ARRAYS AND ARRAY PROCESSORS - FUTURE REAL TIME APPLICATIONS IN OCEANOGRAPHY AND SONAR

by

Prof. Arthur B. Baggeroer
Depts. of Ocean And Electrical Engineering
Massachusetts Institute of Technology
Cambridge, Mass. USA 02139

ABSTRACT In the last several years oceanographic applications of arrays have increased substantially. The spatial resolution and redundancy provided by arrays have been necessary in the interpretation of signal propagation in complex environments. While arrays have also been employed extensively in sonar systems, the demands of higher resolution and capabilities of digital signal processing algorithms are still further increasing their use. With is increased use of arrays in oceanography and sonar, the attendent demands of processing the data have also risen. Often, this must be done in real time or at least on site, while the array is still deployed.

Historically the needs of geophysical exploration for oil were a prime mover in the development of array processors. This was principally motivated by the use of large arrays, now with up to 500 channels operating at kilohertz bandwidths, for seismic reflection studies. Fortunately, there are many parallels between geophysical exploration for oil and oceanography and sonar, so some inferences about future applications of arrays and array processors may be made. Here we examine some of these potential applications, particularly those areas in geophysical exploration related to methods of beam forming, frequency wave function estimation, propagation analysis, and remote sensing. We find that arrays and array processors are integral components making possible studies that could not be reasonably accomplished without them.

INTRODUCTION

Much of oceanography and sonar essentially concerns mapping. In oceanography we map the seabed bathymetry, the seismic strata, surface and internal waves and acoustical propagation and reverberation. In sonar we map targets which may be ships at audio frequencies to medical images at ultrasonic frequencies. The spatial information required to create these maps is acquired by arrays of sensors. These arrays may exist physically as a collection of sensors,or they may be synthesized from repeated observations by a moving sensor. The important point is that arrays are used and all the data required must be processed to convert the information into a map, chart, or image depending upon one's particular application.

In the last several years the technologies for deploying arrays, recording the data, and processing it have increased dramatically. Low power, integrated circuit technology has advanced sensor capabilities; high speed digital equipment has led to recording systems with high dynamic range over wide bandwidths, and the flexibility and speed of programmable array processors have led to rapid, often real-time results and analyses. The full impact of this array technology upon oceanography and sonar has yet to be felt. In fact, the advant of this technology is driving the course of future experiments.

In the sequel we examine future uses of arrays and array processors in oceanography and sonar. While the space available here requires brevity, it is hoped that it is indicative of the range of applications. Moreover, we have not attempted to cite references because of the immense diversity of the field. We draw heavily upon the work that has been done in the geophysical exploration for oil where maps of the seismic strata are the most important data in placing wells. If the experience in geophysical exploration is indicative, then we may anticipate that arrays will strongly influence future oceanographic research and sonar systems.

The discussion of the use of arrays in oceanography focuses on marine geophysics. While other areas in oceanography may also employ arrays, this area will probably dominate the usage for the foreseeable future. Marine geophysics primarily concerns the seabed--its present structure and its evolution. Array applications usually involve the analysis and synthesis of how low frequency sound propagates through the seismic strata. Closely related to marine geophysics is ocean acoustics which focuses upon how sound propagates within the water. Array applications typically involve hydrophones for measuring directional spectra, scattering and multipath phenomena, and propagation analyses.

1 MARINE GEOPHYSICAL EXPLORATION

Marine geophysics as applied to exploring for sources of oil can claim much of the credit for stimulating the evolutions of arrays and array processors. It is only now with the dramatic reduction in costs brought about by integrated circuits that these technologies are being employed more broadly in oceanography. Marine geophysical exploration uses large, multichannel towed arrays extensively for seismic reflection surveys. Oceanographers are now using them for both reflection and refraction studies. The geometries for these studies are illustrated in Figure 1.

In a seismic reflection operation,an impulsive acoustic source, e.g. an explosive or high pressure airgun,generates signals that propagate into the seismic strata and reflect off the strata interfaces where there are changes in the acoustic impedance of the seabed. This is repeated at closely spaced intervals as the source and array are towed along a "seismic line." Depending upon the equipment and seabed structure, signals at depths up to the Mohorovic discontinuity (15km) can be detected. In a refraction operation an impulsive acoustic source is also used. The separation between the acoustic source and the receiver array, however, is increased to a range that is beyond the critical angles for the seismic strata. At these ranges, interface or head waves are excited. It is fairly common to excite head waves at the Mohorovic discontinuity and operate at source receiver separations in excess of 100km using high charge weights.

