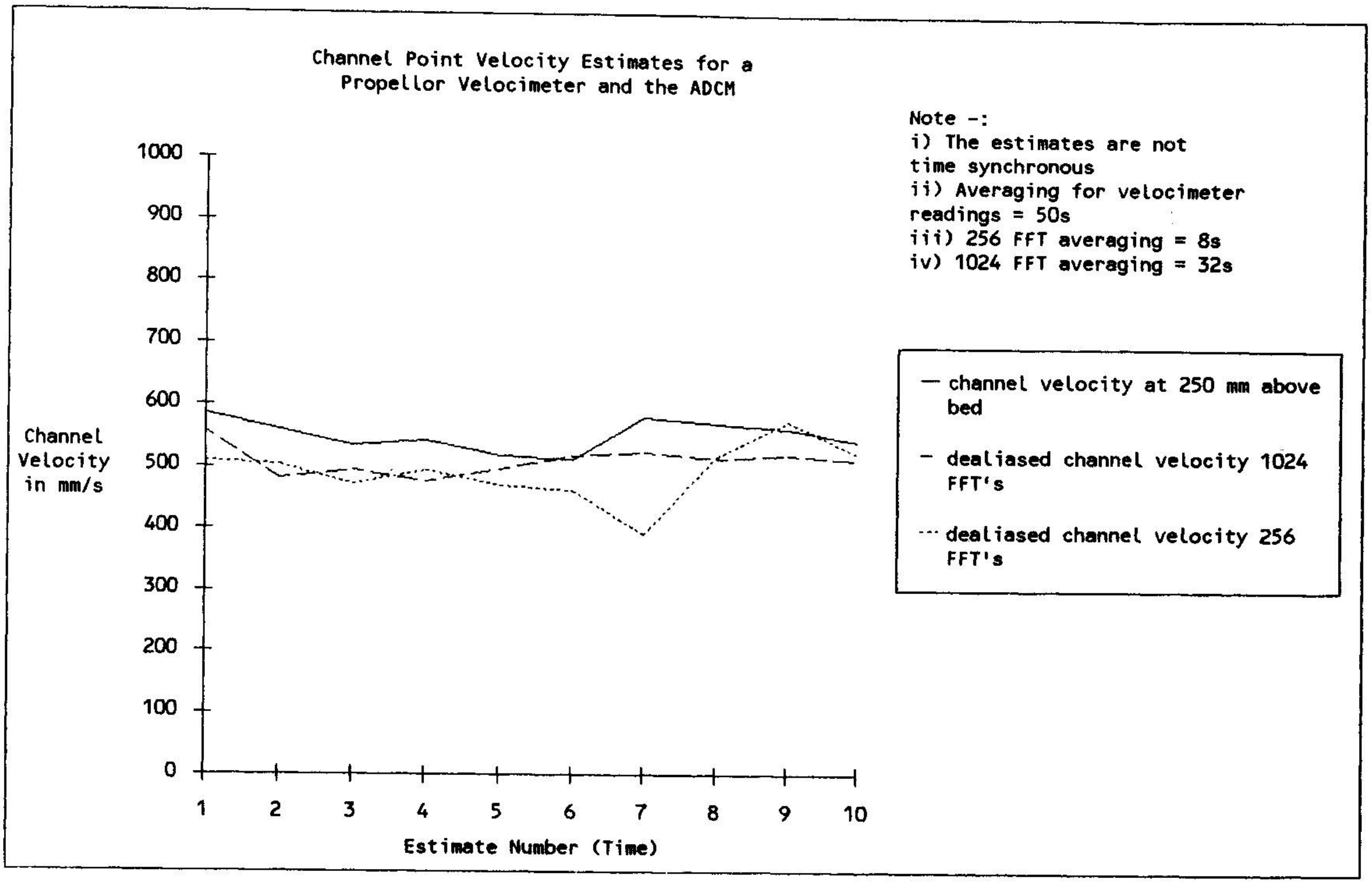

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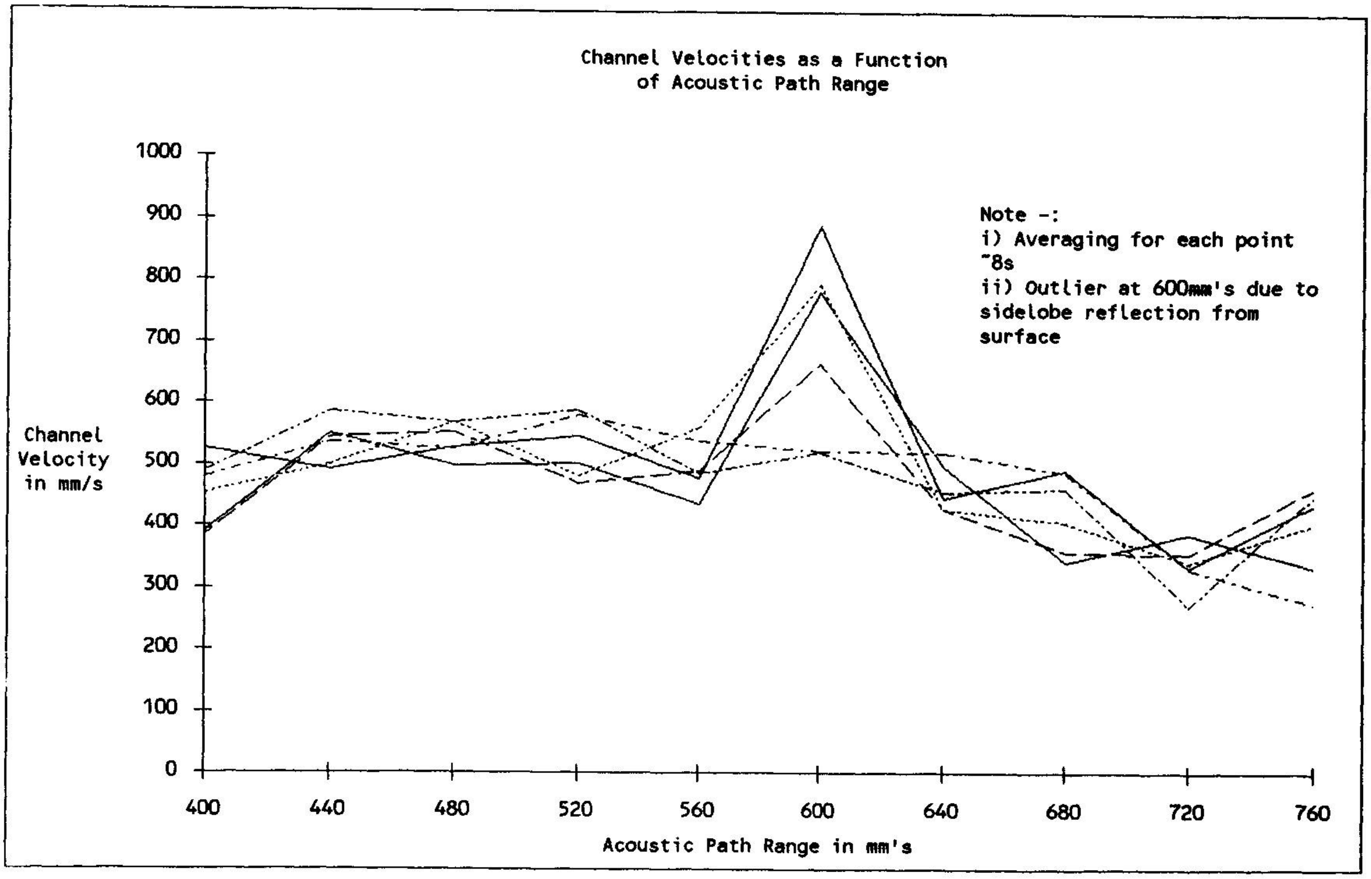

