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ASSESSING THE OCEAN ACOUSTIC ENVIRONMENT USING SATELLITE REMOTE SENSING

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1. INTRODUCTION

Acoustic propagation in the ocean is determined by the three-dimensional temperature and salinity fields of the ocean. These are particularly complex, being subject to both temporal and spatial variability due to solar and atmospheric influences on scales from hours to centuries over the earth's liquid surface [1]. The ocean's spatial variability thus includes the global scale, but it also extends right down to centimetre scales. Different mechanisms come into play at the different scales, and some of these are still at early stages of scientific investigation.

This paper will consider the types of spatial variability observed in the ocean, as far as they concern acoustic propagation. The techniques of satellite remote sensing will be examined in this light, concentrating on techniques giving spatial images of the accessible upper surface of the ocean. The possibility of using space remote sensing for monitoring ice cover and for estimating ocean ambient noise will not be considered. We also omit reference to acoustic monitoring - e.g. tomography - although such 'inverse' techniques are clearly making steady progress, and may play a valuable future role.

The paper deals first with examples of the significant spatial variability of the ocean, indicating the extent of the monitoring problem. It then considers ways in which infra-red and radar imaging techniques can be used to detect the important ocean features, and finally highlights some of the outstanding interpretive problems.

2. DETAILS OF THE OCEAN ENVIRONMENT

The variability length scales of interest depend critically on the acoustic frequency concerned. Variability on scales smaller than an acoustic wavelength is rarely important, and the upper length limit increases rapidly as the wavelength increases, as acoustic attenuation becomes increasingly small. In the lower frequency range, propagation paths of tens or hundreds of kilometres can be of interest. Eventually, the effect of the seabed becomes important, and even a 4km deep ocean can be shallow in this context.

This paper will deal with ocean features which involve length scales between 1km and 100km. Features such as fronts, eddies and internal waves come into this range, and we will consider them simply as strongly range-dependent sonar propagation environments [1].

Frontal boundaries are formed where different water masses meet. In the case of the Iceland-Faeroes Frontal System, the two water masses are the Atlantic Ocean to the South and the Norwegian Sea to the North. The Nordic Seas are constrained in position by the system of relatively shallow ridges which run between Greenland and Norway via the UK Continental Shelf. For the purposes of our present study, Iceland-Faeroes contains all the characteristics necessary for demonstrating the problems of environmental monitoring.

The ridge between Iceland and the Faeroes is both the longest and shallowest of these ridges, severely limiting the Southwards flow of cold water from the Norwegian Sea. The less dense Atlantic water, however, is able to flow over the ridge to form part of the Norwegian Atlantic Current. This warm input plays a large part in keeping Norway free from ice all the year round, and monitoring the ridges gives a valuable insight into the mechanisms involved.

In the vicinity of the Iceland-Faeroes Ridge there is generally a warm upper layer of Atlantic water, 200-400m thick, above colder, less saline Norwegian Sea water, which rises along the Northern slope of the Ridge. In places, some of this colder water is able to overflow the Ridge in a layer a few tens of metres thick. Figure 1a shows a schematic diagram of the basic situation.

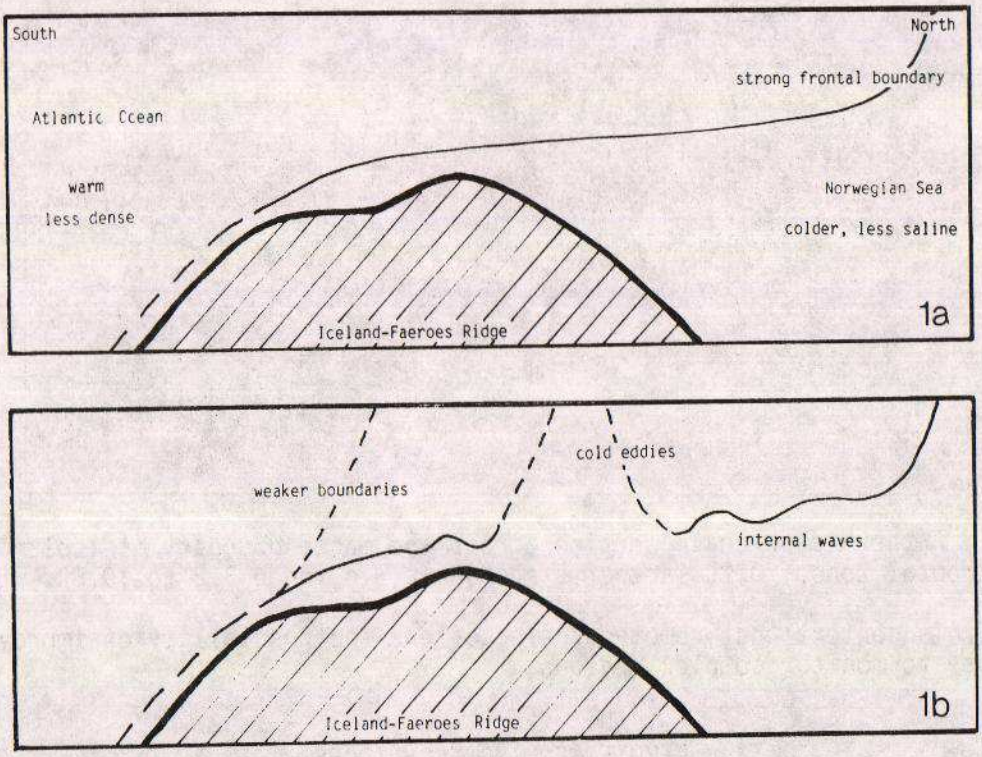
In practice, the structure here is usually more complex. Both water masses are moving: to the North the Iceland Current flows Eastwards and to the South the currents are more complex, but also have an Eastwards trend. Tidal forcing and atmospheric forcing cause mixing of the upper and lower boundary layers, and the separation of the two water masses is thus always diffuse, all of these influences causing mixing of the water masses. The actual structure of the interface therefore varies markedly with position along the frontal zone.

