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Panel on Ocean Bottom Positioning
Committee on Geodesy
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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1 Executive Summary

1.1 INTRODUCTION

The Panel on Ocean Bottom Positioning of the National Research Council's Committee on Geodesy was created to provide the Committee and its sponsors with the following:

1. A review of the requirements for position-locating functions in the study and use of the ocean, particularly in relation to the seafloor;
2. An assessment of current capabilities; and
3. Conclusions as to what capabilities could be achieved in the future if recommended courses of action are followed.

Our purpose is to provide a view that emphasizes technological and operational aspects, while cutting across the various scientific and applied uses in which these techniques may be employed.

From the outset ocean-bottom positioning will be presented in two ways. First is the navigational context, in which the objective is to know the successive locations of some movable object in or on the water in relation to a coordinate system fixed to the seafloor. Second is the geodetic one, in which the purpose is to establish the locations of points on the seafloor relative to one another and their coordinates in some accepted global scheme. In both, the essential element is that the seafloor is the zone of primary interest and the site of the principal reference points.

Discussion of "requirements" will be carried out as they relate to each of these two categories. The treatment of techniques is organized on the basis of the physical phenomena that can be used to establish or transfer position information and in terms of systems that might combine several different technical elements.

The bulk of the panel's activity was carried out by mail. Two meetings were held, primarily to discuss requirements with representatives of various federal government agencies–Defense Mapping Agency, National Aeronautics and Space Administration, National Geodetic Survey/National Oceanic and Atmospheric Administration, and U.S. Geological Survey–and to receive presentations from a number of commercial organizations. The individuals who participated in the two meetings are listed in Appendix A.

1.2 CONCLUSIONS AND RECOMMENDATIONS

Our conclusion with regard to navigation requirements is that most of today's seafloor-oriented navigation problems can be solved with systems capable of precision of the order of 1 part in 10^4 of the range over which the system must operate. Most requirements imply durations of no more than a few years and coverage of areas about 10 km across, although some survey or search activities may cover substantially larger extent (10^3 km). A few navigational situations, however, generate more demanding requirements than those noted above. Fortunately none stresses all the triumvirate of accuracy, range, and lifetime simultaneously. Table 1.1 lists the most demanding of the requirements established during this investigation. In each of the three navigational situations it is illusory to combine the range and accuracy requirements into criteria such as "a part in 10^6," since the accuracy and range are really separately dictated by the nature of the problem.

Seafloor-related geodetic positioning requirements arise primarily in two classes of situations–boundary marking and geodynamics. The former, whether related to political interactions or resource exploitation, lead to accuracy requirements in the 1- to 10-m range that can be met under the sea with currently available near-bottom acoustic transponder systems. Ability to tie these acoustically determined positions to an appropriate global coordinate system will vary with location. In nearshore areas electromagnetic systems can provide an adequate tie. In midocean regions only the Global Positioning System (GPS), which is currently operational on a limited basis, can be expected to achieve the desired accuracy.

Geodetic problems arise in a variety of geodynamic contexts. Large-scale slumping of thick sediment columns and earthquake-induced crustal motions are the most obvious, but aspects directly associated with plate tectonics enter as well–in terms of interplate motion, intraplate deformation, and strain buildup patterns at plate edges (rise crests, transform faults, and subduction zones). These all lead to much more stringent requirements, falling in the

TABLE 1.1 Requirements Generated in the Five Most Demanding Situations Found in this Study[a]

Problems	Accuracy	Range	Lifetime
1. 3-D seismic survey	10 cm	10 km	1 mo
2. Missile-firing evaluation	10 m	10,000 km	1 mo
3. Radioactive waste disposal	10 m	10 km	10^5 yr
4. Geodynamics–spreading centers, transform faults, slump zones	1-10 cm	10 km	10 yr
5. Geodynamics–subduction, interplate motion, intraplate deformation	1-10 cm	1,000 km	10 yr

[a]While all of these goals appear to be achievable, none are currently met by validated operational systems.

1-10-cm accuracy range (Table 1.1). The problems also tend to fall into two separate categories, partly based on technological considerations. Those involving areas having lateral extent of 10 km and less can be attacked primarily with underwater acoustic and optical approaches, while those concerned with longer ranges must include ties from the seafloor to near-surface points that can provide access to systems utilizing transmission of electromagnetic signals, whether from shore, satellite, or other intermediate platforms.

Our major conclusion with regard to technology is that current capabilities, including seafloor acoustic transponders and a variety of electromagnetic systems, can meet the 1 part in 10^4 requirement if they are carefully used. Today's technology is thus adequate to cope with most of the situations that were brought to the panel's attention.

Hypothetical systems to meet the more stringent requirements of Table 1.1 are discussed in Chapter 4. These are assembled in part from existing technology, in part from items that have not been used in these particular contexts but that could be made available without any particular development work, and in part from elements that can be visualized and could be built but that have not yet been validated in the laboratory or in the field.

In order to make progress toward the performance requirements listed in Table 1.1, we *recommend that the following items be built and used both to validate the technology involved and to study the environmental aspects to which they relate:*

1. Acoustic transponders capable of 10^{-5} sec time resolution (Problems 1, 4. and 5).

2. A sound velocity meter capable of making in situ *measurements to 1 part in 10^5 (Problems 1, 4, and 5).*

3. An at-sea Global Positioning System geodetic receiving capability comparable with that for on-land use (Problem 5).

4. A laser-ranging system for underwater use (optical frequencies and very low received light levels) (Problem 4).

5. A precision acoustic system utilizing time-difference measurements to relate a sea-surface location to a seafloor reference point with 1-cm to 10-cm accuracy (Problem 5).

6. Seafloor work systems having the capability of mounting acoustic or optical markers on the seafloor at greater than diver depths (Problems 4 and 5).

No component development recommendations appear relating to Problems 2 and 3 of Table 1.1, since they can be solved with direct application of proven technology, as discussed in Chapter 4.

Development and validation of components and understanding of the environment do not alone solve these problems. Individual pieces must be combined with other elements and used as complete systems, including computing software, to achieve the desired results. Finally, it should be kept in mind that execution of the recommendations given above and the start of higher accuracy distance measurement in the sea will probably lead to recognition of other limiting factors whose importance has not, because of lack of actual at-sea experience, been established.

Implementation of these recommendations will require some adjustment of institutional arrangements. Marine physics (particularly underwater acoustics and optics) must play a major role in seafloor-oriented geodesy. Most of the investigators who understand marine physics and carry out innovative work in it are supported by groups within the U.S. Navy whose primary interests do not include either geodesy or geodynamics. Traditional geodetic activities are centered in the Defense Mapping Agency (DMA) and the National Geodetic Survey (NGS). While DMA has marine interests, their seafloor mapping missions do not extend to the spatial and temporal scales to which the above recommendations are relevant. NGS is primarily concerned with requirements for terrestrial control, leaving only minimal resources at this time for marine problems. The most comprehensive fundamental geodynamics research programs are those of the National Science Foundation, whose interest in geodesy, either on land or sea, is quite small. The National Aeronautics and Space Administration, with its focus on application of space-oriented techniques, has become the major supporter of geodesy in the geodynamic context but has not to date sponsored any related major undersea programs. The U.S. Geological Survey has been involved in geodesy in a geodynamic context in connection with earthquake-related research, but again this has been primarily a land-based effort. It is hoped that this report, by concentrating on requirements and technologies, can provide a rationale on which some of these agencies may act to change their traditional roles and bring these opportunities to reality.

2 Requirements

Our concern in this chapter is with operational activities or research opportunities within which geodetic or navigational functions play an essential role and with discussion of these functions in a quantitative way. Our goal is to elicit characteristics that can be evaluated both in terms of the pressure for their realization and the level of difficulty in achieving them.

The characteristics of most concern generally are primary performance requirements (accuracy, area coverage, and lifetime) and cost. Other elements, such as ease of installation, play a role, but it usually is a secondary one, which may lead a user to make some particular choice among otherwise nearly equal competing alternatives. The desirable performance characteristics usually cannot be spelled out to better than a factor of 10, although one must be careful in translating overall requirements to those relating to individual components. In some instances one must overspecify accuracy of some system element, for example, knowing that overall performance is often degraded in the real oceanic world. On the other hand, errors may be such, in combination with the nature of the observations, that averaging can produce a final result that is substantially better than any single observation. (The terms accuracy, precision, repeatability, resolution, and uncertainty are used as defined in *Webster's Third New International Dictionary*.)

In this report we have not attempted to address costs or cost-benefit relationships. On the one hand, prediction of costs for operational utilization of techniques that are in an early developmental stage is difficult to do without detailed analyses of quite specific pieces of hardware. Beyond that is the question of distribution of the development and validation costs among the development sponsors and the users. Determination of benefits is even more specific to the user. Particularly in the geodynamics research area, the benefits of being able to make a particular measurement may be evaluated quite differently by different scientists and sponsors even though their primary research goals may all be the same. Our hope in this report is to lay out performance measures and technological options, leaving to those concerned with specific problems or inventions the tasks of analyzing and justifying the desirability of solving a particular problem in some specific manner.

2.1 NAVIGATIONAL REQUIREMENTS

Discussions were held with representatives of government, industry, and the academic community on a wide variety of navigational problems. These included position determination for instruments or vehicles involved in on- or near-bottom search and work functions, seafloor and subbottom geophysical surveying (echo sounding, seismic reflection, magnetic, gravity, and other techniques), bottom sampling, missile launching and impact location, radioactive waste disposal, near-bottom fishing and biological studies (particularly with regard to bottom obstacle avoidance), and seafloor resource development (hydrocarbons, hydrothermal energy, and mining), among others.

The resulting seafloor-oriented navigation requirements come in a variety of styles, most of which do not strain the state of the art. Most seafloor exploration, search, and geologic studies can be carried out quite well with local systems having internal uncertainties of the order of 10 m and uncertainties relative to global coordinates of a kilometer. The latter requirement arises from a need to be able to return to a particular area to carry out subsequent operations, while the 10-m local accuracy assures that one could return within visual range to photograph, sample, or inspect any particular seafloor feature without undue position determination difficulty (control of the position of the camera or sampling device will generally be a more difficult requirement than position determination). In some instances there are needs for much better accuracy (centimeter or even millimeter) in localized situations in which relative positioning is the important element. In such cases the allowable uncertainties translate into greater than one part in a thousand of the ranges over which the system must operate—for example, in the guidance of seafloor work devices or in placement of large objects precisely in register with some already-in-place indexing system or some other object (e.g., placing the end of a pipe against its termination). These cases can be considered as successive approximation problems. For example, the requirement for millimeter accuracy in order to join two pipes or connectors together can be met by a sequence of systems each having successively better resolution, but without requiring any single one to achieve better than a few parts in a thousand. As the distance of separation decreases, the magnitude of the allowable uncertainty decreases proportionally, thus never becoming particularly demanding as a position-determination activity.