The reflected or refracted signals are sensed by hydrophones in a towed array. Electronics on the recording ship perform the necessary signal conditioning and are converted to digital data. Presently there exist towed multichannel arrays with 500 separate channels, up to 10 km in length, and digital recording dynamic range of 120 dB and bandwidths in excess of 1 kHz(6). This corresponds to recording data rates of 10 M bits/sec. These data (are recorded on magnetic tape for subsequent analysis) or processed in real time, which is becoming increasingly common.

2 ARRAY PROCESSING FOR GEOPHYSICAL EXPLORATION

The array technology for seismic reflection and refraction studies is advancing very rapidly--far faster than comparable sonar efforts. Moreover, the methods of data analysis and the array processing capabilities for implementing them in marine geophysical exploration are also well advanced. The overall significance of both these observations is that we may make some valuable inferences about future applications in oceanograpy and sonar from this area. The data analysis for mapping the seismic strata in both reflection and refraction involves stacking a beamforming operation, and velocity analysis, a spatial analog of spectral analysis. The essentials of the signal flow are illustrated in Figure 2. Both the stacking and the velocity analysis are heavily dependent upon the capabilities of array processors, especially for real time operations.

2.1 Velocity Analysis

First we examine the velocity analysis operation. It is fundamentally a problem in frequency-wave number fuction estimation. The complicating factor in geophysical exploration is the inhomogeneity of the medium. At best it is only vertically dependent in well-stratified media, while at worst it is very anistropic in regions such as continental shelf breaks and near med-oceanic ridges. Virtually, all the analysis methods are based upon models for horizontally stratified environments. Velocity analysis refer to the methods of spectral analysis that are employed to resolve this horizontal stratification.

The essential concept of a velocity analysis for both reflection and refraction is similar to an angular spectral estimate, or bearing intensity plot. The major difference is the transient character of the signals. In the reflection operation the wavefront curvature of the nearfield environment must be modelled, this leads to spectral estimates where the intensity of the reflected signals are measured as a function of normal incidence travel time which measures the distance to a reflecting horizon and a root mean square velocity which characterizes the wavefront curvature of the near field environment. The highlights of the spectral estimate are used to specify a velocity model for the seismic strata model by inversion methods.

In the refraction operation the spectral intensity as a function of the source to receiver travel time and the horizontal phase velocity across the array is measured. The highlights of this spectra can also be used with model inversion methods to specify a structure for the seismic strata. Figure 3, for example, illustrates a phase velocity spectra for a thinly sedimented seabed.

In either the reflection or refraction operations, the signal processing required to form the velocity spectral estimates is extensive. (In fact, this was one of the prime motivating factors that led the geophysical exploration industry to develop special purpose array processors). For example, a single velocity spectra may require up to 4000 separate spectral analysis with an equivalent two dimensional data base of 64 x 4 samples. Furthermore, the demands for precise model estimates have led to the introduction of velocity spectral estimation methods that are computationally intensive, such as those based upon high resolution spectral estimation algorithms. The important emphasis is that array processors will be extensively used in oceanography for resolving the spectral structure of signals propagating in the complex environment of the seabed. More particularly, there will be strong emphasis for real time operations so that the important features of an area can be defined and surveyed while the research vessel is in location.

2.2 Stacking and Beamforming

The seismic model from a velocity analysis in reflection operations is used to specify a stacking, or beamforming, operation. The output of this stacking operation is the map of the seismic strata. In its simplest form, the stacking operation consists of determining the travel time delays to a particular depth and then performing travel time dependent, delay and sum, time domain beamforming, which is illustrated in Figure 4. Typically, however, more complicated processing in both the time and frequency domains is also done. The most important processing methods are time varying filtering, deconvolution, velocity filtering, common depth point stacking, and migration. These are illustrated in Figure 5. All can and are done very efficiently using array processors and all are very applicable to beamography and sonar. The properties of the acoustic sources and the frequency selective attenuation properties of the seismic strata as well as the ambient noise require multichannel bandpass filters whose characteristics ideally change with travel time into the strata. Finite impulse response (FIR) and recursive infinite impulse response (IIR) filters with time varying coefficients are commonly used for time domain implementations. In addition, fast Fourier transform (FFT) methods are also used for frequency domain implementations. All of the applications are strongly dependent upon the extensive digital filtering literature in this area. Since both oceanography and sonar often involve frequency selective phenomena, these advances in filtering theory are very relevant to future signal processing.