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Surface Current Monitoring in Coastal Waters
Enregistrement des courants de surface dans les eaux côtiéres
Ueberwachung von Oberflächenströmungen in Küstengewässern

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SUMMARY
An HF coastal ocean surface radar (COSRAD) has been operated in several areas of engineering importance in Australian waters, for which technical information is given on the system. Areas of typically 200 km^2 can be mapped in half an hour. Observations show that the surface water responds rapidly to mescoscale boundary layer winds to provide complex convergence and divergence flows. Some recent work is reviewed which uses radar determinations of surface water movement to calibrate 3D flow models.
This technique has a unique monitoring role when warm or low-salinity water forms a thin stratified layer which is not well coupled to the main water column

Enregistrement des courants de surface dans les eaux côtières

Résumé
Une technique de radar à haute fréquence (COSRAD= coastal ocean surface radar) a été utilisée dans plusieurs régions côtières australiennes. Des explications techniques sont données. Des zones de 200 km2 peuvent être enregistrées en une demi-heure. L'observation montre que les eaux de surface réagissent rapidement à certains vents locaux et produisent des courants marins complexes. Un travail récent est passé en revue lequel utilise une détermination par radar des mouvement d'eaux de surface permettant la calibration de modèles de courants tridimensionnels. Cette technique joue un rôle d'enregistrement exceptionel lorsque des eaux chaudes ou de faible salinité forment une couche stratifiée fine, laquelle ne participe pas aux courants marins principaux.

Ueberwachung von Oberflächenströmungen in Küstengewässern

Zusammenfassung
In mehreren Regionen der australischen Küstengewässer wurde eine Hochfrequenzradartechnik (COSRAD = costal ocean surface radar) der nachfolgend beschriebenen Technik eingesetzt. Daten über Zonen von üblicherweise 200 Quadratkilometern können binnen einer halben Stunde aufgenommen werden. Beobachtungen zeigen, dass das Oberflächenwasser sehr schnell auf gewisse lokale Winde mit komplexen maritimen Strömungen reagiert. In einer kürzlich erschienenen Arbeit wurden Radarbestimmungen der Oberflächenwasserbewegung zum Kalibrieren dreidimensionaler Strömungsmodelle verwendet. Diese Technik spielt eine Rolle bei der Ueberwachung von warmen oder schwach salzhaltigen Strömungen, die dünne, geschichtete Lagen bilden, die nicht gut mit der Hauptwassersäule gekoppelt sind.

1. HF OCEAN RADAR

1.1 Principle of Operation

When a radio wave encounters the ocean surface it is scattered into a polar pattern which is determined by the wave–wave interactions between the electromagnetic wave and the spectrum of sea–surface gravity waves. In particular there is a resonant backscatter from the two sea–surface gravity waves which have vector wave numbers $\pm\ 2\underset{\sim}{k}$ when the grazing incident radio wave has wavenumber $\underset{\sim}{k}$ [3]. The radar echo from these two very specific ocean waves is a pair of first–order echoes in the Doppler shift spectrum which generally dominate over the other backscattered energy. This is shown by peaks A and B in Figure 1.

The two sea surface gravity waves which produce the resonant backscatter peaks have phase velocities given by the deep water dispersion relation

$$c = \pm(g/2k)^{\frac{1}{2}}$$

and the corresponding Doppler shifts for the resonance or Bragg spectral peaks are

$$\omega_B = \pm\ (2gk)^{\frac{1}{2}}$$

If there is a current present then to a very good approximation the Doppler shift of the Bragg peaks becomes

$$\omega = \omega_B - 2\underset{\sim}{v}.\underset{\sim}{k}$$

This means that it is the radial component of the current, as seen from the radar station, which contributes Doppler shift.

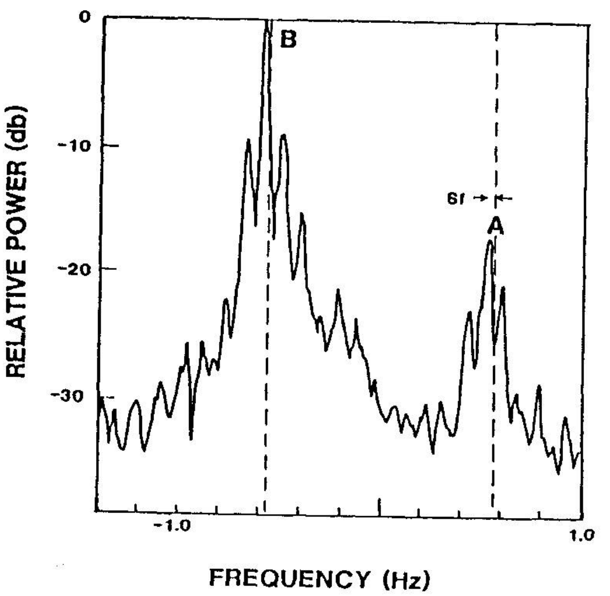


Figure 1. A typical ocean surface backscatter spectrum at 30 MHz. The spectral lines marked A and B are used to determine surface currents. The Doppler frequency shift f is caused by currents.

The wave–wave interaction which produces the backscattered Doppler shift spectrum is limited to the sea–surface by virtue of the finite depth penetration of the sea surface gravity wave which has wavenumber $2\underset{\sim}{k}$. Stewart and Joy [10] and Barrick et al [2] have analysed the effective depth of the surface current layer to which the HF radar would respond. For a linear vertical shear in current ($\frac{dv}{dz}$ = constant) the Doppler shift produced corresponds to the mean velocity over a water depth of approximately 1/2k where k is the radio wavenumber.

The second–order energy on the Doppler shift spectrum shown in Figure 1 is characteristic of a further wave–wave interaction at the point of scatter due to double scatter and hydrodynamical non–linearities. Barrick [1] and Robson [8] have provided two different approaches to the calculation of the second–order Doppler shift spectrum starting from the full directional wave spectrum of the sea–surface waves. The second–order energy may be used to measure wave heights, wave periods and wave directions. [7], [6], [11].

1.2 Radar Configurations

For the mapping of sea–surface currents it is usual to use a pair of radar stations sweeping across the mapped area from different vantage points. At each pixel in the target area, components of the surface current are measured in two different directions and the surface current vector may be calculated. This general technique has been used by several groups [4].

There are several different radar configurations of radar systems for HF ocean surface current mapping which are reviewed by Shearman [10]. The Coastal Ocean Surface Radar system used for the work in Australia consists of a single narrow beam antenna which is used for both transmission and reception. This offers a convenient and efficient use of the radio–frequency power and represents a solution to the problem of switching from about 10^3 watt to about 10^{-14} watt of power in a few microseconds.

The single antenna for the 30MHz COSRAD system is 8 wavelengths long (80 metres). The system is transportable and can be installed in a few hours.

A typical two station configuration is shown in Figure 2. The computer software plots a current vector at each diamond–shaped area of intersection, however the spatial resolution of the mapping is approximately 1.5 cm. Validation tests have indicated that the current components measured have an accuracy of better than 1.5 km per second, [6].