Situations dictating more stringent requirements than those implied above for accuracy, area coverage, and long life fortunately do not stress all three aspects simultaneously, thus in any given case one or two of these characteristics can be optimized at the expense of others. The four most severely demanding navigational problems are radioactive waste disposal, missile impact location, gravity surveys, and seismic reflection surveys.

2.1.1 Radioactive Waste Disposal

It is inevitable that high-level muclear wastes will accumulate to some degree on the seafloor or be buried within the sediments of the sea bottom. For example, the two known losses of U.S. nuclear submarines, *Thresher* (Spiess and Maxwell, 1964) and *Scorpion*, constitute oceanic repositories of high-level wastes. Consideration is now being given to permanent disposal of high-level wastes in canisters deposited within the deep-sea sediments (Hollister *et al*., 1981). Various other circumstances may arise in which either deliberate or inadvertent disposal will occur. An important issue is the possibility of dispersal of waste materials from disposal sites into the ocean itself. This will certainly need to be monitored if we are to be able to respond to dangerous sources of leakage that may require recovery of damaged, decaying, or imperfect receptacles (Triplett *et al*., 1981). These functions imply accurate positioning of the monitoring or recovery instruments. The unique feature of navigational requirements relating to high-level wastes is their very long life. Many of the radioactive isotopes involved have half-lives measured in tens or hundreds of millenia. There is thus a demand for adequate accuracy to be able to locate monitoring units for periodic replacement or to retrieve data for a very long time. The requirement of accuracy, say 1 to 10 m relative to the repository position, is easily achieved with modern acoustic transponding beacon methods. Techniques have been developed by which active transponder units can be replaced without loss of original position information, at least to the 10-m level (in principle, with more than average survey effort, the accuracy could be an order of magnitude better). While this technique would provide indefinite lifetime for the navigational net, there could well be external constraints (war or breakdown of government, for example) that might prevent the responsible agency from revisiting a particular site during the time interval in which replacement would be required. This implies a need for some type of very durable passive markers that could provide a minimal number of local reference points that would be used to re-establish a complete new transponder net for later use.

2.1.2 Missile-Firing Evaluation

The most stringent large-area navigational requirement brought out during this study was in the evaluation of missile firings (Applied Physics Laboratory, 1980; Schwimmer, 1981). Missile testing conducted from submarines requires high-accuracy at-sea position determination for both the submarine launcher and the missile impact on the ocean surface at the end of its flight. Land firings require only the latter. In either type the most difficult job is locating the missile impact since this is likely to be in distant waters and its location is to some extent unpredictable. The location system must thus be easily and quickly transported and installed. The requirements include an absolute, geodetically relocatable accuracy of about 10 m measured at a distance from the launcher, which may be as much as 10,000 km.

2.1.3 Offshore Oil and Gas Resource Exploitation

A variety of aspects of offshore oil and gas field exploitation provide examples from which navigational requirements emerge. Exploration activity is not particularly demanding, but some field development phases are.

The principal technique used during the exploration phase is seismic profiling to produce two-dimensional (2-D) (horizontal coordinate along track plus vertical coordinate) sections. During a 2-D survey, the surface is sampled every 25 to 50 m along lines that form a grid extending over the area of interest. This area could extend for many hundreds of kilometers, and the grid could consist of such 2-D seismic lines spaced a few hundred meters to a few kilometers apart. The method of data collection is such that redundant subsurface coverage is obtained from successive source–receiver positions. This allows the data to be stacked to enhance the signal-to-noise ratio. The quality of the stacked data is directly related to the positioning accuracy of both the sequence of shots and the streamer hydrophones. The exploration objectives and economics usually set the positioning goals of a 2-D survey. The shot interval can be maintained to an accuracy of a few meters. Because of sea currents and tides, the streamer (typically 2 to 3 km long) does not follow directly in line with the ship's track, and feathering angles of 1 to 5 deg are common. Tolerances of 5 to 10 deg are usually set as the allowable limit for the feathering angle during the collection of 2-D data. The positioning accuracy of the seismic lines is specified to be within 50 to 500 m with reference to the local geodetic control.

The issues change dramatically during the oil or gas field development and production phases. Now the interest is in description of the reservoir with emphasis on the fine-scale details of the sediment structure. High-resolution 3-D techniques (Brown, 1980; Nelson, 1981) are under development for this application. To resolve details of a subsurface structure requires that the line spacing should be equal to the in-line sampling interval. This implies line separations of as little as 30 m. Significant degradation of coherent combination of signals will occur if they are out of phase by as much as $\lambda/8$, where λ is the wavelength, which at 200 Hz implies just under 1 m. Any positional error will appear as a distortion in the process of combining the signals. Since the purpose is to achieve improved performance against noise and to produce good spatial resolution, it is desirable to maintain the distortion due to navigation at a negligible level. Moreover, since the shot time is a short interval and the various relevant independent elements of the received signal are likewise of short duration, the determination of the positions of sources and receivers at the desired times cannot take advantage of averaging in any simple way. The conclusion is that 10-cm accuracy for individual position determinations should be the goal. The areal extent of such a 3-D survey is typically 10 km × 10 km, and the time over which the precision tracking system must operate continuously is of the order of a few weeks. It should be emphasized that the accuracy requirement is not related to the accuracy with which the geographic coordinates of the subbottom structure must be known but arises from the manner in which the various signals are to be combined with one another.

Well-site surveys are conducted with high-frequency sources such as a sparker and subsurface profiling equipment. Typically, the area is smaller than that of a 3-D survey with line spacing of 300 to 500 m. The generally accepted accuracy requirements are repeatability, 50 m; absolute positioning, 100 m.

The drilling vessel is normally located on a seismic shot point with some specified position error tolerance defined. The position error usually takes the form of a circle of 50 to 200 m or a rectangle 100 to 500 m on a side. During drilling operations, the drilling vessel is kept within the required 1 to 3 percent of the water depth from the hole location either by a system of anchors or by a dynamic positioning system that derives its information from a short baseline acoustic system (e.g., Deep Sea Drilling Program, 1971; Geyer *et al* , 1978).

During oil field development, many tasks on the seafloor require local high-accuracy positioning. These tasks are generally accomplished by a combination of television and high-frequency acoustic systems. Invariably, the total system is designed specifically for the project at hand. The critical positioning requirement in the operation of marine pipeline construction is the laying of the pipe along a previously surveyed corridor. This is achieved either by using the same positioning system that was used by the original corridor survey or by transponders left in position by the corridor survey crew. Here again the requirements are of the order of meters in most instances but become tighter as one approaches specific connection points. Fortunately, these involve only very short ranges, and thus special-purpose, very-high-frequency systems can be used.

2.1.4 Gravity Surveys

Another type of geophysical survey approach utilizes the measurement of gravity. This has been applied effectively on land and in shallow water to define certain geologic formations (e.g., salt domes) that have a high probability of being associated with oil reservoirs. In such surveys relative gravity measurements are made over any given area with uncertainties of 1 part in 10^7–10^8. On the ocean floor similar uncertainties are achievable if the meter is placed on the bottom. While this is in principle feasible for any water depth, it has not been done at greater than about 200 m except in a few instances in which gravity meters have been operated in small submersibles such as *Trieste* and *Alvin* resting on the bottom (East Pacific Rise Study Group, 1981). Instead, at-sea gravity measurements have been made in large, near-surface-operating submarines or surface ships (Harrison and Spiess, 1963; Talwani, 1970). When this is done, it is necessary to correct for the fact that the gravity meter is not rigidly attached to the Earth and thus does not feel the same centrifugal acceleration component as would an on-bottom measuring instrument. In order to obtain measurement accuracies comparable with those on land one would need to know the instrument's east–west velocity component relative to the seafloor to an accuracy of about 10^{-3} m/sec. This is the most demanding requirement for velocity information encountered during this study. Lack of means for achieving this limits present-day systems for at-sea gravity surveys to large-scale problems in which relative uncertainties of 10^{-5} or 10^{-6} are acceptable.

2.2 GEODETIC REQUIREMENTS

At present, and for the foreseeable future, the need for high accuracy in establishing the coordinates of locations on the seafloor, either relatively within localized areas or on a global scale, arises primarily in connection with motions of the seafloor on various temporal and spatial scales. Requirements for reference points in other contexts arise primarily in relation to definition of national boundaries and in description of plots being exploited for their mineral resources. It should be noted that in this study our concern is with seafloor-referenced position determination rather than with the full range of possible marine geodetic activities (Saxena, 1980).

2.2.1 Establishing Boundaries

In the case of establishing political boundary locations (whether between nations or, for the United States, between states) the issues are such that 10-m accuracy will suffice. A need for such boundaries to be defined by permanent, on-bottom markers of some kind has not been established. This may be desirable in a few instances in which exploitation of seabed resources is particularly intensive, but, in general, a combination of general-purpose surface-referenced systems good to a few tens or even hundreds of meters (in relation to fishing activity) and temporary bottom-oriented systems good to 10 m (in connection with mineral and hydrocarbon resource development) appear to represent the requirements.

Seabed resources of most interest at present are in modest water depths and nearshore environments. In addition to the obvious oil and gas deposits they include principally sand, gravel, tin, and coal. In the deep ocean there are potential activities in relation to manganese nodules and exposed rise crest hydrothermal deposits. In every case the recovery techniques are such that plot boundary uncertainties of at least 10 m can be tolerated, and bottom marking systems need only be in place during periods of active development.

2.2.2 Geodynamics—Plate Tectonics

Much more stringent requirements on accuracy, time scale, and cost arise in connection with description of motion of the seafloor. Such descriptions can be of immediate practical importance, as well as basic scientific significance.

The largest spatial scale sections of the Earth's crust are the tectonic plates—hundreds to thousands of kilometers across. These are in continuous motion (measured on a geologic time scale) relative to one another, with speeds ranging from a few centimeters per year to almost 20 cm/yr (Minster and Jordan, 1978). As they move apart, new crust is produced on the seafloor, with attendant hydrothermal effects (heat release, mineral deposition, and dense biological communities) (RISE Group, 1980). Where they slide past one another or collide (producing trenches or mountain ranges) there are major earthquakes and, behind the subduction zones, extensive volcanic activity. Knowledge of how and why these motions take place on a time scale of years or less can help us to understand a wide variety of geologic (and in some instances biological) problems. This understanding may lead to other important implications—particularly for earthquake prediction and mineral-resource development.