Deconvolution is a term used to describe a large number of signal processing algorithms that attempt to compress long duration signals into impulsive ones. There are, however, two important applications of deconvolution that are used extensively. In the first, an FIR filter is designed using the data itself which attempts to compress the finite duration impulse response of the source into an impulsive one. Unfortunately, there are several theoretical considerations that indicate that this cannot be done in most practical situations. In the second application one also constructs an FIR filter from the data which attempts to remove the reverberation that is excited by multiple reflections between the sea surface and seabed. There are limitations upon the effectiveness of this application as well. All deconvolution procedures are fundamentally coupled to linear filtering theory, so there is a rich literature supporting them. More importantly, deconvolution can be shown to consist of a whitening operation which is a fundamental operation in spectral analysis, dereverberation and optimal filtering method. With the appearance of array processors multichannel deconvolution filters are being investigated extensively in marine geophysical exploration as well as in many other fields.

Velocity filtering is intrincically a spatial filter that exploits the properties of the multidimensional Fourier transforms of the propagating signals. The essential concept is that the wave equation governing a propagating signal constrains the allowable domain for its temporal frequency and spatial wave number. Signals that may be present that propagate via different wave equations, e.g. surface waves and noise may be rejected to the extent that they do not overlap the allowable frequency wave number domain of the desired signal. The array geometry, more particularly its finite extent and the spatial separation of the sensors, limits one's ability to do this exactly. As a result, there is a large amount of literature on array processing algorithms that is now accumulating in the digital signal processing literature journals. Much of this concerns the design of velocity filters for realistic array geometries, which is very relevant to future beamforming methods in both oceanography and sonar. Implicit in all this work are the tradeoffs vis a vis array processing capability to implement these filters.

Common depth point (CDP) stacking is the basic beamforming operation in marine geophysical exploration. It's output is the map, or time section, of the seismic strata. An example of one is illustrated in Figure 6. In generating a CDP stack, a sequence of reflections from successive sources impulses are used to synthesize an array. By proper spacing which is created by appropriate timing of the source impulses as the ship moves through the water the correct geometry for focusing the synthesized array can be created. The CDP method has proven to be surprisingly robust, and several attempts to improve upon it using adaptive filtering have not been particular successful. It is, however, computationally demanding. For example, 1km of a typical seismic section requires 10^5 CDP points, or beam outputs, involving 10^8 operations. When combined with the computational burdens of the signal processing previously discussed that occur before the CDP operation, it is easy to appreciate the demands for both high speed array processors and efficient computational algorithms. Nevertheless, several real time systems for processing marine geophysical data at sea now exist. The important point is that both the hardware and software for high speed implementations of the CDP is very applicable to mapping and beamforming operations now done in oceanography and sonar.

Migration is the final step in the signal processing for marine geophysical data. It is an active field of research which uses array processors extensively. Fundamentally, it converts map of seismic section versus travel time into a map versus true depth. In most respects the travel time and depth maps are quite similar; however, the near field array geometry introduces effects such as diffractions which distort the time section from a true indication of the reflector depths. This is easy to perceive if one notes that the reflection sequence from a point target generates a hyperbolic time section as one passes accross the point of closest approach. Most of the current research on migration is strongly coupled to partial differential equations where the recorded multichannel array data forms the boundary conditions. Generally the equations are factored wave equations which result in parabolic partial differental equations. While equations of this type are directly relevant to calculating range dependent sonar propagation conditions, the more important perspective is that the migration is an array processing method that directly incorporates the propagation dynamics and their effects upon the signals while mapping the true structure of the seismic strata. This is very valuable since it constrains the signal processing in a way that is fundamentally coupled to the physics. Continuing further,wave equation models for signal propagation occur in all facets of ocean ography, so migration methods are applicable to a diverse number of problems. The major difficulty in employing migration methods is that they are computationally demanding. The capabilities of an array processor are needed in order to solve the partial differential equations that are intrinsic to the methods.