In practice, the situation is closer to that shown in figure 1b, where it is indicated that the whole of the warm upper layer can so be modified by the underlying cold water, that an extra weak boundary appears to the South. The possibility of cold eddies and internal waves is also indicated.

Overall, the picture is one of a frontal zone, perhaps 100km wide, containing a complex mixture of water masses which are constantly in motion. This zone is normally bounded to the North by a strong frontal boundary, and there can be one or more weaker boundaries South of this, before unmodified Atlantic water is reached. In order to predict the sound-propagating characteristics of the region we need to monitor the positions and structures of these boundaries, and also those of any eddies contained in the frontal zone.

We have investigated the structure of the frontal zone using a 400m long thermistor chain which, when towed, tells us the detailed thermal structure

REMOTE SENSING OF THE OCEAN ACOUSTIC ENVIRONMENT



Figures 1a,b. Schematic diagrams showing the role of a ridge in determining frontal structure: a) a simplified view; b) a more realistic view.

down to about 300m [1,2]. This measures spatial scales down to a few metres, the oversampling giving confidence in the data for a wide range of applications.

An example of the detailed structure of the main frontal boundary of this frontal zone is shown in figure 2. This structure varies considerably at different locations in the frontal zone, becoming more complex and diffuse, and the boundary slope decreasing. The changes are associated with the increased mixing of the water masses as they progress Eastwards.

Figure 3 shows an example of data from a cold eddy within the frontal zone. The sharpness of the boundaries, occupying less than 1km, should be noted. Internal waves in the region can have amplitudes of many tens of metres, and making sampling of the overall structures prone to error.

The problems of acquiring enough in-water data to give adequate localization and characterization of these boundaries are clearly very difficult. In view of the high levels of variability at short length scales there is also a problem of interpreting sparsely sampled data, of the sort normally available.