Geodetic measurement programs in a variety of forms can contribute to our knowledge of various aspects of the dynamics of plate tectonics. At spreading centers, geologic evidence (Heirztler, 1980; Normark, 1980) indicates that crustal strain builds up over a very narrow zone (less than 10 km for intermediate-rate spreading centers) leading in such cases to strain rates as high as 10^{-5} per year. Documentation of the spatial and temporal patterns of strain buildup could shed light on driving mechanisms, plate growth, and hydrothermal activity. Along transform faults on land, the area over which the strain related to the slipping of one plate past another builds up is considerably larger than for similar features in the ocean. Oceanic trenches should exhibit comparable (but inverse) displacements with those at spreading centers. However, since old crust is involved, there is nearly always a considerable sediment column present, with complex interactions on the overriding side in which some material may be forced from the oceanic side up onto the overriding plate, while the bulk of it is subducted. For these reasons, in the vicinity of trenches the region of strain buildup may be 100 km or more across. There is also the question of whether the plates are truly rigid. This involves comparison of measurements of displacements at boundaries with those made on a larger scale between interior points of adjacent plates. Some of the plates are primarily oceanic and, while island locations can be visualized as useful measuring sites, they can be suspect because they may individually be subject to local motions owing to isostatic readjustments as they ride on the cooling crust away from the source ridges. It would thus be desirable to be able to link deep-seafloor points in midocean with others in midcontinent.

The general problems of worldwide measurement of tectonic deformation were addressed by a panel of the National Research Council (Committee on Geodesy/Committee on Seismology, 1981). As a result of the membership of that group, their focus was primarily on means for monitoring displacements between terrestrial points. Among their recommendations they included a requirement for development of a capability to measure, to an accuracy of 10 cm, motions of points on the ocean floor up to several hundred kilometers offshore with respect to reference points on land. They also recommended a substantial program of measurements in the San Andreas Fault region—one of the largest continental transform fault zones. The possibility of carrying out measurement programs at rise crests and oceanic sections of transform faults was not discussed. All of these, however, lead to requirements for centimeter accuracy in interrelating sets of seafloor points, some of which (as at oceanic spreading centers and transform faults) are a few kilometers to 10 km apart and others in which the spacings are separated by 10^2 to 10^3 km (subduction zones or plate deformation).

2.2.3 Geodynamics—Localized Motions

Seafloor dimensional changes also occur in other contexts than plate tectonics. Vertical motions can occur in association with changes of loading due to ice cover or removal. These are only of major importance, however, on land or in water shallow enough to allow the ice to rest on the seafloor. Geodetic measurements in such marine areas can usually be carried out by direct extension of land-surveying techniques.

Effects of sediment deposition can extend substantially farther out to sea, particularly off the mouths of major rivers. As such depositional materials are compacted or slide down the continental slopes, appreciable displacements can occur. On the steeper zones this results in episodic slumping when slopes build up beyond the maximum angle of repose for the sediment type involved. In other cases, even with slopes of only a fraction of a degree, large masses of material may creep slowly downhill, accompanied by deformations of various styles, such as fissures, faults, and mud waves. Monitoring and understanding such motions can have direct implications in relation to the survival of man-made structures such as pipelines or oil drilling and storage units. The requirements for geodetic measurements in such regions are quite similar to those at spreading centers and transform faults—measurements with 1- to 10-cm uncertainty over distances of a few kilometers, although here in the face of more severe inhomogeneities, currents, and turbidity in the water column.

Currents interacting with the seafloor can also produce measurable topographic alterations, although usually of smaller scale than those discussed above. Combinations of erosion and redeposition can produce fields of migrating dunes and transitory furrows that can be particularly troublesome when they interact with seafloor cable or pipeline installations. These tend to change more rapidly (although often only episodically) than the slower creeping and plate-tectonic effects. Survey requirements are thus not so stringent, and documentation of the development of these features can usually be carried out with large-area positioning techniques in the meter range, supplemented by higher-resolution local mapping on a relative basis using photography, side-looking sonars, and swath-mapping echo sounders.

2.3 SUMMARY OF REQUIREMENTS

Reviewing the discussions above leads to the conclusion that only a limited number of applications drive the requirements for more advanced ocean-bottom positioning systems. In the navigational realm most problems imply allowable uncertainties of a few meters to tens of meters, with areas covered being tens of kilometers across with system lifetimes of a few years. Four particular activities dictate much more severe design goals, but, fortunately, in each case only one of the three parameters of accuracy, area coverage, and lifetime is stressed in each problem area. The most demanding precision is the 10-cm requirement arising in the 3-D seismic reflection survey problem. This requirement is coupled with a 10 km × 10 km area and a lifetime of the order of a month. The extent of coverage is most demanding in connection with missile-firing evaluation, in which the distances are of the order of 10,000 km, with accuracy of 10 m and lifetime of a few tens of days. The radioactivity disposal problem, while only needing a few meters' accuracy over areas a few tens of kilometers across, must maintain its effectiveness for essentially an infinite time. Finally, detailed gravity surveys require platform velocity determinations with uncertainties less than 10^{-3} m/sec.

The geodetic requirements associated with national boundaries and resource exploitation seem to be in the range of a few meters to tens of meters if one takes a pragmatic view of the manner in which positional information is used in normal circumstances.

Geodetic requirements associated with seafloor motions, however, cannot benefit much from systems that define positions with a few meters' uncertainty. Almost all of the important geodynamic problems involve motions that take place so slowly in relation to the time scales of interest that changes of the order of a few centimeters to a few tens of centimeters must be set as measurement goals. Within this range there are many questions that can be dealt with effectively employing fairly localized networks. This is particularly true of studies of slumping on continental or island slopes and the patterns of strain buildup in the vicinity of seafloor spreading centers and transform faults. These aspects all fall in areas of the order of 5 to 20 km across, although in the plate-tectonic situations one will, in the long run, be interested in the along-strike gradients of these motions for many tens of kilometers. Strain buildup across oceanic trenches (subduction zones), however, must include distances of the order of hundreds of kilometers, while studies of internal deformation of plates and of their large-scale relative motions need to consider lateral dimensions in the range of thousands of kilometers.

3 Phenomena Available for Ocean-Bottom Positioning

A wide variety of physical phenomena and sampling devices are in principle useful for establishing seafloor reference points and linking these together with each other or with mobile vehicles. These include geologic, acoustic, electromagnetic, and radioactive phenomena and mechanical devices (measuring rods, pressure gauges, gyroscopes, and accelerometers). Some of these (e.g., radioactive decay radiation and permanent magnets) have such short-range effects that they are useful only as markers in fine-scale situations, and, as a result, no substantial position determination technology has been built around them and they will only be discussed as potential elements of composite systems. Major parts of the electromagnetic spectrum—the wavelength regime from a kilometer through meters and millimeters and on into the infrared—are essentially completely useless in any direct way in seawater because of their substantial absorption. Low-frequency electromagnetic radiation (wavelengths *in vacuo* of over a kilometer) can penetrate to useful depths in the sea but is poor for precision navigation or geodetic work because of inherent lack of spatial resolution.

The principal useful options within the water column are underwater acoustics, optical (photographic approaches and laser-based ranging) systems, mechanical systems, and geologic phenomena. Since ties over long distances may be made by relating intermediate points on vehicles at the sea surface to points on land and to the seafloor near the vehicles, electromagnetic systems using transmitters on land or in space will come into play. In each of these categories there is a substantial, well-developed body of technology that can be related to our problems and from which basic limitations and potential for improved performance can logically be discussed. The various categories will be treated individually, including relating their capabilities to the requirements of Chapter 2. Chapter 4 will draw on this chapter in discussing composite systems that make use of these phenomena in mutually supporting ways.

3.1 UNDERWATER ACOUSTICS

3.1.1 Travel-Time Measurement

Measurement of the travel time of acoustic energy between two points in the ocean is the most frequently used means of navigating or relating positions of objects underwater. Applications of variations to this approach during the last few decades have resulted in systems that measure locations over hundreds of kilometers to within a few kilometers, over 10 km to meters, and over tens of meters to within centimeters (Cestone *et al.*, 1976; Christensen, 1979). In general, the accuracies have been limited by costs in relation to needs, and in a few instances substantially higher accuracy has been achieved. There are, however, several factors that effectively limit possible accuracies. These are the increase in attenuation with sound frequency; the change in sound velocity with temperature, pressure, and salinity; varying current structure in the water column; multipaths resulting from the latter two variables plus reflection from boundaries; and the noise background produced by natural and man-made phenomena.

Existence of useful, stable acoustic paths linking the reference points and the vehicles to be navigated is the first-order requirement. This is controlled primarily by combinations of refraction and topography that can either enhance (convergence zones) or block (shadow zones) sound propagation.

One's ability to measure distances underwater acoustically where good paths exist depends most simply on two aspects: the available signal bandwidth and knowledge of the speed with which the sound has traveled. The available bandwidth determines one's ability to make a definitive measurement of the signal travel time and is primarily controlled by the absorption of sound in the water and by the nature of the background noise, which puts practical limits on signal-to-noise ratios. Sound absorption in seawater is produced primarily by a succession of chemical relaxation processes (Fisher and Simmons, 1977). It increases monotonically with frequency (Figure 3.1), implying that for longer ranges the optimum frequencies for effective systems will decrease, with a corresponding decrease in available bandwidth.