2.3 Synthesis of Multichannel Data

Signal propagation in the seabed is complex, and it requires complex models. One encounters many types of waves which use sophisticated mathematical methods, particularly the complex variable theory, to obtain closed form results in even the simplest of situations. This has led investigators to revert to the original partial differential equations for predicting the behavior of signals propagating in the seabed.

The methods that have evolved can be grossly separated into time domain and frequency domain procedures. In the time domain methods one numerically determines the impulse or step response by integrating the wave equations subject to the appropriate boundary conditions at the strata interfaces. Performing this is computationally very demanding.

In the frequency domain, procedures one determines the solution of the wave equation with harmonic excitation. There are a number of techniques available for doing this. The most extensively used involves characterizing the medium into incremental layers with plane wave reflection and transmission scattering matrices for the downgoing and upgoing waves across these layers. One must then integrate overall the plane wave components in the source radiation pattern to obtain the complete response at a particular temporal frequency. In an alternative approach, one separates the variables of the inhomogeneous wave equation, solves this equation numerically, and then sums over the separated variable, the horizontal wave number to obtain the complete solution at any particular temporal frequency. In both methods fast Fourier transform methods are used extensively. The plane waves in the spatial dimension lead naturally to discrete Fourier representation when they are sampled spatially and the temporal Fourier representation is intrinsic for a time invariant system. These methods are being used extensively now in geophysical research. The principal motivation is that the traditional use of arrival time for the various waves encountered does not lead to unique models. As a result, one is now using amphlitude dependences to further constrain the model. These methods also help in determining the importance of mode conversion such as the compressional to shear among the various waves. This is particularly difficult in refraction analysis when one can only observe compressional waves on a hydrophone.

All these methods are very demanding computationally. Array processors are really the only possible option for the forseeable future in performing the numerical analysis required by them in a reasonable amount of time.

SUMMARY

We have given a very brief overview of how arrays and array processors are used for geophysical exploration. These methods have been used extensively in the search for oil. With the increased use of arrays in oceanography and sonar, all of them are very applicable to future research, especially when one demands real time operations.