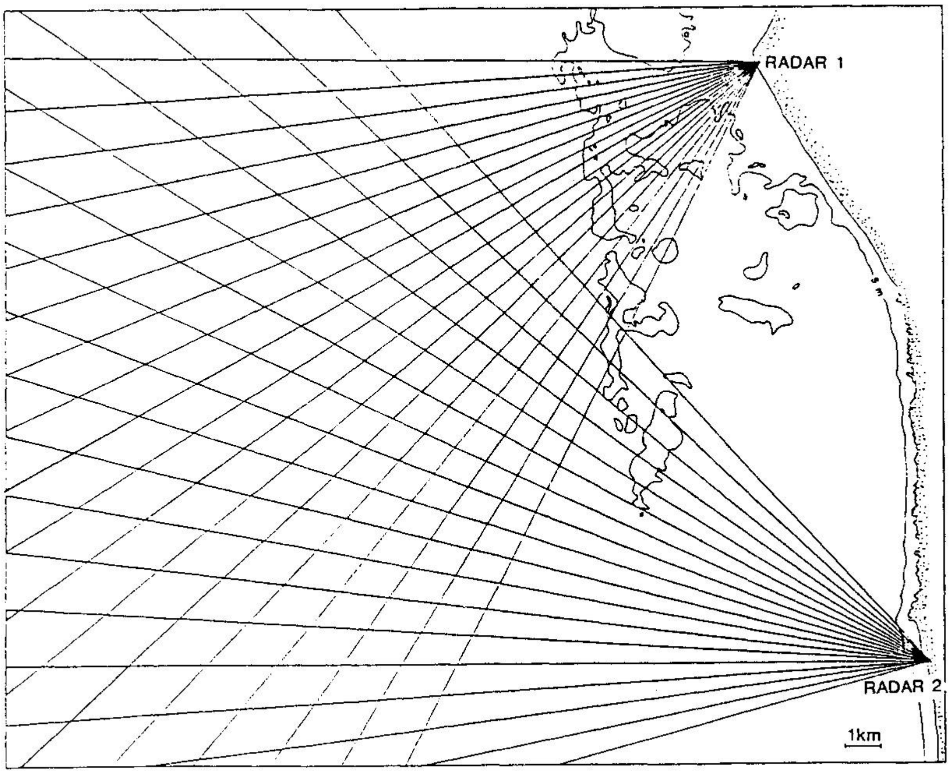


Figure 2. Scanning pattern of two COSRAD stations deployed to monitor surface currents. Current vectors are plotted at each diamond–shaped overlap area.

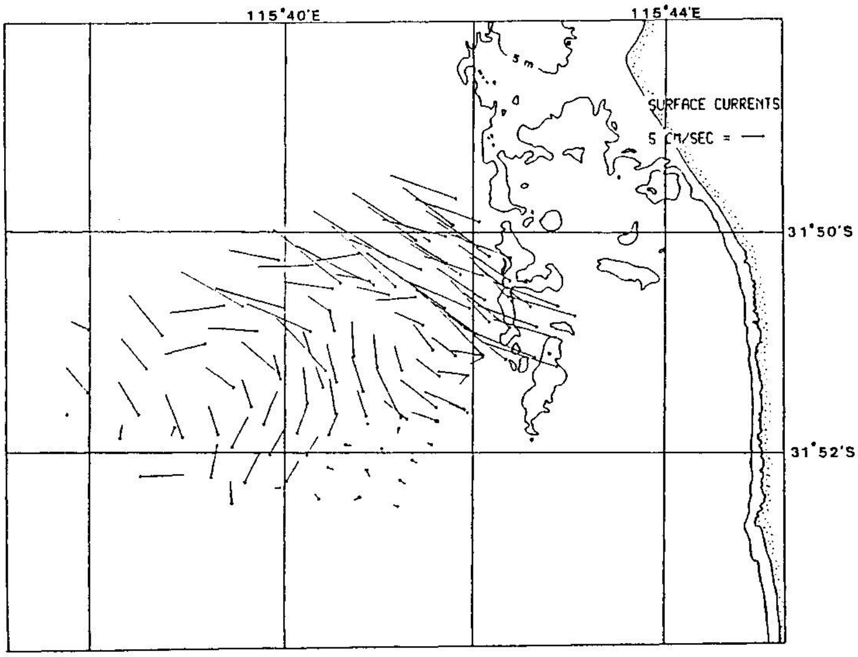


Figure 3. Surface current map during the early part of a storm in shallow water close to Perth, Australia

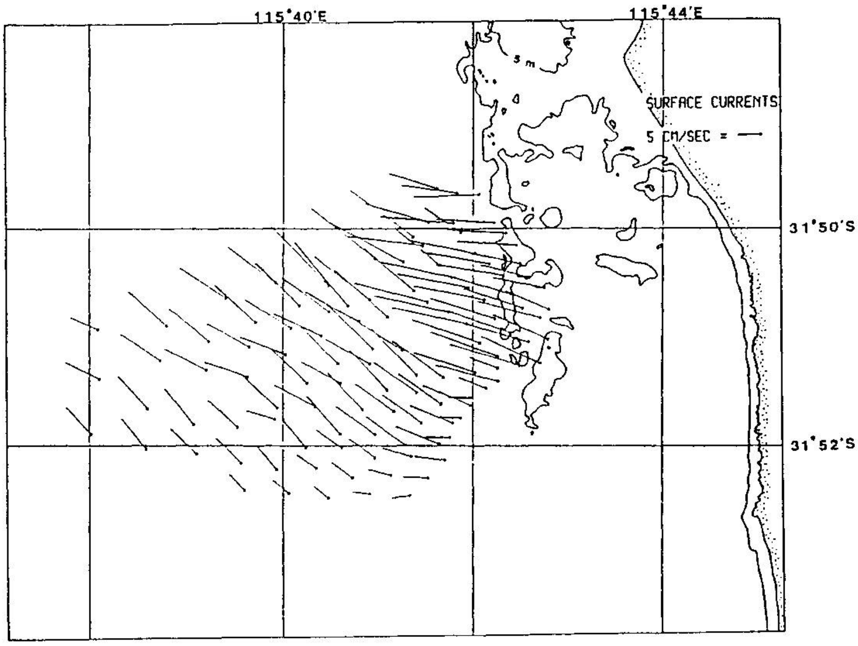
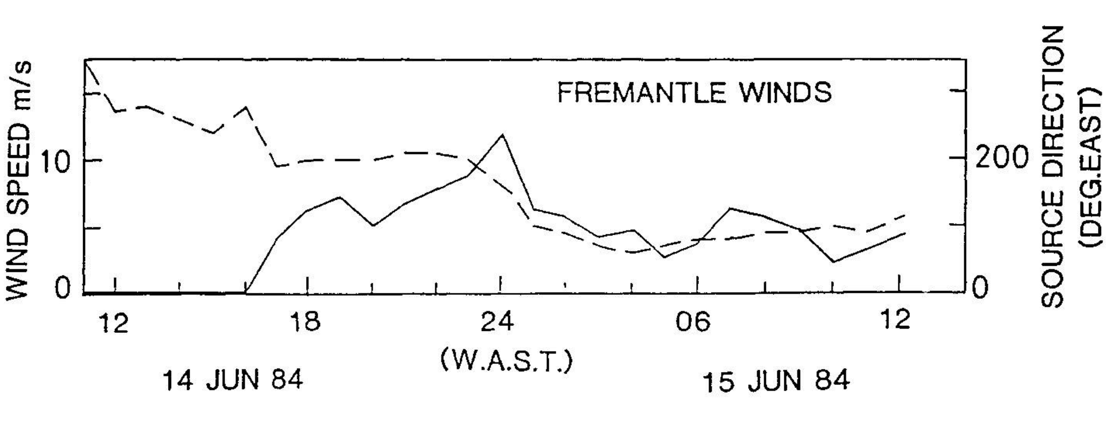


Figure 4. Surface current map subsequent to that in figure 3.

Figure 5. Surface wind during the storm relating to Figures 3 and 4. Wind speed is shown as a solid line; wind source direction is shown with a broken line.