Over most of the useful frequency range, receiving elements can be built with enough sensitivity that they are limited by the acoustic noise in the ocean rather than by circuit noise. Sea noise arises from three major sources—in the

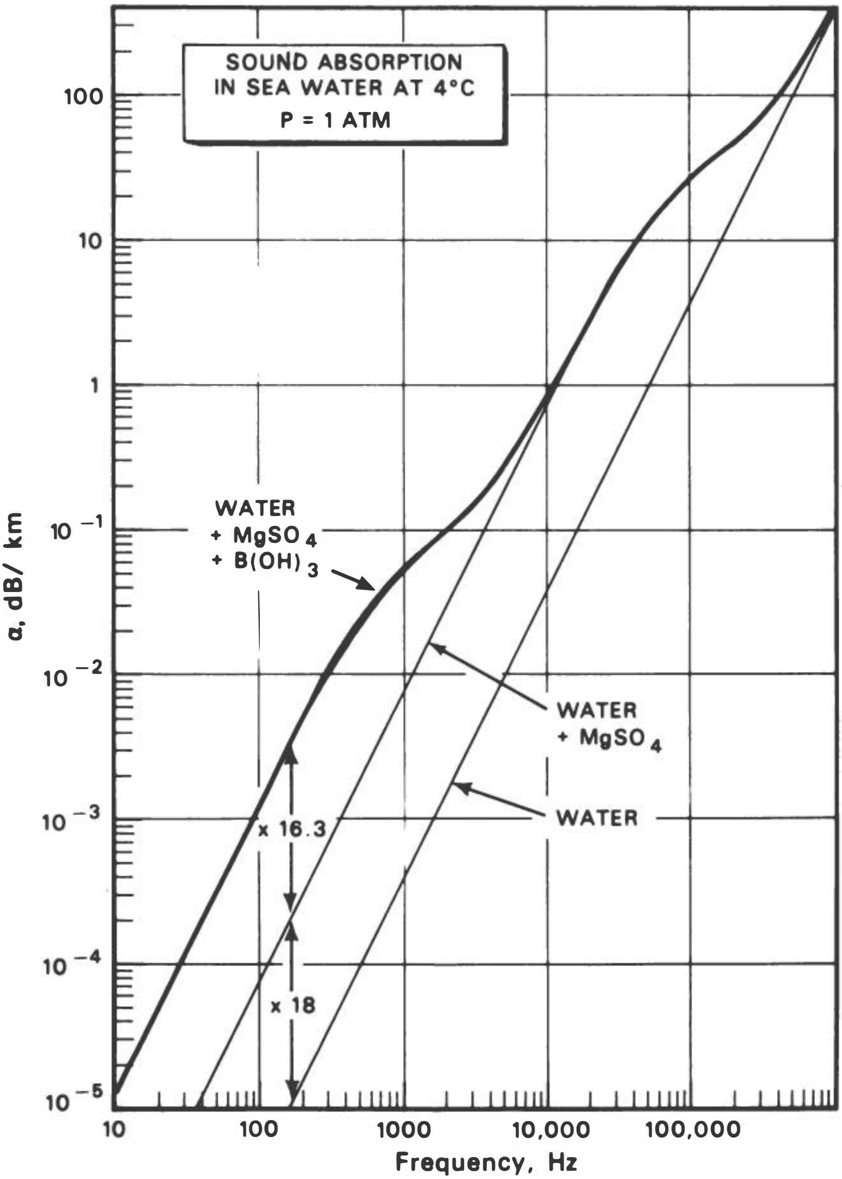

FIGURE 3.1 Sound absorption in seawater as a function of frequency (from Fisher and Simmons, 1977).

few-hundred-hertz regime distant shipping makes the primary contribution. In the range from a kilohertz or so to tens of kilohertz, dynamic effects at the sea surface control the situation, while as one approaches 100 kHz the thermal agitation of the water molecules predominates. The nature of these phenomena are such that, in general, the sea noise falls off as frequency increases until one reaches a minimum beyond which the thermal noise takes over and the background level begins to increase with increasing frequency. As one works deeper in the sea, the sound absorption attenuates the surface-generated noise, and, although the background can be expected to be lower in magnitude, the spectral shape will change, with the thermal noise beginning to dominate even at frequencies of tens of kilohertz.

The combined result of these attenuation and noise characteristics is that at a few tens of kilometers range, signals can be generated and transmitted such that travel times can be determined to within 10 μsec, given reasonable output power. At a few hundreds of kilometers, however, the limitation to lower frequencies (and thus smaller bandwidths) will drive the uncertainty into the millisecond range (Spiesberger and Worcester, 1981). Since the average sound speed is about 1500 m/sec, the 10-μsec uncertainty in measurement of round-trip travel time will give rise to slightly less than 1-cm-range errors, while 1 msec will lead to about a meter uncertainty. If one could average over long enough times, it might be possible to improve these numbers by a factor of 10, bringing the 1 msec barely into the useful 10-cm range.

Once one has made a travel-time measurement, the next step is to convert this to actual distance, and the question of spatial and temporal variations in the speed with which sound travels dominates the situation. Sound speed can either be measured directly or inferred from measurement of other parameters (temperature, pressure, and salinity). The best laboratory measurements of sound speed have uncertainties of the order of 1 part in 10^6 (Greenspan, 1972). This means that in any event one is limited to 10-cm uncertainty at a range of 100 km (10^5 m). As a practical matter, the situation is worse than this, since the best sound velocity meters now in the field only have a 1 part in 10^4 capability, although one research model is currently under development that is expected to achieve 1 part in 10^5 (10 cm in 10 km) (Fisher, 1982)

The relationships between sound speed and other relevant seawater parameters (temperature, pressure, and salinity) have been studied in the laboratory by a number of investigators. Lovett (1978) summarizes the most generally accepted experimental results and generates a number of alternate equations to fit the data and to compare with the equations of Wilson (1960) and Del Grosso (1974), which had been in general use. From all of these, two things emerge. First, the approximate effects of small changes are, for temperature, 5 m/sec increase per °C; for pressure, 1.6×10^{-2} m/sec per meter of depth; and for salinity, 1.33 m/sec per part per thousand. Second, the various curvefitting efforts all have standard deviations, relative to the data, of the order of 0.05 m/sec, which is about 3 parts in 10^5. These factors make it clear that use of a sound speed meter, if it can achieve 1 part in 10^5, is the desirable approach for actual field work. On the other hand, we can discuss the expected variability of the environment by looking at the temperature, pressure, and salinity variations.

The goal of a part in 10^5 (1-10 cm in 1-10 km) corresponds to a speed change of 1.5×10^{-2} m/sec, which is 3×10^{-3} °C or one decibar (meter of depth). With regard to pressure this implies that one must have a rough measurement of the tidal conditions at the time of each acoustic observation, since the full tidal excursion can range from 1 to 2 m in much of the open sea to over 10 m in some coastal areas.

Temperature variability is the primary source of difficulty. Particularly in the upper few hundred meters in coastal environments, where one might be studying gravitationally induced displacements associated with large accumulations of sediment, the variations of temperature can far exceed 0.003°C. In such areas some simple temperature-measuring surveys should be made prior to initiating any major field program to determine the range to which it would be logical to expect success. It may very well be that simple acoustic ranging systems can only achieve a part in 10^3 or 10^4 in such areas (because of the time scale on which the sound velocity field may vary) and that other means must be used in combination with underwater acoustics.

Salinity variations will be particularly important in the vicinity of large river outflows. Since these may be areas of rapid sediment accumulation, with associated slow creeping of the resulting sediment prism, they can be important zones for marine geodetic studies. Here again preliminary surveys, including careful fine-scale salinity measurements, must be made to determine the ranges to which acoustic techniques can achieve the accuracy required for whatever geodetic program is being planned.

In short, in coastal regions environmental limitations on determinations of sound speed may control the situation at ranges so short that the problem of making an adequate measurement of travel time *per se* will be a trivial one.

Below about 1- or 2-km depth, the ocean in most locations is far more homogeneous, and one can expect that in most areas one will be able to define sound speed to a part in 10^5 in deep water by making direct measurements without invoking unreasonable demands on the spatial and temporal scales of the supporting sound-velocity surveys. Such measurements, however, will be required in association with each geodetic survey operation, at least until some understanding of long-term environmental processes is achieved in the area of interest.

The major exception to the above statement about homogeneity occurs in the geodetically interesting rise crest zones in which hydrothermal activity is now well known to occur (RISE Group, 1980). Even here, mixing of the warm outpouring water with the overlying ocean is such that the effects on mean value of sound speed and on the root-mean-square fluctuations (see below) appear to be manageable except for patches of the order of tens of meters in horizontal extent centered on individual concentrated vent areas. Any near-bottom geodetic measurement system must be designed to cope with the advent and extinction of small warm patches. Our present knowledge is imperfect; however, it seems likely that individual hot-water vents may have lifetimes measured in terms of only a few years (Macdonald *et al.*, 1980).

Even with very good sound-velocity measurement one will still be faced with small-scale variations arising from thermal microstructure. These may vary with time on a scale such that they can only be treated statistically, with hope that they will average out to a net effect along the path that can be neglected. Observations of thermal microstructure on the East Pacific Rise crest (Crane and Normark, 1977) show a characteristic length of approximately 100 m and a root-mean-square temperature fluctuation of 5 mdeg C. The theoretical bases for treating sound propagation through media having variable sound-speed properties that can only be described statistically have been developed over the last 40 years by various authors. The most recent and all encompassing is the account assembled by Flatte (1979). This treats a variety of scales, with particular emphasis on long-range oceanic sound propagation situations. Unfortunately, no amount of analysis is able to overcome the fact that our present lack of ability to describe the sound-speed environment to better than a part in 10^5 places quite definite limitations on the navigational and geodetic applications of underwater acoustics to meet the requirements discussed in Chapter 2. Present research programs in which sound is being used to probe the ocean environment (Munk and Wunsch, 1979; Pinkel, 1981) may eventually lead to improvements in this situation, but, for the present, even older treatments of the fluctuation problem (e.g., Chernov, 1960) at relatively short ranges are relevant. These translate the temperature observations cited above into range uncertainties between 0.5 and 1.5 cm as the path length increases from 1 to 10 km. It thus appears that these rise-crest circumstances should indeed be manageable, particularly if many travel-time measurements are made, separated by distances at least comparable with the thermal microstructure correlation lengths, which are of the order of 10–100 m.

The topography of the area in which the measurements are to be made will also influence the details of an acoustic system, since direct obstruction of the sound path by hills or valley walls will obviously limit the usefulness of near-bottom paths. Below a depth of 1 or 2 km in most oceanic areas the water is close to isothermal and the sound speed increases with depth. This gives rise to upward refraction such that, even if the seafloor is a horizontal plane, no direct path may exist between near-bottom source–receiver pairs. In isothermal water sound rays will travel in a vertical plane with a radius of upward curvature of about 90 km. This means that if the source and receiver are each 2 m off a level seafloor, their limiting separation will be only 1200 m. For this reason typical transponder navigation systems float the acoustic transducer 100 m or so above the seafloor when they are being used with near-bottom vehicles (Figure 3.2). If one must tie together pairs of seafloor points in a geodetic context, these effects must be mitigated by using intermediate vehicles operating well off the bottom, particularly since the transponders themselves must be fixed very close to the bottom if they are to maintain their positional integrity to within a centimeter.