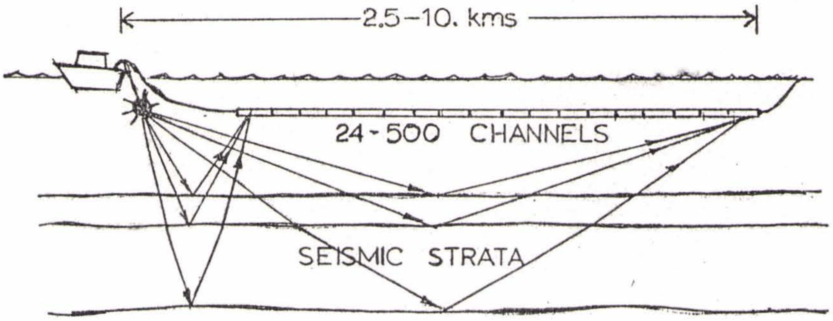


FIG. 1a SEISMIC REFLECTION

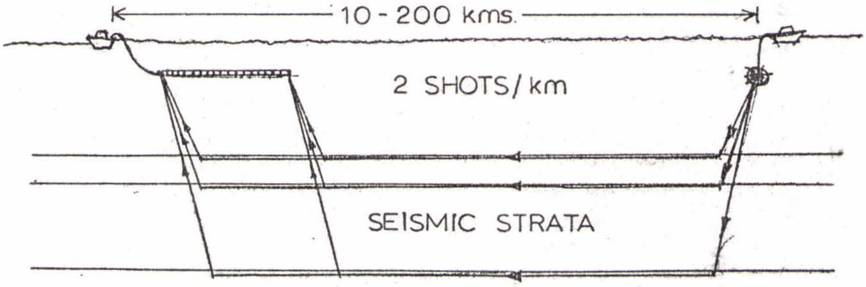


FIG. 1b SEISMIC REFRACTION

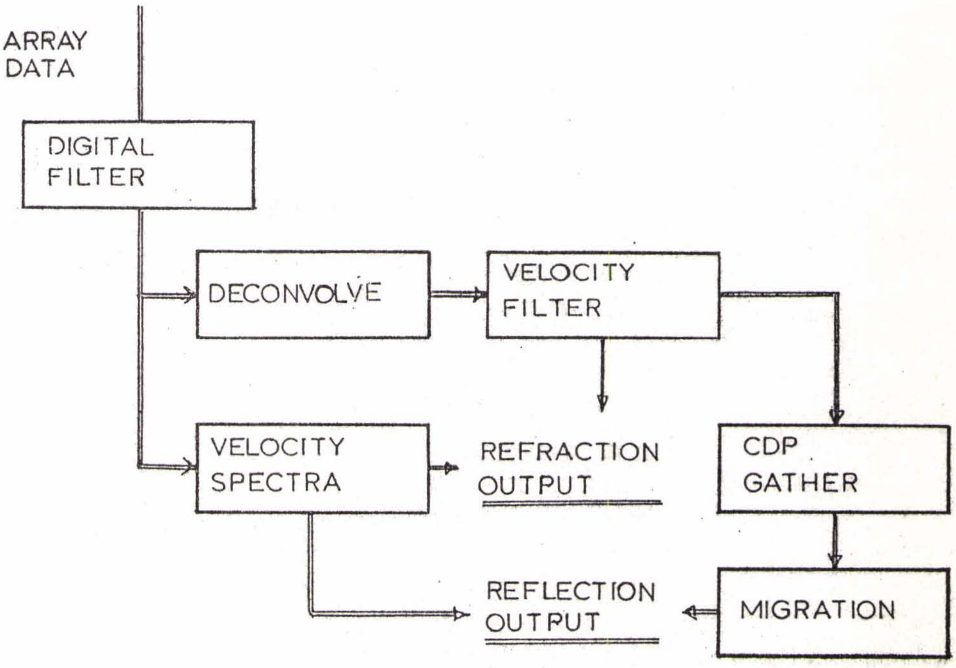


FIG. 2 GEOPHYSICAL EXPLORATION SIGNAL FLOW