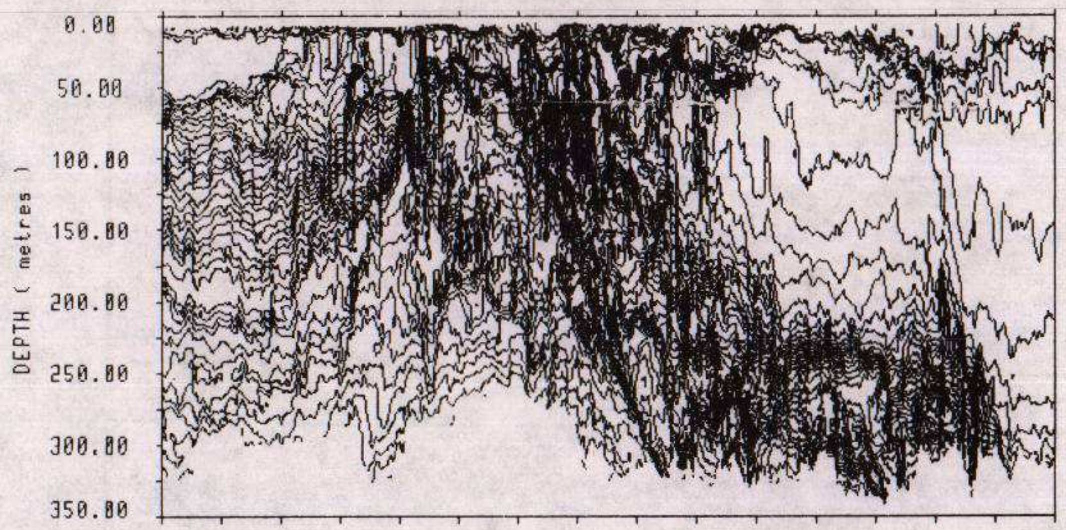


Figure 2. A thermistor chain section across the major boundary of Iceland-Faeroes Frontal Zone. 0.2C isotherms are shown, in range 3.2 to 10.8C.

It is in this context that remote sensing offers the possibility of improving our ability to monitor complex regions.

3. REMOTE SENSING TECHNIQUES

The imaging techniques considered are available or planned from 'commercial' satellites. Some planned non-imaging sensors have some potential, either for monitoring, or for improving the performance of imaging methods, but these are beyond our present scope. Airborne systems are similarly not treated here; although cheaper in initial outlay, they have much smaller coverage, and much greater running costs; they are useful, however, as research tools.

Assuming that we have techniques which give large-area images of a surface property related in some way to the deep ocean structure, the problem becomes that of relating images to structures. Note that the measured surface property need not be accurately 'mapped' to one of the important structure characteristics; the relationship can be heuristic, based on observational experience. This is the possibility considered here. The value of very detailed data for image/structure comparison is evident from figures 2 and 3.

Infra-red images have been available continuously since the late 1970s, and two NOAA-TIROS satellites currently carry the multi-channel Advanced Very High Resolution Radiometer (AVHRR) sensor. Promising results using airborne radars in the 1970s led to the SEASAT synthetic aperture radar (SAR) in 1978, but

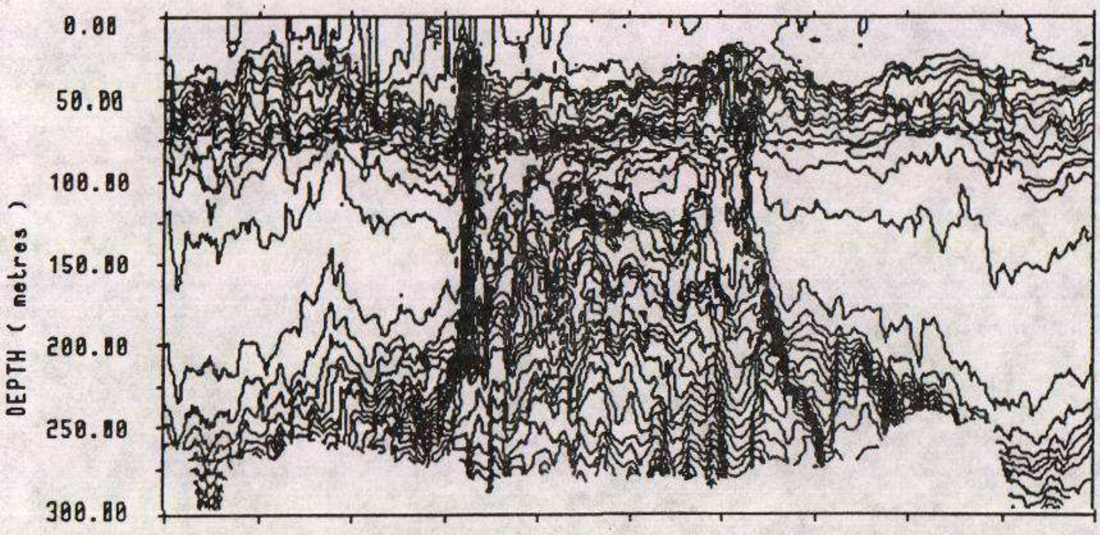


Figure 3. A thermistor chain section across a cold eddy in July 1987.

since that satellite's brief life, radar images have not been available, apart from a few days of data from NASA Space Shuttle experiments (SIR-A and SIR-B).

Passive microwave imagery was also provided by SEASAT. The passive microwave sensor SMMR, also available for some years on the NIMBUS-7 satellite, gave very coarse images of sea surface temperature. Passive microwave temperature data tend to be too coarse for our needs, but wind data are also possible and these have potential value as input to predictive ocean models.

The remote sensing scene, almost static since the demise of SEASAT, should be re-vitalised by the imminent launch of the ERS-1 satellite and several other satellites of oceanographic relevance, and the build-up throughout the decade towards the US Earth Observations Program.