In principle a wide variety of options are available as to the general configurations of acoustic travel-time measurement systems (Spindel *et al.*, 1975). Among those that can be used are multiple ranges, direction determination, range and direction combined, and range differences (hyperbolic). They can use active transmissions from either the vehicle or the reference point or both, and the reference points themselves can contain either active sources, transmitting from their own power, or simply be passive reflectors. They may undertake the entire 3-D location problem, or they may rely on other means

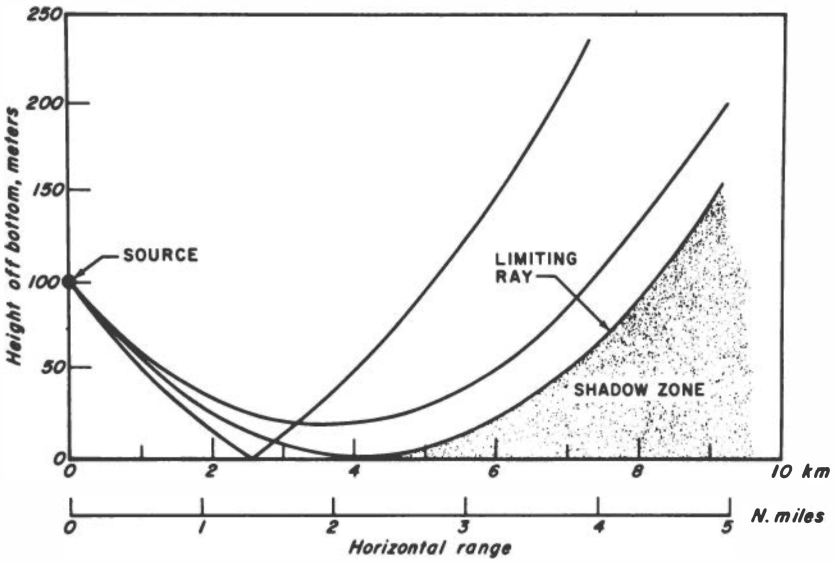

FIGURE 3.2 Effects of upward refraction for a near-bottom sound source in isothermal water (from Spiess, 1966).

(usually pressure measurement or an uplooking echo sounder) to determine the vertical coordinate.

In choosing among the various options there is one further environmental influence. Ocean currents, even at normal seafloor depths, will typically be on the order of 10 cm/sec, with values occasionally ranging (particularly near the surface) to 1 m/sec or somewhat more. If one uses one-way transmission only, then these speeds must also be measured and added to the intrinsic sound speed of the water itself. On the other hand, this effect will be essentially eliminated if one measures round-trip travel times. This leads to a preference for systems using transponders and reflectors.

There may, however, be special circumstances in which one-way travel-time systems may be useful, if the range accuracy requirements are not overtaken by the magnitudes of local water currents. Two important cases exist, both arising because of man's own presence in the environment. First is the situation in which the platform being navigated is a very noisy one and the water is rather shallow. In this case the radio-acoustic-ranging concept originated in the 1930's by the U.S. Coast and Geodetic Survey and recently revived by a Miami-based group (Daubin, 1982) may be useful. Here the transponder (in a quiet environment) listens for the acoustic interrogation from the noisy ship and replies through a buoy-mounted radio transmission system hard wired to the acoustic receiver. The second situation is one in which there may be several simultaneous users of the system or a platform being tracked is unduly noisy. In this case use can be made of units that are moored to the seafloor or placed on the noisy vehicle and contain an accurate clock and transmit at predetermined times to the receiver, which has its own clock synchronized with that of the transmitter and records the arrival time of the signal for telemetry or later processing.

Although a wide variety of options have been tried, the principal large-area, precise systems in actual use today rely on acoustic transponders (Figure 3.3) to provide the basic reference markers and operate using range information only. Since they are generally developed because of perceived needs, and these have centered on requirements for 1- to 10-m accuracy over areas the order of 10 km across, with lifetimes of months, these are the characteristics of the systems that represent the state of the art.

The fact that a few meters of uncertainty have been acceptable has been very convenient. A number of sources of error fall in this range, and thus system development has been simplified. Typical transponder response times are finite and vary to some extent with either received signal level or signal-to-noise ratio. This variability is of the order of 1 to 5 msec for most commercially available transponders, or about 0.75 to 4 m, since round-trip travel time is being measured. Since vehicle speeds are generally less than 2 m/sec and ranges less than 10 km, the problem of vehicle motion during the time the pulse is in

FIGURE 3.3 Launching an acoustic transponder. The acoustic package (electronics, batteries, transducer) is on deck, and the flotation units are in the water streaming astern.

the water can be treated with simple approximations, or even ignored. Errors due to neglect of ray-path curvature also fall in this general magnitude.

Extent of area coverage is achieved in general by use of as many transponders as may be needed, with a standard accepted sonar range of about 10 km. The primary real limits to the useful range are (1) refraction and topography for near-bottom navigation and (2) ship noise, plus the need to cope with the water depth as part of the slant range to the transponder, in the case of near-surface vehicles. Lifetime in the listening mode is usually between 1 and 2 yr, although through use of lithium batteries this can be extended to as much as 5 yr. Operational techniques for replacing transponders (surveying new units in relation to older ones) have been developed that essentially can meet the requirements for indefinite lifetime for the net, provided it can be revisited every few years.

In short, the technology actually in use today is capable of meeting the requirements for most problems, albeit occasionally at the expense of having to use large numbers of units or return to the area at shorter intervals than might otherwise be desired.

The basic technology to make the leap by a factor of 100 from the few meters' to the few centimeters' precision range exists (Spiess, 1980). Transponder designs have been devised that can control the response time delay to within a few microseconds, with 10-μsec-recognition time resolution (Spiess *et al.*, 1980). Combined with the 10-km ranges that conventional transponders can achieve, these could satisfy the 3-D seismic survey requirement and the local area rise crest or slump area geodynamic requirements for time measurement, although to convert the travel times to distances would require auxiliary systems to measure pressure versus time and sound velocity spatial variability, as will be discussed under system considerations in Chapter 4.

Continuous-wave acoustic navigation methods have been developed as alternatives and adjuncts to transponder systems for high precision (Spindel *et al.*, 1976, 1978). Transponders are replaced by beacons transmitting continuous tones of known frequency. Navigation and position keeping are accomplished by observing the progressive buildup of phase difference between the received and transmitted signals. The principle is identical to that used in electromagnetic navigation systems such as Omega. A typical implementation employed transmissions near 10 kHz and achieved 10-km ranges with centimeter accuracy of equivalent time measurement resolution.

3.1.2 Direction Measurement

The discussion to this point has focused on use of underwater sound as a means for measuring distances. There is also the possibility of making angle measurements. Many of the same limitations apply. The primary one, corresponding to bandwidth in travel-time processing, is the size of the receiving system aperture measured in wavelengths. Thus, again, the higher the frequency the better. The limitations discussed above due to sound absorption and background-noise spectrum shape are still relevant, and practical systems utilize frequencies of the order of 10 kHz and above.

Angle measurement can be made using one of two approaches—imaging or phase (time) difference determination. In the former the measurement is made on the basis of the difference of received signal intensity as one scans across the sound field, and resolution is usually no better than 10 to 20 percent of the beam width of the receiving hydrophone array (depending on contrast between signal and angularly adjacent background noise). The actual beam width in any plane depends on the geometry of the receiving elements but is always given approximately, in radians, by the inverse of the width of the receiving array measured in wavelengths. To achieve 1-m resolution at 10 km one would need between 1000 and 2000 wavelengths of aperture. Given that the wavelength for 10-kHz sound in the ocean is about 15 cm, such a system would require a filled aperture of unreasonably large dimensions (e.g., 150 to 300 m).

The other approach utilizes a pair of well-separated receivers (or a more-or-less continuous distribution of elements, split in half), and the phase or time difference between the signals received from the two parts is measured in a manner similar to the approaches used in radio astronomy. Given normally achievable signal-to-noise ratio one can push such systems to resolutions corresponding to about $\lambda/100$, thus reducing receiving array size to about one tenth of that for an imaging system.

Knowledge of sound speed enters in a different way than in range-measuring systems. In using phase or time differences one must know the speed of sound at the receiving array in order to convert the time differences into angles. The relationship is $CT = D \sin \theta$, where C is the sound speed, T the time difference, D the receiver spacing, and θ the angle. Since best performance is achieved near broadside (small θ), the fractional lateral position error at any given range will be approximately proportional to the fractional errors in the sound speed. Thus, to achieve 10 cm at 10 km ($\theta = 10^{-5}$ rad), one must know the sound speed at the receiver, and the receiver separation as well, to a part in 10^5. Knowledge of the direction of arrival of a signal does not, of course, translate directly into knowledge of the position of the sound source. Sound-speed gradients across the ray path will produce deflections and resulting displacements of the beam from the line projected from the receiver at the measured angle.

Systems using angle measurement have been used at sea primarily in situations where there is some need for a compact geometry. They are well adapted to tracking an object (towed body, submersible) from a nearby ship and can be used with good results when the sound path is nearly vertical, since temperature-induced horizontal gradients of sound velocity are usually two orders of magnitude less than the vertical gradients and the effects due to pressure produce sound-speed variations only in the vertical. This is particularly useful for keeping a ship nearly directly above a particular seafloor point, as when carrying out deep-sea drilling operations (Deep Sea Drilling Program, 1971; Geyer *et al.*, 1978).

One final point—although the discussion above has been phrased in terms of a source and a pair of receivers the situation can be reversed, using a pair of carefully matched transmitters and a single receiver. In such a configuration, the system becomes a more obviously hyperbolic one, analogous to loran and other similar electromagnetic approaches.

In summary, it appears that, primarily because of lack of ability to know the speed of sound, acoustic systems are now limited to precision of a few parts in 10^5. Improvements in sound-speed measurement can be expected to allow achievement of a part in 10^5 in the future, but it seems unlikely that 10^6 will be reached in the field except under special circumstances, primarily because of the fine-scale spatial variability, which changes on time scales too short to visualize being able to describe the sound-field details except on a statistical basis. Acoustic systems may thus be useful out to a 100-km range if 1-m accuracy suffices, but they can stand alone in relation to the most demanding geodetic problems only out to ranges of the order of 10 km. Beyond that, some sort of hybrid systems will be required.

3.1.3 Measurement of Vehicle Velocity

Acoustic techniques can also be used to provide vehicle velocity information. Two approaches are available. First is the use of Doppler techniques. Here one transmits a known signal and measures the difference between the transmitted frequency and that of the returning reverberation from the seafloor. As with other navigation systems, it is desirable to operate at as high a frequency as possible in order to achieve the best velocity-component resolution. At the same time, sound absorption drives one to lower frequencies as the vehicle being navigated moves farther from the bottom. One can (and in most deep-water operational systems, does) work with reverberation from the water volume near the vehicle; however, this is of little value in the gravity survey context of Section 2.1.4 since the water itself may well be in motion with speeds of 10 cm/sec or more relative to the Earth.

With reasonable care and operating within a kilometer of the seafloor, one can achieve accuracies somewhat better than 1 cm/sec. While this does not meet the ultimate requirement for gravity surveys, it is substantially better than most ship's systems in use today. Unfortunately, for near-surface platforms in the open sea the slant-range requirement is large enough (7 km) that the high frequencies used in centimeter per second systems cannot produce the required backscattered reverberation levels, and lower-frequency systems lead to both frequency resolution and beam-width problems. A system is under development that may circumvent the beam-pattern problem by using the nonlinear acoustic effects produced when high-level dual-frequency signals are transmitted (parametric transducers). This approach is expected to give resolution of a few centimeters per second in deep-water use.