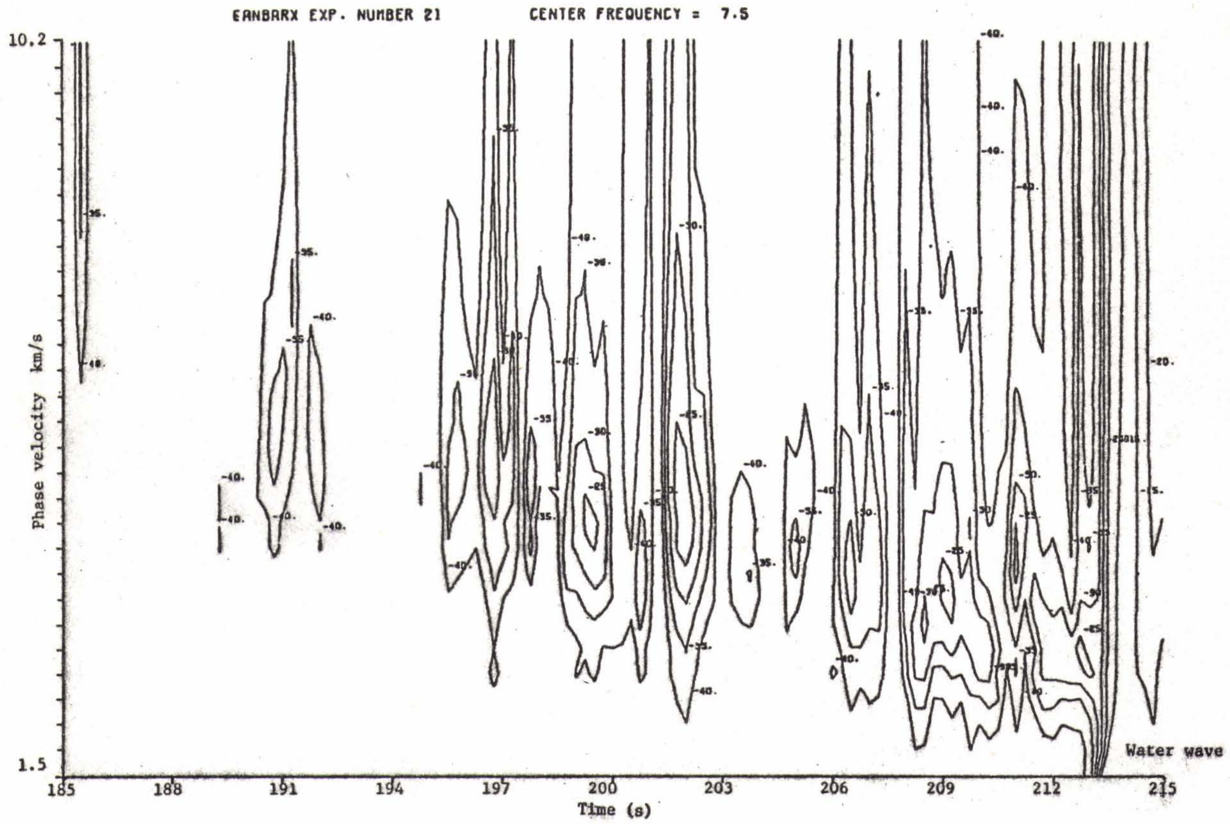


FIG. 3 PHASE VELOCITY SPECTRAL ESTIMATE FOR REFRACTED SEISMIC WAVES

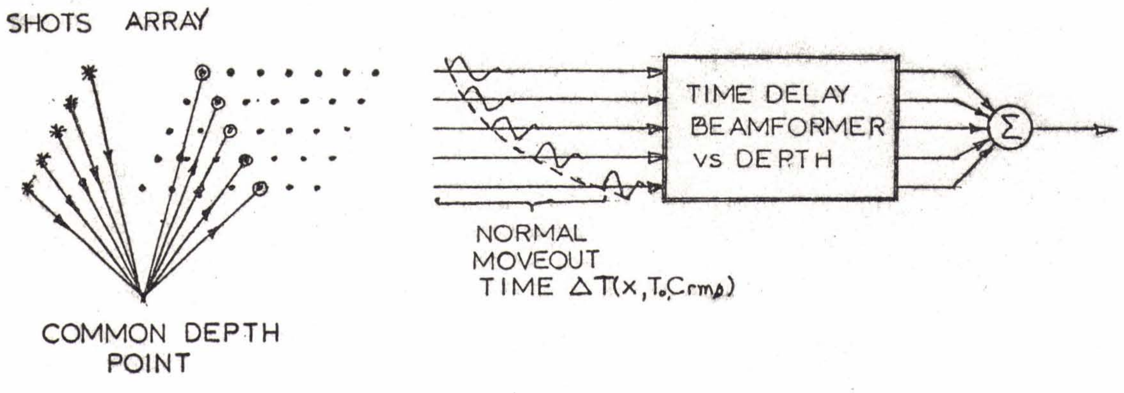


FIG. 4 COMMON DEPTH POINT STACKING

FIG. 5a DECONVOLUTION OPERATION

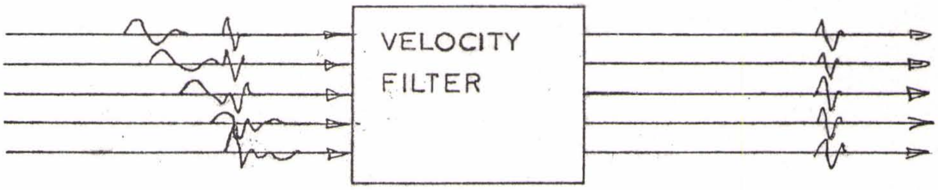