The routine operation of the COSRAD system involves moving sequentially from one azimuthal beam position to the next, spending 102.4 seconds on each sector and completing the sweep of 17 sectors (corresponding to ± 30°) in 30 minutes. At each beam position all of the range cells are recorded within the 102.4 second record length. In this prototype system the spectral analysis of the multiple time series to produce Doppler shift echo spectra is done off–line back in the laboratory.

2. RESULTS

2.1 Case Study – Western Australia

An experimental deployment was made on metropolitan beaches in the northern suburbs of the City of Perth in 1984. During the study period the tidal range was small and the surface currents were dominated by the passage of a meteorological cold front and its accompanying stormy weather.

Two successive four–hour averages of surface currents are shown in Figure 3 and 4. The wind record is shown in Figure 5. The surface currents are dynamic and changing rapidly in response to the wind. Simultaneous measurements on a current meter moored in mid–column in the mapped area showed no such fast responses. Work done more recently at another site (unpublished) incidates that the surface has localised convergences and divergences as surface water moves in response to localised storms.

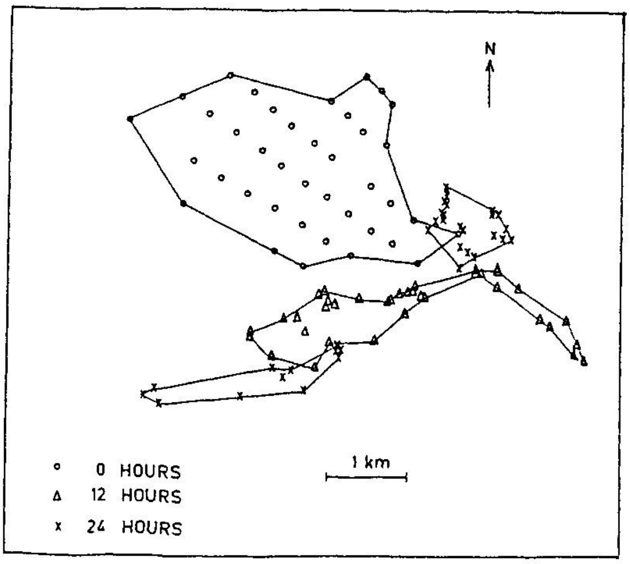


Figure 6. Notional particle tracking at points o before the storm then after 12 hours they would be located at Δ and after 24 hours they would be at x

A further analysis of this event can be done by tracking notional particles along Lagrangian paths using successive half–hour maps of vector surface currents. Figure 6 shows a matrix of starting points for particles and then their positions after 12 hours and 24 hours. Quite clearly on this scale of time and space the normal separation of particles according to the law

$$\frac{1}{2}\frac{d}{dt}\langle s^2\rangle = a\,\langle s^2\rangle^{2/3}$$

has not worked, where s is particle separation.

2.2 Case Study – Sydney Sewerage Outfalls Area

The Sydney Water Board is in the process of commissioning deep water diffusive sewerage outfalls to minimise the impact of ocean sewage disposal on the metropolitan beaches. As a part of a feasibility study for long term monitoring the COSRAD system was deployed in July 1989 in a demonstration phase. Under normal conditions the surface water cleared the area to the south. However under certain meteorological conditions a persistent gyre was found to recur off the Sydney coast (Fig. 7). This is an advective vortex which may be associated with the south–bound East Australian Current.

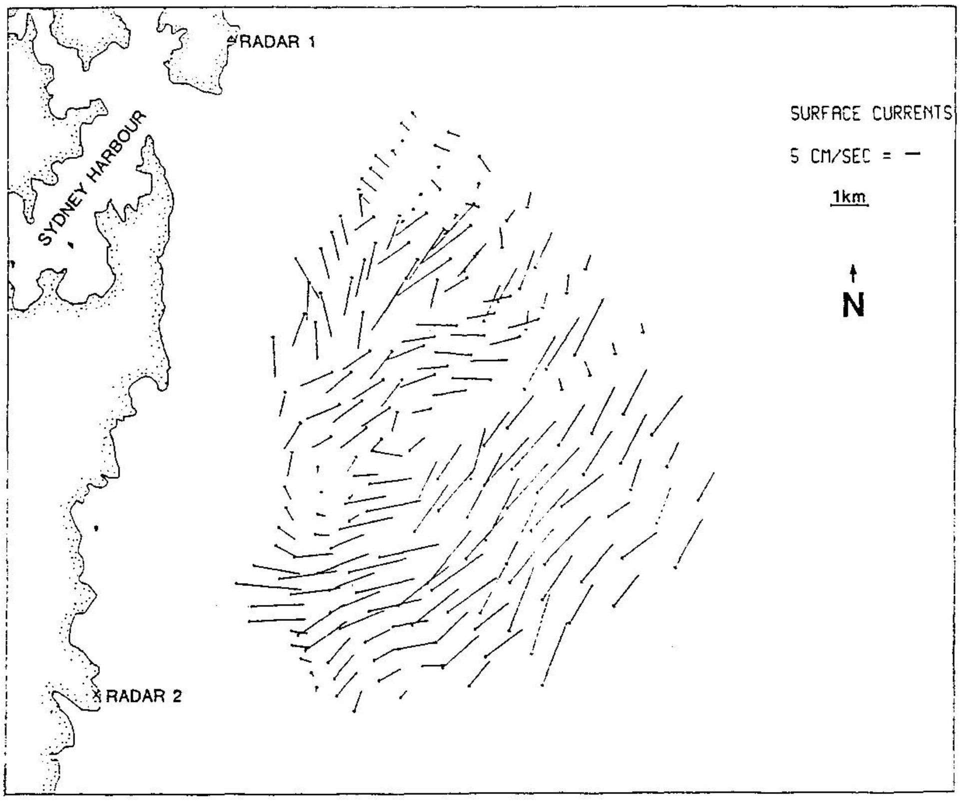


Figure 7. Surface current maps in near the edge of the continential shelf off Sydney, Australia

2.3 Case Study – Moreton Bay, Brisbane

The Brisbane River debouches into Moreton Bay in the South–East corner of Queensland. Moreton Bay is effectively closed on all sides except the North, and within it are several wide–mouthed bays including Bramble Bay and Deception Bay. A programme of mapping of surface currents has been undertaken in Bramble and Deception Bays to find the flow patterns under low wind conditions. A selected sample of particle tracks for Deception Bay is shown in Figure 8 which illustrates our general conclusion. There is a topographical line of divergence in the surface flow which separates Deception Bay water from the larger Moreton Bay. On the basis of these data one would advise locating waste outfalls to the East of the divergence line.