3.1 Infra-Red Imaging

Infra-red senses the sea surface temperature. Since the features of interest tend to involve strong changes in temperature which often reach to the surface, this sensor is of obvious value for monitoring. Frontal boundaries and eddies have been observed in infra-red images for many years now, with 1km resolution since the advent of the AVHRR sensor of the NOAA-TIROS satellites.

Figure 4 is an AVHRR image from Iceland-Faeroes, showing a highly dynamic situation of cold jet and eddy features near the major frontal boundary.

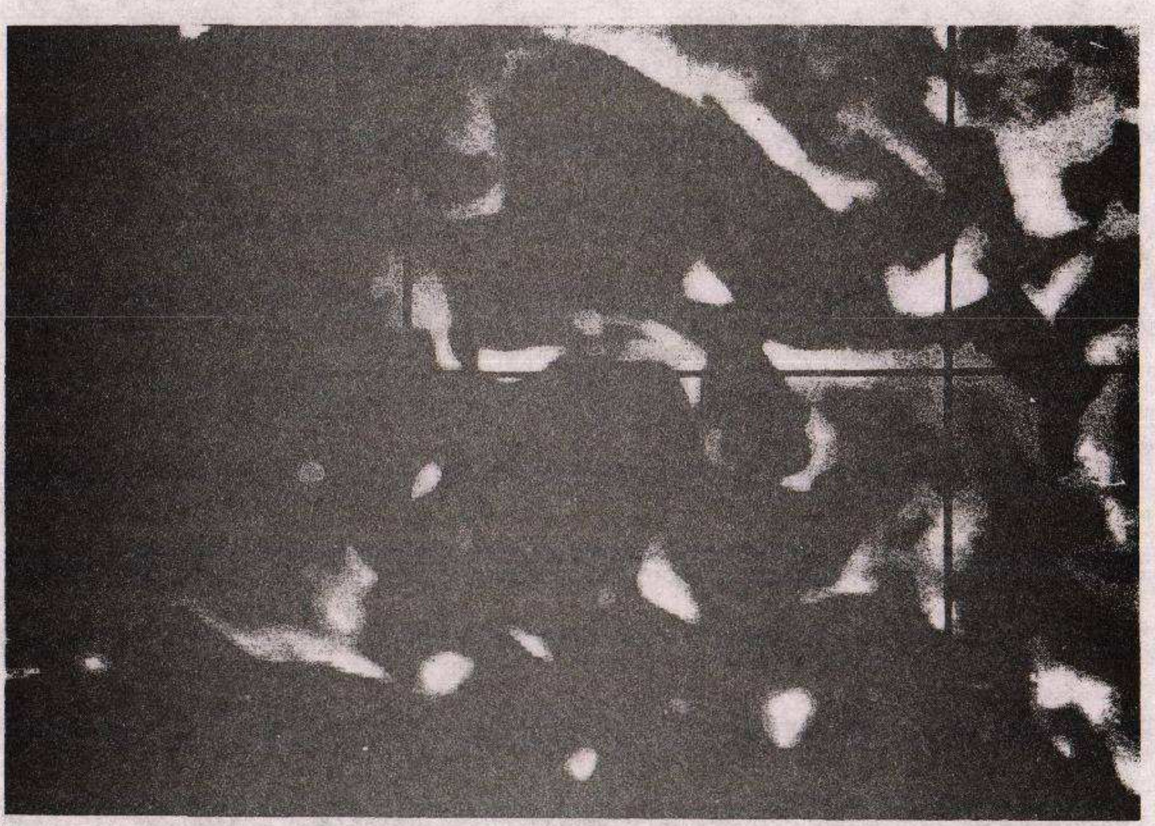


Figure 4. An infra-red image of part of the Iceland-Faeroes Frontal Zone.

Images such as these are ideal for developing an understanding of the relationship between images and in-water structures [3].

The weaknesses of infra-red twofold: firstly there are problems in deriving the image/structure relationship; and secondly, optically dense cloud frequently obscures the sea surface.

We will look first at the cloud problem. In regions North of the UK this is such that images cannot be expected with any degree of confidence for the majority of the year. April and May tend to be the clearest months, with typically 2-4 reasonably large area images per month, but the December-January period is much more poorly served. Assembling a collage of images from different overpasses can give improved spatial coverage in some regions, but many regions are too changeable for this to help.

Let us turn now to the question of image interpretation. Even after more than a decade of infra-red data, it is still not clear how well surface temperature images represent the deeper thermal structure. For our application we do not need to deduce accurate surface temperatures, as long as we can detect spatial changes. If we can locate a boundary, and deduce the underlying structure using prior knowledge, the absolute values of temperature are not important.