A further problem, particularly for surface craft far above the seafloor, is that the velocity components of the ship at both the times of signal transmission and reception enter into the determination of the round-trip travel time, and this interval, for 5 km of water and a 45° down-tilted beam, will be about 10 sec (round-trip travel time). Given normal ocean-wave spectra and ship-response characteristics this can lead to serious aliasing problems in sampling, with subsequent difficulties in attempting to average out the short-term fluctuations in ship speed.

It should be feasible to build Doppler systems capable of meeting the gravity survey velocity requirement of 10^{-3} m/sec, although this probably can only be done within a few hundred meters of the seafloor, since the frequencies involved would of necessity approach a megahertz. At this level of resolution it is necessary to exercise some care in determining the sound velocity. Given that the gravity measurements would be made with vehicle speeds substantially less than 20 knots (10 m/sec), and that the vehicle speed is directly proportional to the frequency difference and the sound speed, this leads to a sound-speed accuracy requirement of only a part in 10^4, which can be achieved with existing commercial sound velocity meters.

A completely different acoustic approach has been proposed (Dickey and Edwards, 1978) in which a downlooking sonar with relatively wide beamwidth is used as the transmitter and several similar beamwidth transducers are used as receivers. Two identical pulses are transmitted, and the received signals are cross-correlated among various receiving hydrophone pairs. A peak in the cross-correlation will occur for some particular (interpolated) spacing, and this displacement, with the time difference between the two pulses, can be used to calculate the platform velocity vector. Shallow-water tests have yielded average errors over an entire run of 0.02 knot (1 cm/sec). Readings based on 30-sec averages had a standard deviation of about 0.1 knot (5 cm/sec) (Dickey and Edwards, 1978). Unlike the Doppler systems, for which there are several commercially available units capable of 0.1-knot shallow-water performance, there are as yet no available production systems of this correlation type.

3.2 OPTICAL TECHNIQUES

Optical techniques can be used under water to provide imagery from which angular measurements can be made or in a ranging mode using short pulses or amplitude-modulated light from lasers. While both of these techniques are quite useful in air or free space, they are quite restricted in range when used in the ocean. Both photography and ranging are discussed in this section.

Photography from aircraft or satellites provides a commonly used and effective means for surveying the Earth's surface over large distances. Limiting factors are aberrations of the optical system, control of height and orientation, the resolving power of the film, and the ratio between object and image sizes (McNeil, 1949). These factors are important in photography in the ocean as well, but additional factors enter:

1. Light must be provided locally;
2. The attenuation of light by seawater is high (the maximum absorption length in the optical spectrum being about 30 m, with 15–20 m a much more common range for "clear" water); and

3. Backscattering is appreciable even in the clearest deep waters.

Present-day, high-quality underwater systems can resolve something like 0.5 to 1 cm in a field that is 30 m × 30 m (McNeil, 1972; Pollio *et al.*, 1979). With a pattern of reflectors sown along the line of measurement, one can take overlapping photos and make a montage from which distances can be measured. For a path 300 m in length the number of overlapping photos might be 20, and the application of the simplest statistics, based on an individual measurement uncertainty of 0.5 cm, would say that the root-mean-square error would be 2.2 cm. Actual attempts to do this type of measurement have produced errors larger than this by about a factor of 3–5. Thus, the use of deep-sea photography in its present state of development does not match the displacement/distance ratios that are involved in many of the geodynamic motions within a reasonable time. However, it is possible that the optical systems could be improved by an order of magnitude or more. This would put them within the ranges needed. Given the short ranges involved, such systems would have to be useful under circumstances in which the local topographic relief is of the same magnitude as the height of the cameras off bottom. This aspect would have to be looked into as part of the process of developing higher-accuracy photographic systems.

The most severe limitation to use of photographic systems is the directly obscuring effect of suspended particulate material in the near-bottom water. This is most severe in sediment-covered regions that are traversed by strong currents. While this occurs most frequently in shallow water, it can occasionally be a severe problem in deep water as well. For example, during the summer of 1981, in the Atlantic at lat. 40° N, long. 62° W, and a depth of 4500 m, there were periods of several consecutive days in which the suspended material was so dense that a photographic system operated only 3 m off bottom could not produce a discernable image of the seafloor. There were, however, adjacent periods of several days during which clear images were obtained from 8 m off bottom. It appears that, if one can visit a given site frequently and maintain persistent coverage, conditions of clear water will emerge in some locations. Where one is near the mouth of a major river, however, poor visibility may be almost continuous. Situations of this sort are most likely to occur in connection with studies of heavily sedimented areas where seafloor deformation may be occurring because of slumping, erosion, or deposition.

Some concern with regard to water clarity has been expressed in connection with seafloor-spreading centers, where tectonic phenomena may be important over the relatively localized regions for which photographic techniques would be useful. While there are dramatic photographs of vents spewing forth 300°C water laden with particulates (RISE Group, 1980), these phenomena are of limited extent. The particulate materials are dispersed over distances of a few meters to tens of meters, and the hot water is mixed with the surrounding cold water such that temperature anomalies are reduced to less than 0.1°C over comparable distances. The existence of quite clear, undistorted photographs in these regions attests to the existence of reasonable optical properties. It appears that, with some improvements in technique, useful measurements could be made over areas a few hundreds of meters across in these regions.

Use of laser-ranging techniques underwater is controlled by the attenuation of light beams as they pass through the water. Beam energy is reduced by a combination of scattering and absorption over relatively short distances even in the clearest ocean water. The *e*-folding decay distance of a beam in the blue-green portion of the spectrum (450 nm) under the best natural conditions is approximately 25 m (Smith and Baker, 1981). Despite this high attenuation it is probable that distances can be accurately measured over paths of many hundreds of meters by pulse methods. It has been found (Smith, 1981) that short pulses of light are attenuated from a beam by scattering and absorption, but that the rise time of the leading edge of the pulse is unaffected and the intensity of the initial part of the pulse can be predicted by simple attenuation at the beam attenuation rate. Since a laser can produce a very short pulse of very high intensity, the leading edge of the pulse should be detectable by a photon counter after propagation through many *e*-folding lengths. Assuming the possibility of detecting 100 photons, existing picosecond lasers should produce detectable signals at ranges of 30–35 *e*-folding lengths. The key element is a suitable low-light-level fast detector. The fastest photon counter is the multiplier phototube using a microchannel plate multiplier. Units are now commercially available (Bender, 1982) and can have rise times of about 100 psec. The rise times of conventional multiplier phototubes are relatively slow because the process of electron multiplication involves sequential cascades of slowly moving electrons. The microchannel plate multipliers are relatively fast because the cascades are shorter than in other multiplier types. Nevertheless they are slow compared with the capabilities of picosecond lasers. Therefore the detector is the limiting element in time sensitivity. With 100-psec rise times the reception of a single pulse should permit measurements to an accuracy of 3 cm to ranges of perhaps 600–800 m in clear water. With statistical pulse-averaging techniques, the ultimate accuracy achievable will depend on the number of pulses averaged and should easily achieve an accuracy of 3 mm. For comparison, the accuracy claimed for a commercial laser-ranging device using an amplitude-modulated continuous-transmission laser is 2 mm at a range of 1 km in air.

The accuracy figure quoted for ranging underwater assumes that the group velocity of light in water is known with perfect accuracy. In fact, existing knowledge is far from accurate enough. The group velocity $c_g = c + k(\mathrm{d}c/\mathrm{d}k)$, where the phase velocity is c and k is the wave number, can be estimated by measurement of the index of refraction $n = c_0/c$ at neighboring vacuum wavelengths λ_0. The relations are $k = 2\pi n/\lambda_0$ and $c_0/c_g = n - \lambda_0\, dn/d\lambda_0$.

Available dispersion data (Stanley, 1971) allow one to estimate the group velocity at a vacuum wavelength of about 567 nm in water of 35 $^0/_{00}$ salinity and as functions of pressure and temperature. Internal consistency of the data suggests an uncertainty of more than 10^{-3}, far less than adequate for geodetic purposes where an uncertainty of 10^{-4} to 10^{-5} is needed. This implies a requirement for a laboratory measurement program. On the other hand, the percent variation of speed of light with pressure, temperature, and salinity are an order of magnitude less than the corresponding quantities for underwater sound. Optical ranging could thus be used effectively over 500+-meter distances to determine changes of path length with time, without need for such demanding environmental survey measurements.

The main problem that needs to be examined before optical methods are used is the magnitude of the beam-attenuation coefficient. Certainly optical methods are unlikely to be useful in shallow water where turbidity is high. But even on the bottom in deep water there are turbid clouds, especially in regions of strong bottom currents and near hot springs. The situation will be similar to that discussed above in relation to photographic systems, although there are no beam-attenuation measurements for such situations.

3.3 MECHANICAL SYSTEMS

This category includes inertial systems and such other mechanical devices as pressure gauges and measuring rods.

3.3.1 Inertial Systems

Although inertial systems have long been used as part of submarine navigation systems, they are not, strictly speaking, directly referenced to the seafloor. Their role is to provide a navigational extrapolation capability, starting with a reference point determined by other means such as seafloor transponders, celestial navigation, or satellite navigation systems. A considerable body of technology has been developed, particularly in support of naval submarine operations. Present-day state of the art is represented by the gas spin gyro technology used in the fleet-ballistic-missile submarine Ships Inertial Navigation Systems (SINS). Higher-accuracy systems using electrostatically suspended gyros are planned for deployment on board *Trident* and *Poseidon* submarines (Hall, 1980). These systems have all been of the stabilized gyrocompass type. With the advent of elements capable of coping with large dynamic range circumstances—electrostatically suspended and laser gyros—there is a trend toward strapdown systems in which the gyro system and associated accelerometers are tracked in their orientation and motion relative to the submarine and the outputs used to compute the orientation of the vehicle and its displacement from some original known point (Hall, 1980; Levinson and San Giovanni, 1980).