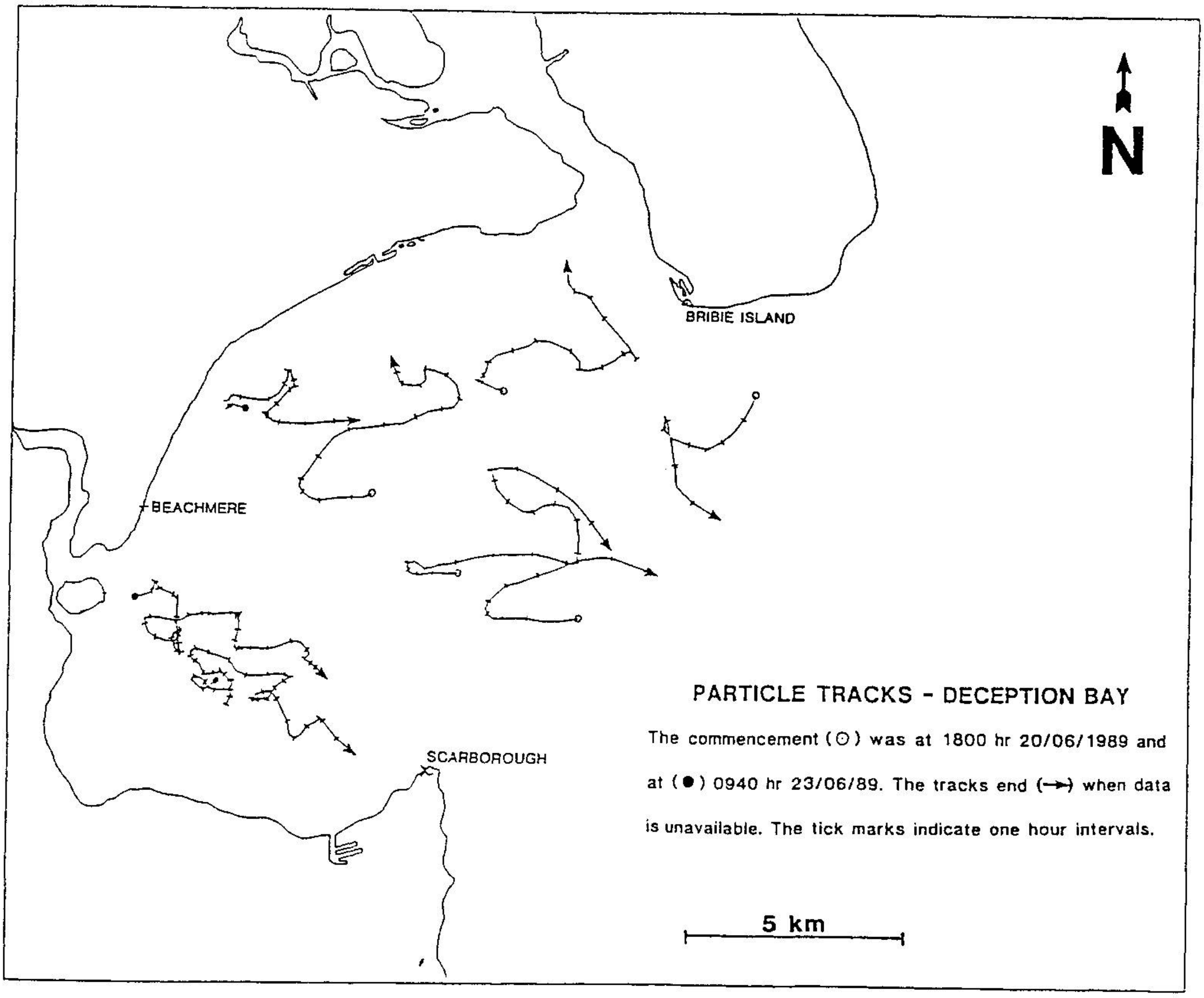


Figure 8. Notional particle tracks in Deception Bay near Brisbane, Australia in low wind conditions

3. LONG RANGE VERSION OF COSRAD

The 30 MHz system described in this paper is transportable and can be set up on public beaches, parks etc for specific studies. It is limited in range to less than 30 km and generally 25 km.

There is a need for the longer ranges in HF radar remote sensing particularly for wave parameters. A prototype system has been developed at Townsville, North Queensland for wave and current measurements. It is not movable, being a fixed antenna operating at 6 – 7 MHz. It is being evaluated by Woodside Offshore Petroleum Pty Ltd for the possible use of this technology in the Remote Offshore Warning System of the North West Shelf Gas Project.

4. CONCLUSION

The use of the 30MHz transportable COSRAD system for mapping currents in bays or harbours of typically 200 sq km has been prototyped to an automatic status. It is a cost effective monitoring system which has provided additional insights into water movement which current meters and drifter drogues cannot provide because of their spatial limitations.

The pure–science thrust of the COSRAD research at James Cook University is now centred on properties of wind–waves and swell.

Due to its ability to measure the bulk surface current in the presence of waves the COSRAD system is finding scientific application in calibrating the value of the eddy diffusion coefficient in 3D numerical currents (Hearn et al, 1987).

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Environmental Monitoring Instrumentation and Data Flow Techniques

Surveillance de l'environnement et techniques de mesure des données

Umweltüberwachung und Messtechnik

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SUMMARY
This paper describes the comprehensive environmental monitoring system which is a key element in the environmental control measures associated with the construction of the tunnel and dual bridge link, connecting the Danish islands Zealand and Funen with the European Continent. Some of the novel approaches regarding instrumentation, communication, data processing and future application in general are also highlighted.

Surveillance de l'environnement et techniques de mesure des données

Résumé
L'article décrit le système global d'enregistrement de l'environnement: il s'agit d'un élément essentiel des mesures de contrôle de l'environnement associé à la construction du tunnel et des deux ponts reliant les îles danoises de Zealand et de Funen avec le continent européen. Certaines approches nouvelles relatives à l'instrumentation, à la communication, au traitement des données et à des applications futures sont décrites.

Umweltüberwachung und Messtechnik

Zusammenfassung
Dieser Artikel beschreibt das umfassende Umweltüberwachungssystem, das ein Schlüsselelement in den Umweltkontrollmassnahmen beim Bau des Tunnels und der Brücken darstellt, die die dänischen Inseln Seeland und Fünen mit dem europäischen Kontinent verbinden. Entsprechende Neuerungen betreffend Messgeräte, Datenübertragung, Datenverarbeitung und zukünftige allgemeine Anwendungen werden beleuchtet.

1. INTRODUCTION

The Great Belt monitoring system is of general technical interest, because:

- It includes a wide range of sensors - including some very advanced types - deployed over a large area.
- It makes use of a combination of data transmission methods in order to provide almost on-line access to the sensor readings.
- It provides input to - and is integrated with - numerical forecast models for currents and water levels, and with numerical model for simulation of dredging spoils.
- It includes computerized "control-room" facilities which enable the operators to maintain a very high data return and quality, and at the same time open up to a range of new applications of the data.
- It has been operating successfully since 1989 and will continue in part until the completion of the Great Belt Link Project in 1996.

These and other features of the Great Belt Monitoring System are described in detail in the following.

2. BACKGROUND - THE GREAT BELT LINK

The Great Belt is located between the brackish Baltic Sea and the saline North Sea, see Fig. 1. In terms of exchange of water between these two water bodies, the Great Belt is the main strait connecting them. The flow in the Great Belt is, accordingly, typically stratified and highly dynamical.

The Baltic Sea is an environmentally strained area and potentially very sensitive to changes in the water exchange with the North Sea. Accordingly, in 1987, when the Great Belt Link Act was passed, the Danish Parliament decided that part of the design requirements for this link should be "neutrality" in terms of the water exchange. See Møller (1989, 1991) for more details.

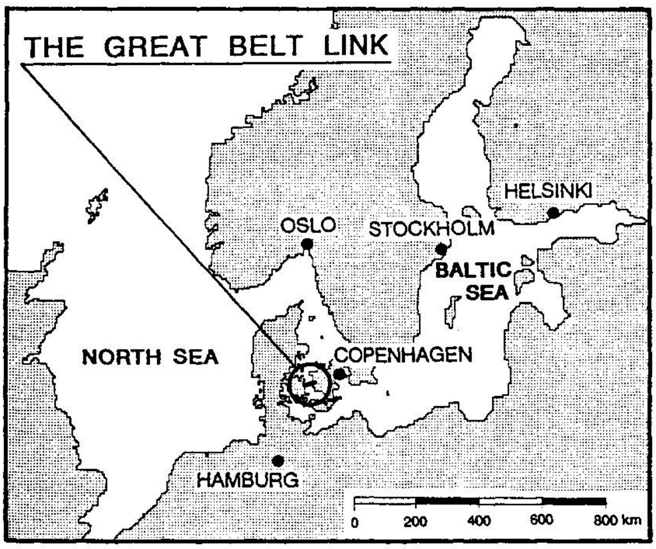


Fig. 1 Location Map.