Figure 3 illustrates two of the problems found in infra-red interpretation. This cold eddy was found in summer, and the distinctive warm summer boundary layer is seen to cover the feature. This 'attenuation' of the deeper thermal signal by the warm layer may lose the feature in the detection noise. We can also see that what there is left of the eddy thermal signature does not reliably reflect the deeper structure. Even sustained light winds could have caused this distortion. It is thus evident that, even if a feature is detected, its signature might be unrecognisably distorted. A further example of this was reported by Scott et al. [4].

A related problem arises which makes warm eddies harder to detect than cold eddies. As is seen in figure 3, a cold eddy can bring cold water towards the surface, where it may be thermally detected. In contrast, a warm eddy involves only a thickening of the warm upper layer; this thickening can sometimes cause a detectable temperature increase, but not always.

It is even possible for conditions to arise in which the colder side of a boundary actually appears warmer, in an infra-red image, than the warmer side. If the near-surface layer is more strongly stratified on the cold side, perhaps as a result of salinity variations or reduced wind stress, this can give less wind mixing for a given solar energy input, and consequently a greater warming of the (shallower) surface layer.

All of these effects depend on season, on local meteorological conditions, and also on the meteorological history over a wider region. However, sustained research effort keeping in mind these factors should eventually lead to improved interpretation.

3.2 Radar Imaging

Radar images the surface using spatial variations of wind-wave backscatter. The data from SEASAT, although limited by its short life, demonstrated that ocean features could be detected in synthetic aperture radar images. Frontal boundaries, eddies and internal waves were detected by the SEASAT SAR in the North-East Atlantic; Fu and Holt [5] review the SEASAT results.

Real-aperture radar (RAR) also has potential for ocean monitoring. Although its resolution from a space platform is much poorer than that of SAR (~1km compared with 20-50m) the imaging mechanisms are better understood. In both cases it is radar-length-scale roughness elements on the surface which cause the detected backscatter, but in the case of SAR, movement of the surface also influences the image, and this makes interpretation more difficult.

For the purposes of the application considered here, it is mainly resolution which distinguishes the two techniques. RAR is limited to relatively gross variations of scattering strength, whereas SAR is able to resolve sea swells down to 100m wavelength, as a result of their modulation of wind-excited surface roughness, and can therefore detect refraction of these waves.

SAR images internal waves as a result of their modulation of the surface wave field, and much work has been done on the mechanisms involved. Backscatter variations can also result from the shear currents associated with frontal boundaries [6]; one mechanism involves spatial variations of wave-damping biogenic film material [7]. Organic surface films are likely to play a role only at low wind speeds, below 10-12 knots; in high winds the film material becomes dispersed by turbulent wave action.

A more effective cause of backscatter variations at higher wind speeds is surface temperature differences. Surface temperature can influence the surface roughness through its effect on the atmospheric boundary layer: when the surface is warmer than the air the flow is inherently unstable, and energy transfer to the surface is greatly increased compared with the stable case. The results of Keller et al. [8] illustrate this effect.

The thermal effect is likely to be particularly useful for frontal boundaries at which the air temperature lies between the two surface temperatures, but we do not yet have enough information on how often suitable conditions may arise.

A further possibility exists, this time only for SAR, in that boundaries may be detected by measuring the refracting effect of their shear currents on swell waves; Barnett et al. [9] have reported a possible method. Another promising technique is that of interferometric SAR [10], detecting phase variations between two separated receiving SAR antennas. Signal phase variations are related to surface currents, and experiments with an aircraft system have detected currents of only a few cm/s.

The imminent launch of the ERS-1 satellite, with its C-band SAR, has the potential to provide regular images of frontal regions, and we will then be able to assess the monitoring capability of imaging radars.

4. CONCLUSIONS

This paper has considered the potential value of present and planned satellite imaging techniques - infra-red and radar - for monitoring the ocean acoustic environment. Infra-red is severely limited by cloud cover in many areas. Even when clear images are obtained, significant interpretation problems remain.

These include possible failure to detect features in summer conditions, and - in all seasons - the distortion of surface signatures by wind.

The interpretation of radar images is also seen to be a complex process, strongly dependent on meteorological factors. Features are potentially detectable from their surface temperature signature, from the presence of biogenic slicks or internal waves, and from current shear effects on swell.

For neither infra-red or radar imaging do we have enough sea truth data for complete evaluation. A reasonable approach is to build up a comprehensive experience of the relationship between the images and the deeper structures.

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