FIG. 5b VELOCITY FILTERING

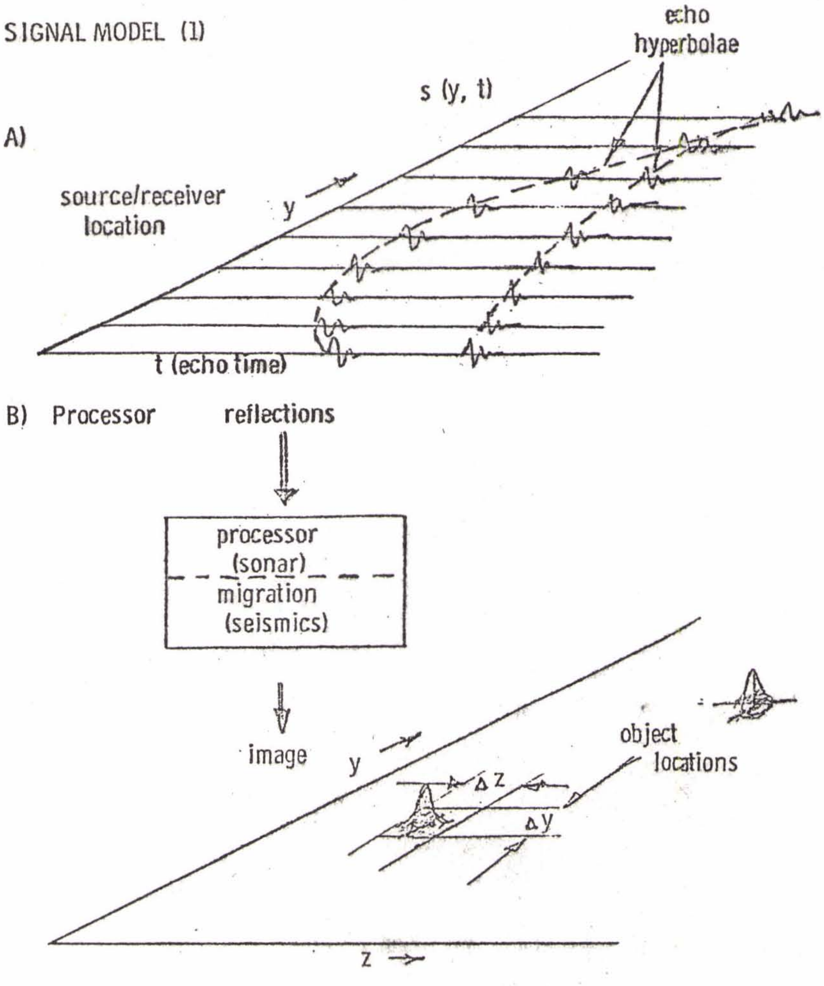
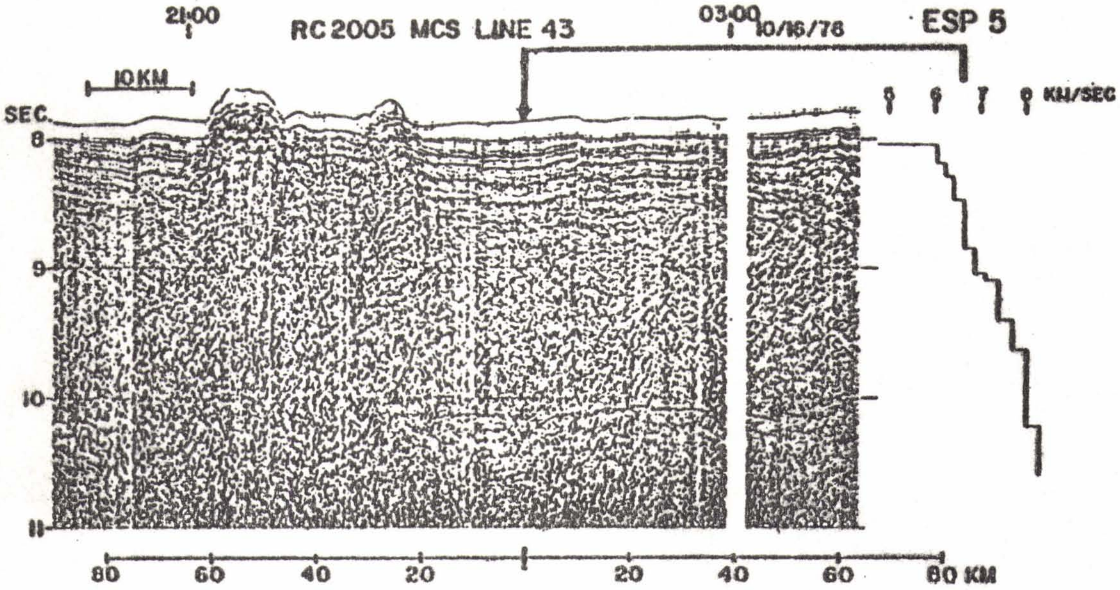


FIG. 5c MIGRATION OPERATIONS



FROM P. STOFFA AND P. BUHL, LAMONT-DOHERTY GEOLOGICAL OBSERVATORY (1978)

FIG. 6 CDP SEISMIC PROFILE