This neutrality is ensured by compensating for certain effects - like for instance the increased resistance caused by the bridge causeways and piers - by the introduction of similar effects working in the opposite direction - for instance by compensation dredging in selected areas.

The design of these measures has to a large extent been based on the use of numerical models, primarily a model based on the SYSTEM 22, which is a generalized hydrodynamic modelling system for two-layer flow. Such a model requires a significant amount of measured data for model calibration and validation.

3. A MULTI-PURPOSE MONITORING SYSTEM

Apart from providing the necessary data for the modelling tasks in the design phases, the environmental monitoring system also serves the following purposes:

- To assist in the daily supervision of the environmental impact of the operations in the Great Belt area.
- To serve as part of an on-line forecast system for use by the contractors during weather sensitive operations.
- To demonstrate - through long term measurements - that the "neutrality" requirement has actually been met.

4. SYSTEM OVERVIEW

The environmental monitoring system is an important element in the complete hydrographic information system, which has been established for the Great Belt. Fig. 2 gives an overview of the complete hydrographic information system.

Apart from the measuring stations which are distributed over a wide area, also the other parts of the information system are distributed:

The forecast services based on numerical models for prediction of the weather conditions and the hydrographic parameters - are operated by the Danish Meteorological Institute (DMI) at their main computer facilities in Copenhagen.

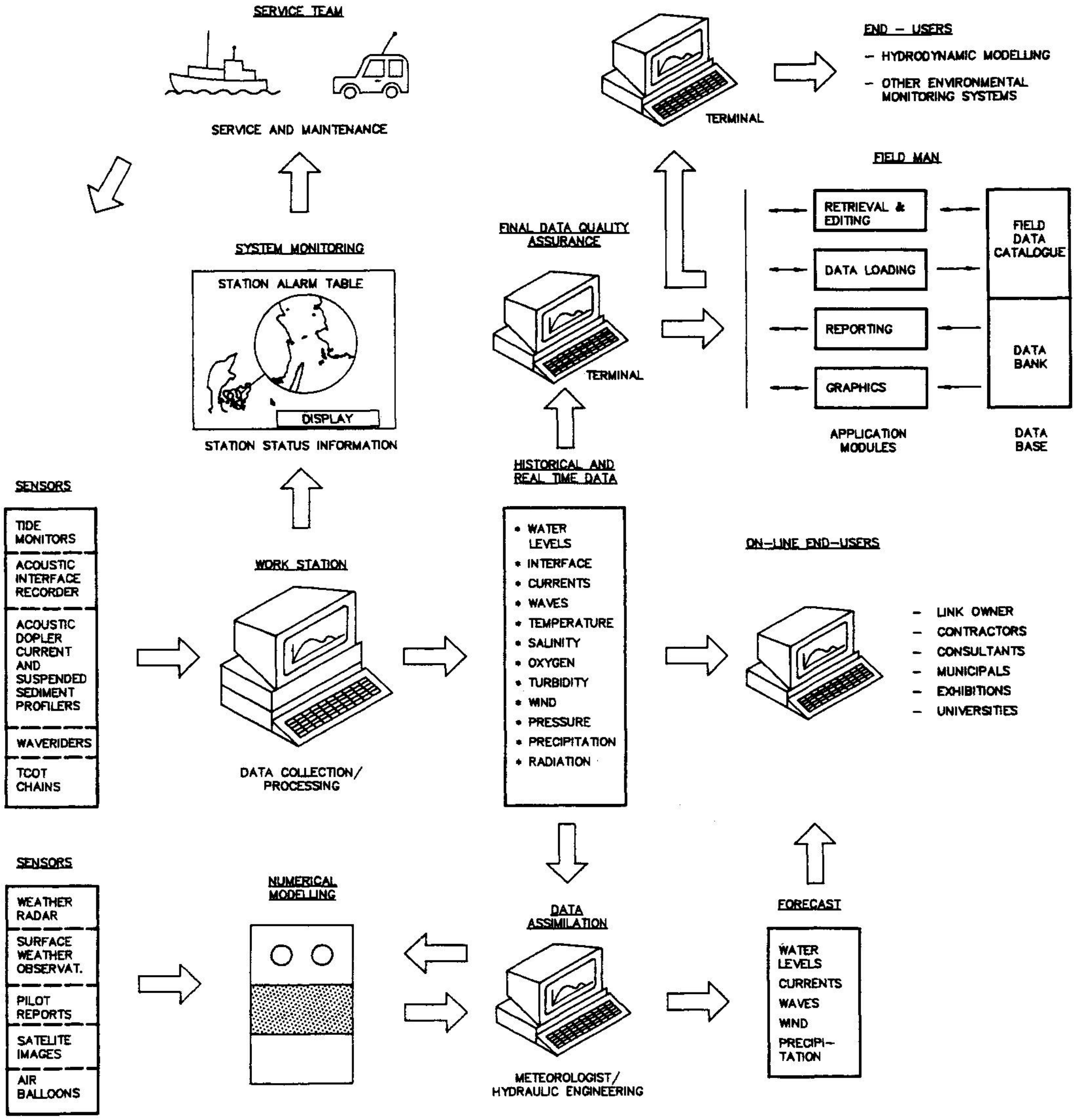


Fig. 2 Hydrographic Information System Setup.

- The supervision of the monitoring system, central storage of data, data quality control, etc. takes place at DHI in Hørsholm (125 km from the project site and 20 km from DMI).

The users of the system can get access to information from the system in one of the following ways:

- They can log in directly on the Great Belt computer "Hub", which is hooked on to the ETHERNET network at DHI. This requires a network connection to DHI and proper authorization. Normally, only DHI engineers are allowed to use this method.
- They can get access to (i.e. browse and copy for later local processing) selected data through a PC with modem. This is of course also subject to proper authorization.
- Finally they can subscribe to reports sent by telefax with only limited forecast information.

5. MONITORING SYSTEM

5.1 Design Aspects

The first step of the development of the Great Belt monitoring system began in connection with a Field Measurement Programme in 1987. New measuring techniques were introduced, eg. the acoustic doppler current profiler, and measuring schemes for the hydrographic parameters relevant for the verification and calibration of the numerical models were defined. Furthermore, the survey vessel instrumentation setup and tactical survey plans required to obtain the geographical distribution and variation of current and stratification conditions were established. However, the challenge involved with design, installation and operation of the present monitoring system were still many after 1987:

- To find the correct mix of physical monitoring instrumentation tailored to meet the specifications set forth by the modelling people but with an eye towards compatibility and application flexibility.
- To monitor the aquatic environment data accuracy is of primary importance and, as the system interrogates many remote measuring stations, it should therefore be capable to efficiently manage the complex tasks of data collection, processing, analysis, control, report and display the information.
- A monitoring system involving real-time acquisition and remote control application software requires a robust design of the data communication link as well as of the autonomous operated field measurement platforms.

Below a very brief description of the setup is given followed by a few selected examples of novel approaches within the field of environmental monitoring.

5.2 System setup

At the peak in 1990 the monitoring system comprised 18 stationary measuring stations and one vessel based station based on the survey vessel M/S PIP, see Fig. 3.