While such systems can maintain adequate accuracy for many undersea navigation situations, they are always subject to gradual drift, which eventual-

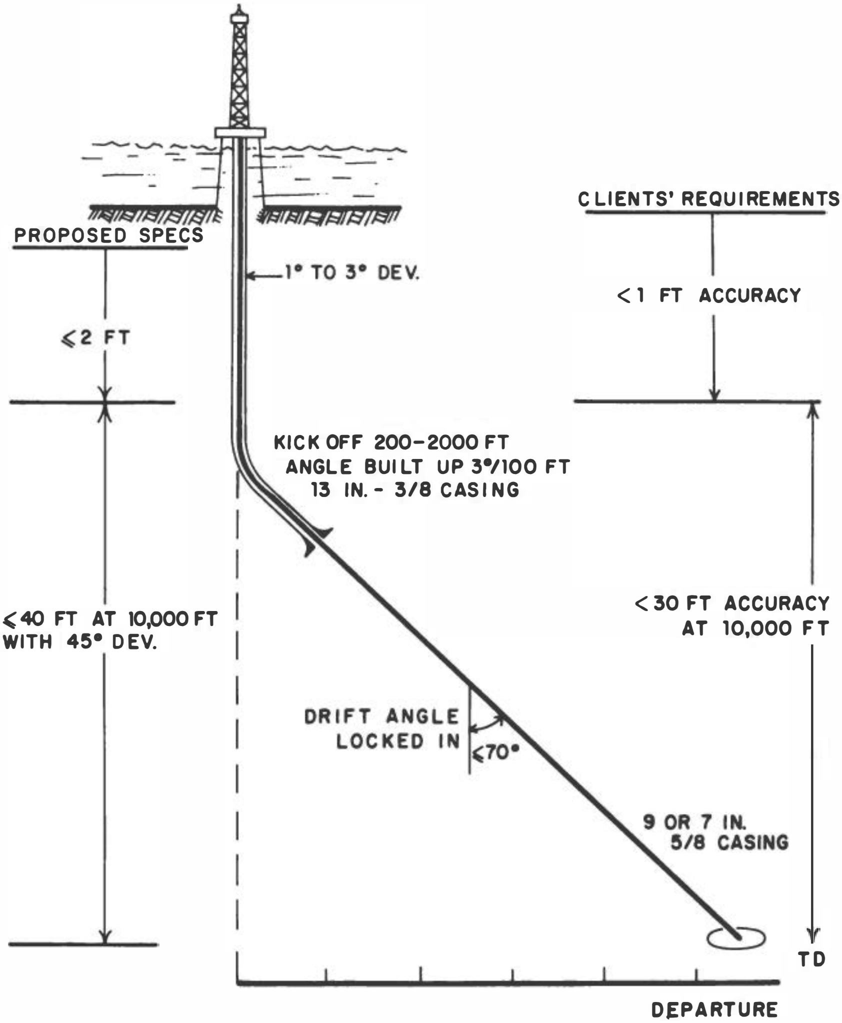

FIGURE 3.4 Schematic of a plan for logging the location of an oil well borehole using an inertial navigation package.

ly builds up to an unacceptable level. Since submarines can remain submerged for periods substantially longer than these degradation times and since it is desirable to keep times between reset as long as possible, there are continuing programs in several corporations and laboratories to reduce drift rates.

These systems are also not well adapted to use in small vehicles (i.e., unmanned, untethered, remotely operated survey platforms) except for very-short-duration missions; thus there are further development requirements in this area, related to reduction of both size and cost.

The one seafloor-related situation in which inertial systems appear to be of importance as the primary positioning system is in determining the trajectory of an oil- or gas-well borehole. In this context small gyroscope systems are being developed (e.g., Sperry-Sun, Schlumberger) to operate down the drill hole, making a continuous log from which the successive points within the well can be plotted. Figure 3.4 shows a typical survey plan for an oil well and indicates many of the design issues. Most significantly, the accuracy requirements are in the 10-m range not the 0.1-m range needed by geodynamics and 3-D seismic applications.

Existing systems are true three-axis gyroscopic platforms, but in very small-diameter housings. Specifications are dependent on logging time that is kept short; they are summarized in Tables 3.1 and 3.2. Major limitations are due to elevated temperatures, shock loads, and high deviations.

Performance values are difficult to obtain directly. Instead, it is usual to measure closure, defined as the estimated change in position, obtained by lowering the platform to the bottom of the well and raising it back to the same point. In a recent test the closures on repeat runs obtained in seven wells showed normal errors of less than 5 m for well depths of 3000 m.

With existing performance capabilities these systems could also be used to track the lowering of an acoustic marker from a ship, documenting its placement to within 5 m relative to a position obtained at the sea surface using the Global Positioning System. The present technology could be easily improved to produce 0.5-m accuracy simply by reducing the temperature requirement to the 0–30°C range of the ocean and by allowing the gyro package to grow in diameter. Beyond this, accuracy of 0.1 m or better appears to require significant changes in technology. This would primarily imply packaging a different type of sensing element. There are several possible candidates with floated gyros, electrostatic sphere, and a laser gyro showing the most promise of an additional order-of-magnitude improvement.

3.3.2 Pressure Gauges

Pressure gauges play a major supporting role in any of the high-precision acoustic systems and to a lesser extent in other situations. Sound speed will

TABLE 3.1 Well-Logging Directional Survey Specifications

Deviation less than 70°
Fast deviation variations <10°/sec
Average deviation variations <10°/100 m
Cable speed <2500 m/h (8000 ft/h)
Sonde acceleration <1 *G*
Shock <3 *G*
Vibrations <1 *G* (1–10 Hz)
Latitude <70° (only if gyro compassing is required)
Accuracy on cable length 3×10^{-4}
Periodic calibration (once per month)
Hole pressure 20,000 psi
Hole temperature <120°C

TABLE 3.2 Well-Logging Directional Survey—Manufacturer Specifications

For a standard hole:
- L = 3000-m depth
- H = 600-m horizontal departure
- Logging time: 3 h
- Vertical error: 2 m
- Horizontal error:
  - East departure: $0.4\% H + 0.06\% L = 4$ m
  - North departure: $0.4\% H + 0.06\% L = 4$ m

change about 1.6 cm/sec per decibar (1-m depth) in isothermal water. If one is to know the sound speed along a particular deep-water path to within 1 part in 10^6, then one must know how the pressure varies because of tidal effects to within a pressure equivalent to 10 cm. The best existing gauge having the range necessary for deep-ocean use and this level of resolution is the quartz crystal type, which can, with proper calibration and less than a second of integration time, meet this requirement.

Under some situations it is possible to work with differential pressure measurements, for example, between an isolated reference chamber and the surrounding seawater (McGehee, 1967). In such cases the dynamic range requirement of full ocean depth (10 cm in 5 km) need not be met, and conventional devices such as strain gauges and Bourdon tubes can be used.

3.3.3 Measuring Rods

The most direct distance-measuring devices are simple measuring sticks or tapes. In general, however, these do not seem to be well matched to the lateral distances over which measurements are required. Considering the maximum practical lengths of mechanical structure that could be applied in this context, the conduct of measurements over distances of several kilometers would require a rather large number of successive observations and substantial undersea manipulation. On the other hand, there are certain advantages to using such devices in the deep sea as opposed to their use on land. For one, the temperature is quite stable and predictable near the deep seafloor. The second advantage arises because of the buoyant effects of seawater. This would make it possible to assemble quite large structures having good dimensional stability and that could easily be moved about, albeit rather deliberately, simply by making them neutrally buoyant, thus eliminating sagging and other distorting effects of one member on the other. The most substantial difficulty is raised by the interaction of any large fixed structure with the motion of the water. Even at the deep-ocean floor one usually finds currents of as much as 10 cm/sec, which would cause deflections that would be noticeable at the 1-cm level unless fairly rigid elements are used. While these aspects have a challenging appeal, the existence of acoustic and potential optical distance-measuring methods that could provide adequate results over distances that would require substantial structures to span seems to tilt consideration away from approaches of this type.

3.3.4 Sound-Velocity Meters

The sound-velocity meter is, in a real sense, a mechanical/acoustic measuring rod—a well-defined physical length—with associated acoustic transducers arranged so that the wavelength of sound of a known frequency, or the travel time of a pulse, in the surrounding water can be compared with that known length. The primary skill in its construction and operation is in maintaining the effective acoustic path length constant (or with known variation) to the desired accuracy, without requiring an unduly large physical structure. In the laboratory this has been achieved to about 1 part in 10^6 (Greenspan, 1972). Commercially available instruments for use at sea typically are good to about 1 part in 10^4. A seagoing instrument designed to achieve 1 part in 10^5 has been built but not as yet tested (Fisher, 1982). A velocity meter of that caliber is required if one is to achieve 10-cm accuracy over a 10-km range and would make possible the measurement of strain buildup (a few centimeters per year over a few kilometers) at intermediate or fast-spreading centers on reasonable time scales.

3.4 ELECTROMAGNETIC SYSTEMS

Systems relying on radio, radar, or optical-frequency electromagnetic propagation from fixed sites or satellites have been treated in detail by many authors because of their importance in surface and air navigation and land geodetic applications (Committee on Geodesy/Committee on Seismology, 1981). Since those that can achieve accuracy in the range of 10 m or better cannot penetrate into the sea to any useful extent, they are not able, as completely independent systems, to solve ocean-bottom positioning problems in any of the contexts discussed in Chapters 1 and 2. On the other hand, they are the only ones available, considering the range limitations on the underwater acoustic systems (Section 3.1), to provide the possibility of linking together bottom-referenced systems over usefully long ranges (> 100 km).

Electronic positioning depends on an accurate measurement of time or phase of a radio signal from a transmitter to a receiver. For the measurement to be directly related to distance only the ground or direct wave can be used for accurate positioning.

Today there are available electronic navigation and positioning systems that operate at frequencies of 10 kHz to 10 GHz. Generally, the position accuracy achievable with a system is related to its operating frequency; the higher the frequency, the greater the accuracy. The useful range is generally inversely related to the system's operating frequency.

The systems are classified by the geometry of the lines of position generated by each system's transmitters. These classifications are hyperbolic, elliptical, circular (or ranging), azimuthal, and composite. Of these systems, hyperbolic and circular are used extensively for offshore exploration and hydrographic surveys. Because of the divergence of the lines of position of hyperbolic systems with distance from the baselines of the shore stations, circular systems are inherently more accurate and are preferred for accurate marine survey positioning.

The absolute positional accuracies and the effective ranges of radio positioning systems are usually quoted by the system manufacturer in terms of the measurement resolution of the equipment and a standard or modified atmosphere along an all-sea transmission path. Experience with the shorter-range systems where there are benchmarks in the sea, such as oil field platforms, and long-range systems where correlation with bathymetric and seismic data allow determination of accuracy, indicates the following practical positional accuracy and range for today's ranging systems:

1. Microwave systems: range to 50 km, accuracy 2 to 10 m.
2. Very-high-frequency (VHF) systems: range to 200 km, accuracy 10 to 50 m.
3. Medium-frequency systems: range to 400 km, accuracy 10 to 30 m.
4. Low-frequency systems: range to 1000 km, accuracy 50 to 300 m.

The anomaly in the accuracy of the VHF systems is due to the transmission mode of these systems. To achieve the extended range, these systems rely on ducting, an atmospheric phenomenon that is not stable.