The full monitoring setup involves more than hundred sensors which, on an almost real time basis, provide data on **stratification** by measuring temperature, salinity, oxygen and turbidity along vertical strings supported by acoustic interface recordings measured with an instrument developed by DHI for this project - **current** conditions by measuring velocity profiles with Acoustic Doppler Current Profilers - **wave** conditions obtained by wave rider buoys and **water levels** measured with acoustic tide monitors.

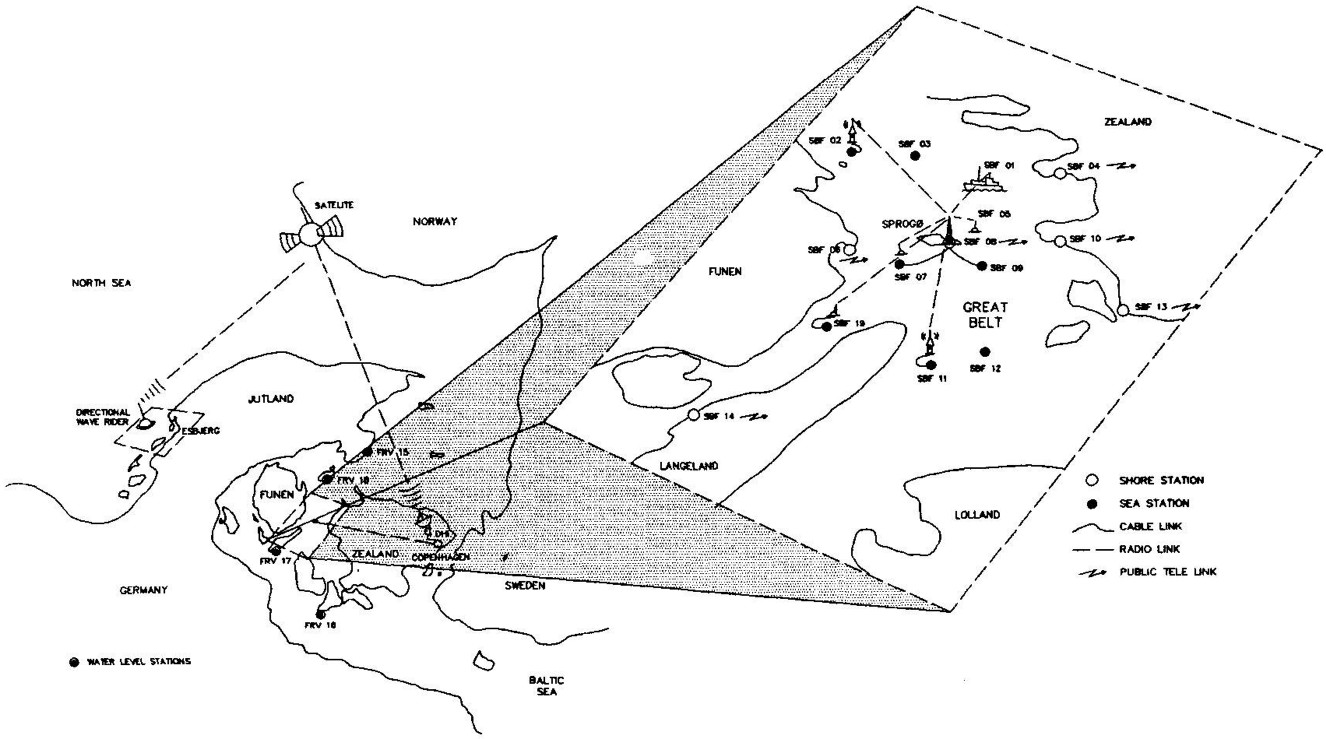
Meteorological parameters - wind speed and direction, temperature, pressure, precipitation and radiation - are measured on Sprogø and are also transmitted to the data central at DHI.

The ship based station is used for service and maintenance of the fixed sea stations, temporary replacement of malfunctioning sea stations, intensive hydraulic surveys for establishment of the horizontal distribution of hydrographic parameters and tracing of sediment plume during dredging operations.

For these tasks it is equipped with a variety of profiling instruments and a radio- and data communication link to the data central and directly to the sea stations.

The on-line communication takes place directly through the public tele net work for the Shore Stations (water levels) and for the sea stations via the Data Link Centre on Sprogø. The Data Link Centre communicates with the sea stations by either cable or radio link, see Figure 3.

On the figure is also shown a satellite communication link to a directional waverider located offshore the West coast of Jutland. This arrangement is part of an environmental monitoring programme carried out by DHI for the Port Authorities in Esbjerg. Six monitoring stations are included in this programme. The satellite passes the area approximately eight times a day and wave spectra are transmitted directly to DHI from the Danish Meteorological radar station in Rude Skov 3 km from DHI.



STATION	NAME	INSTRUMENTATION
SBF01	SURVEY VESSEL	AIR, ADCP, ASP, CTD, EMCP ES, POS, VAR, WS, VC
SBF02	ROMSØ TUE	WLR, AIR, TCOT
SBF03	ELEFANT GRUNDEN	AIR
SBF04	REERSØ	WLR
SBF05	SPROGØ NE	WR
SBF06	SLIPSHAVN	WLR
SBF07	VESTERRENDEN	AIR, ADCP, WR, TCOT
SBF08	SPROGØ	MET, DATA LINK CENTER
SBF09	ØSTERRENDEN	AIR, ADCP, TCOT
SBF10	KORSØR	WLR
SBF11	LANGELANDSBÆLT	WLR, AIR, TCOT
SBF12	OMØ WSW	AIR
SBF13	STIGSNÆS	WLR, AIR
SBF14	RUDKØBING	WLR
FRV15	GRENÅ	WLR
FRV16	HESNÆS	WLR
FRV17	BALLEN	WLR
FRV18	SPODSBJERG	WLR
SBF19	LANGELANDSSUND	AIR, TCO

ABBREVIATIONS	
WLR	WATER LEVEL RECORDER
AIR	ACOUSTIC INTERFACE RECORDER
ADCP	ACOUSTIC DOPPLER CURRENT PROFILER
ASP	ACOUSTIC SUSPENDED SEDIMENT PROFILER
WR	WAVERIDER
TCOT	TEMPERATURE/CONDUCTIVITY/OXYGEN/TURBIDITY CHAIN
EMCP	ELECTROMAGNECTIC CURRENT PROFILER
VAR	VARIOSENS
WS	WATER SAMPLER
MET	WEATHER STATION
POS	POSITIONING SYSTEM
ES	ECHO SOUNDERS
CTD	WATER COLOUMN PROFILER
VC	VIDEO CAMERA

Fig. 3 The Great Belt Monitoring System - Station and Instrumentation Plan.

6. NOVEL APPROACHES

6.1 Instrumentation

Two measuring principles and instruments, which are new, or at least not that widely used yet, and employed by the monitoring programme, are the Acoustic Interface Recorder (AIR) and the Acoustic Suspended sediment Profiler (ASP).

AIR:
In order to obtain data for numerical model verification and on-line environmental data display, and to reduce survey vessel operation time for CTD profiles, the AIR system was designed both as sea bed and vessel mounted versions and as self recording and for on-line transmission and display (see Meister, 1990).

The main purposes of the Acoustic Interface Recorder are:

- to detect the acoustic reflection from the micro organisms settling in the area where temperature and salinity changes rapidly - the stratification layer.
- to digitize all the received signals with stamped signal strength and depth marks.
- to process the data and determined the position of the acoustic interface reflections.

The AIR system consists of four sybsystems: the acoustic, the processing and the data handling subsystem and finally the power supply shown in the simplified block diagram below.

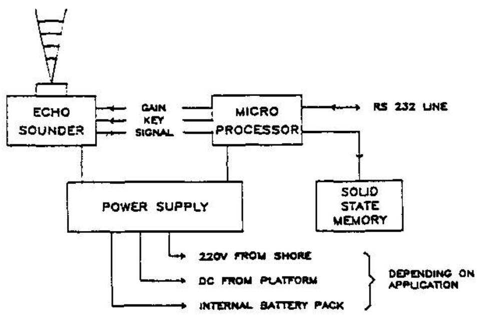


Fig. 4 Simplified block diagram.

In this instrumentation setup the Acoustic Interface Recorder is incorporated in seven deployed sea bed stations and one on the survey vessel.

Today the AIR systems have been in operation for 24 months and the average data coverage has been as good as 90% with no electronic break downs or any major fouling problems on the transducer surface.

Based on the data analysis and the unexplored options in the AIR system, further development will be obviously particularly in three quite different areas:

1. Tracing a sediment cloud in the water column from a survey vessel giving a relative picture of the sediment concentration.
2. Tracing the mixing of atmospheric air bubbles in the upper wave column from sea bed deployed stations.
3. Wave and tide recorder from a sea bed deployed station in shallow waters.

One could even consider that some of the above mentioned parameters could be gathered together with the 'normal' AIR data either as an on-line instrument or a self recording unit.

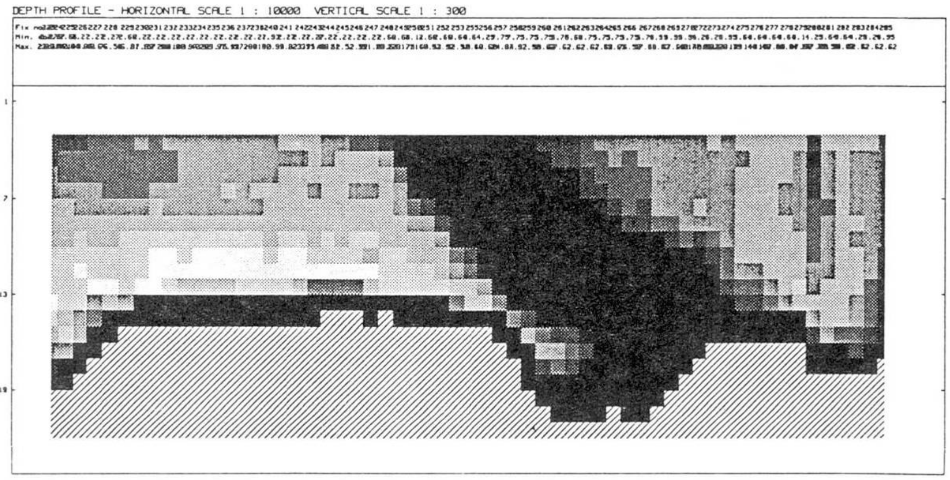
Not to forget the yet undiscovered possibilities which may be in the basic AIR system design.

ASP:
The Acoustic Suspended Sediment Profiler is a kind of bi-product or result of using the Acoustic Doppler Current Profiler, ADCP, (RD Instruments - San Diego, USA). The idea of using an ADCP for measurements of suspended sediments originated from the experience people had with echo sounders. Eg. on 20 kHz echo sounders, the internal waves propagating on the interface when sewage material is dropped into the ocean, can be seen. On 200 kHz echo sounders one can also see the cloud of material in the upper layer after dredge material is dropped from a barge. However, as more detailed information about the plume is required, ordinary displays used with echo sounders were found to be quite inadequate because the sediment plume normally appears as a big black cloud on the paper read out. To be able to display the enormous dynamic

range present in the back scattered signal, the data from the echo sounder have to be digitized an recorded for later processing.

Compared to a echo sounder, the ADCP has much poorer vertical resolution. However, since the data are digitized, the large dynamic range - given the right software - can be displayed and in contrast to the echo sounder the variation in the back-scattering coefficient can also be displayed as a function of space instead of time.

The vessel mounted ADCP system is provided with a software package which enables real time display (colour contour plots) of the intensity of the reflected signal corrected for geometrical spreading and absorption and combined with the current profilings the sediment flux as well as the direction of the plume can be obtained in the surveyed lines - transects. This saves a lot of time "looking" for the sediment plume and makes the ASP unique under operational conditions.



During Plume tracings a number of water samples are gathered for suspended sediment analysis over a wide dB range in order to establish a calibration curve between the back-scattered signals strength and concentration

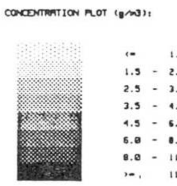


Fig. 5. Contour Plot of Suspended Sediment Concentration .

6.2 Communication

One of the challenges in the design of the monitoirng system was to ensure the ability to receive and analyse the data in real time and at the same time to be able to control and monitor the function of the measuring stations. These facilities would allow the data integrity to be under close scrutiny. For this purpose a special interface, SI, were developed based on the Dallas 5000 microprocessor, to support the operation of the remote sea-stations communicating via radio link. Among other facilities the SI involves two options for communication modes to the deployed instruments. Automatic data collection under the command of SI following a preset sampling scheme or a transparent mode of SI which allows a direct contact between the data control and each Sensor. (See Mogensen et al. 1991).

The SI is installed in the sea stations which use the light houses as platform (SBF02 and SBF11) and in the data gathering buoy launched between Langeland and Funen (SBF19).

6.3 Data Collection Control, Processing and Display System

Data collection and transmission from the various on-line sensors to the Data Centre at DHI is managed and controlled by a central computer - UNIX work station.

The central computer performs under unattended operation a number of background tasks. Eg. built-in diagnostics, generation of alarms and error and information logs.

In the central computer is installed a generalized data display and management package developed for use on engineering work-stations - the X-Windows Display System (X-DISP). The package is based on common industry standards for Graphical User Interfaces, and enables the user to build a customized, interactive graphical user interface for use as front-end to an on-line monitoring system or similar systems (see Vested et al. 1991).

7. COUPLING WITH NUMERICAL MODELS

On-line data collection offers a wide range of possibilities for using computers as assistance to the management of human intervention in the aquatic environment.

Two numerical modelling systems are integrated with the Great Belt monitoring system. The hydrodynamic model SYSTEM 21 is used in combination with meteorological models to provide forecast of water level and current velocity in the upper layer of the Belt for a five day period. The wind and air pressure over the North Sea and the Baltic are together with the tidal motions governing the hydrographic conditions in the Great Belt; but also the density difference between the brackish Baltic Sea and the southern Northsea Water contributes. By use of coupled meteorological and hydrodynamic models, and extensive use of the monitoring system, it is possible to predict the water levels and currents for these complex hydrographic conditions.

The DHI software system PARTICLE is installed on a PC on board the survey vessel to provide information on the spreading of dredging spoils.

A first step in the environmental impact assessment of dredging spoils is to predict how much of the material is brought into suspension, how much will be confined to the dredging/disposal site and the amount which will be carried away by the current and for how long it will remain in suspension.

It is in this context that numerical models are important and powerful tools when provided with sufficient information.

The concept used in PARTICLE is that the dredging spoil (or pollutants) is considered as particles being advected with the surrounding water body and dispersed as a result of random processes. Sedimentation of suspended sediments is accounted for via specified particle settling velocities. The light dampening caused by sediments in suspension is calculated on the sea bottom based on the background dampening for clear water, particle size and spacial distribution and water depth (see Petersen et al., 1990).

Particle assumes that current velocities and water levels can be prescribed in time and space in a computational grid covering the model area. This information can be provided e.g. by means of a proceeding (or parallel) hydrodynamic model simulation.

As the PARTICLE model installed on the survey vessel is used as an operational tool for optimization of the ship-based control measurements it can be run in either a 'Now-Cast' or Forecast mode.

8. REFERENCES

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