The two positioning systems that provide global coverage are the TRANSIT satellite system and Omega. The Omega system has an accuracy of 4 to 9 km and hence cannot be classed as an accurate positioning system. To obtain the potential accuracy of a point position fix from the TRANSIT system on a moving platform requires a precise knowledge of the platform's velocity. Determining platform velocity by terrestrial radio navigation, Doppler sonar, or acoustic transponders will result in a possible fix accuracy of 30 to 150 m.

The GPS now under development will probably supplant most of the other systems for navigational purposes whenever long ranges are required (Milliken and Zoller, 1978). As with the other systems it will only produce results for receiving points that are at the sea surface or above it. With access to the P-code,* a 4- or 5-channel receiver, and an 18-satellite constellation, the probable error of the GPS system in the point positioning mode, at 50 percent confidence level, is predicted to be 10 m (circular error) for horizontal position and 16 m (spherical error) for three-dimensional position.

A variety of studies have been carried out to determine what reductions in the above uncertainties could be achieved for fixed receivers operated to optimize their performance in a geodetic context. Averaging is the most obvious first step. One analysis (Fell, 1980), using 6-sec ranges smoothed over 300 sec and then averaged for 24 h, shifting satellites during that time to maintain optimum coverage (1 h per satellite), led to geodetic coordinate accuracies of 85–125 cm. Primary source of error was satellite ephemeris data. As a second step, use of simultaneous observations at two points up to 300 km apart and similar averaging led to baseline length uncertainties of 10–17 cm, dropping to 4–7 cm with a 5-day average. The advantage of this approach was that each satellite was used simultaneously at both stations; thus the influence of ephemeris errors was substantially reduced.

The third approach uses a different philosophy—the satellites are treated as if they were the radio stars used in the very-long-baseline interferometry (VLBI) approach but providing stronger signals. In this case knowledge of the P-code is not, in principle, required; however, if it is used, it provides an effective signal-to-noise ratio improvement. A number of receiving systems are being developed for use in this interferometer mode (e.g., Counselman, 1982b;

*P-code is a pseudo-random-noise (PRN) modulation applied to one of the carrier frequencies transmitted from the satellite. It is a binary sequence in which the PRN generator produces a 0 or 1 on a randomized basis at a 10.23 megabit per second rate. The PRN generator repeats approximately every 38 weeks, although it may be reset more often. Its purpose is to enhance signal-to-noise ratio and time measurement by broadening the signal bandwidth. Coherent use of this advantage requires that the receiving system have a comparable PRN unit using the same code-generation algorithm as the transmitter (Fell, 1980).

MacDoran *et al.*, 1982; Ward, 1982). One that utilizes full knowledge of the P-code and operates with a nearly omnidirectional antenna is being developed under joint support from the Defense Mapping Agency, the National Geodetic Survey, and the U.S. Geological Survey. Measurement times as short as 20 msec per satellite seem feasible (Ward, 1982) so that, with a multiplexing receiver, each of the necessary four satellites can be observed every 80 msec. Multiplexing is preferable to multiple parallel channels since small variations in properties from one receiver to another do not enter the problem.

In the interferometer mode an accuracy of about 1 cm over short baselines (100 m or less) has been demonstrated for stationary receivers (Counselman *et al.*, 1982; Greenspan *et al.*, 1982). For longer baselines the effects of the GPS satellite orbit uncertainties and the uncertainties in the tropospheric propagation correction due to water vapor in the atmosphere also have to be considered (Committee on Geodesy/Committee on Seismology, 1981). The uncertainty of a 1000-km baseline is expected to be about 10 cm owing to assumed uncertainties of 2 m in the horizontal coordinates of the GPS satellites. However, much lower GPS satellite orbit uncertainties are likely when accurate tracking data are available from a well-distributed set of fixed ground stations (Larden and Bender, 1982). The horizontal position uncertainty typically will be about 5 cm for baseline lengths of more than a few tens of kilometers if only surface meteorological measurements are used to estimate the tropospheric propagation correction.

The above discussion relates to fixed receivers. On the sea surface it is quite feasible to maintain an observation station for a more or less indefinite period in one place within a hundred meters. This can be done with dynamic positioning (Deep Sea Drilling Program, 1971) or a three-point mooring (Bronson, 1975). This opens up the possibilities of averaging and interferometry if the receiving system can cope with the short-term motions of the antenna. Advent of interferometer capabilities using nearly omnidirectional antennas eliminates any severe antenna pointing requirement. Given the further existence of observation points every 80 msec, the prospects for being able to follow the distance changes associated with wave-driven motions (characteristic periods of 5 to 20 sec) appear to be good. Such tracking can be aided by auxiliary measurements (e.g., accelerometers), and the motions themselves can be minimized by use of large ships or stable platforms (Spiess, 1968). This is an aspect of GPS utilization that needs further investigation through simulation and actual at-sea testing.

One further useful attribute of GPS is its ability to provide velocity information. With a proper receiver (e.g., Ward, 1982) an accuracy of 0.1 m/sec should be available, although again it may be necessary to bring in auxiliary measurements to compensate for wave-induced motions that can easily be ten times as large. While 0.1 m/sec does not meet the full requirement noted in Section 2.1.4 it will clearly improve the conduct of large-area surveys in the open ocean.

3.5 GEOLOGIC PHENOMENA

Geologic phenomena can be used for navigation in a map-matching mode, where the particular field has been carefully mapped initially against some other, possibly temporary, position reference system. Four different types of data can be used: bottom topography, bottom roughness patterns, magnetic field, and gravity field. The relative usefulness of the four depends on the ease with which the properties involved can be measured and the gradients that they are likely to have. The gradients are significant because positioning accuracy will be determined by the existence of irregularities in the parameter being matched (Beisner, 1969).

Given the fact that the principal short-wavelength variations in observed gravity arise from the local topography, and that gravity is a difficult parameter to measure from anything but a fixed on-bottom instrument (because of uncertainties in vehicle velocity and perturbing accelerations), this is the least likely method to see practical application.

Magnetic measurements are easy to make, and the total magnetic field, if observed close to the seafloor, often has quite large gradients in relation to measurement resolution. Unfortunately, however, it is not feasible to map the field except on a line-by-line basis, and thus, lines must be either very closely spaced or interpretive contouring must be used, which can lead to navigational inadequacy, particularly if the vehicle is on a course at a considerable angle to the pattern of survey lines. A second problem arises because the magnitudes of the irregularities die off as one moves up from the seafloor. If one does a spatial Fourier analysis of the field on some plane just above the seafloor, any sinusoidal component will die off exponentially in relation to its wave number as one goes up from that plane. As a result, the achievable navigational accuracy decreases with height off bottom. Third, there will occasionally be magnetic storms whose resultant is superposed on the geologically related field, so that there can be temporal effects on the survey magnetometer mixed with spatial variation. Finally, there is the practical fact that iron and steel are useful materials for building vehicles, but their presence requires that the actual sensing element be towed some distance away or that its performance be carefully calibrated on a variety of headings. With care both in the initial surveys and in the navigational process one should often be able to achieve 100-m accuracy (Tyren, 1981).

Bottom topography has been used for navigation by seagoing people for a very long time. With the introduction early in this century of acoustic echo sounders this became a well-known approach (Cohen, 1964), particularly in shallower coastal waters. In deep water the resolution with which the seafloor can be mapped decreases, not because of the physics of the field being mapped but because of the engineering of the acoustic systems. The angular width of the sounding beam is set by the dimensions of the transducer and the wavelength of the sound used. A typical system may have a 30° beam, which means that its footprint on the seafloor will be a few kilometers across (about half the water depth), and thus the lateral resolution is quite poor. Once one moves to narrow-beam sounders, one must either be far enough below the surface that the vehicle does not feel the irregular motion of the surface waves or the beam must be stabilized. This is done either mechanically or electronically. The most effective surface ship systems have a fan of narrow, multiple athwartship beams that can map a swath of width comparable with the water depth, giving from 20 to 50 points across the track for each output sound pulse. In a well-surveyed area having typical relief, one can achieve navigational accuracies of the order of 100 m with a narrow-beam sounder (1°–3° beam). Somewhat better accuracy can be achieved over well-mapped tops of seamounts.

The fourth geologic aspect of the seafloor that can be used for navigation is the variability of its roughness or, more properly, its acoustic backscattering properties (combination of slope and roughness), as observed with side-looking sonar (SLS). Except for one existing system powerful enough to be operated from near the surface (Searle, 1979) and having a rather coarse resolution, all other effective side-looking sonars are operated within a few tens to hundreds of meters off the seafloor. The images that they produce often are capable of being matched to within 10 m (Lowenstein, 1970). The principal difficulty with this approach is that the SLS image, because it involves a mix of bottom roughness and small-scale topography, will depend on both the inherent character of the seafloor and on the direction from which it is viewed. This means that, to some extent, the user must be skilled in the interpretation of this type of data.

Scanning sonars can also be used in this context. An example of this occurred in recent investigations of hydrothermal fields at the East Pacific Rise spreading center in the Guaymas Basin of the Gulf of California. Here a side-looking sonar survey was made in 1980, and the small submersible, *Alvin*, was able to return to these features expeditiously in 1982 by use of its scanning sonar (Lonsdale, 1982). In this case the seafloor features were small spires and the resulting navigational accuracy was of the order of a few meters.

In general these techniques involve matching of patterns, but in simple regions they may merely provide a line of position. Under such circumstances it may be possible to use two phenomena, most obviously topography and magnetics (Spiess, 1974), where their respective contour lines intersect at an adequate angle.

Overall, one can conclude that these map-matching methods will be useful under specialized circumstances in which local on-bottom man-made markers (active or passive) are for some reason not available. They can be particularly useful in establishing the relationship between two transponder nets that may have been used at different times (Hess *et al.*, 1980). In such cases one may even use sets of seafloor photographs when the vehicles involved have that capability.

4 Systems versus Requirements

In order to meet the most demanding of the navigational and geodetic requirements discussed in Chapter 2, it is necessary to assemble complete systems in which two or more of the generic approaches discussed in Chapter 3 are used. In many instances a single approach (acoustic transponders) will play the major role, but even then the primary acoustic data must be supplemented by auxiliary measurements or techniques (e.g., sound velocity and pressure).

Appropriate systems have been devised to meet the needs for ocean-bottom referenced navigation with few meters' accuracy over areas measured in tens of kilometers and times of the order of years. On the other hand, the more stringent requirements summarized in Chapter 2 have not been met to the extent of full operational system tests at sea in spite of the existence of physical understanding and technological potential. In this chapter hypothetical systems to meet the needs of the several major problems will be assembled on paper and their strengths and weaknesses examined. The five cases to be covered are those listed in Table 1.1.

4.1 3-D SEISMIC SURVEY

This problem can be handled using acoustic transponder techniques as the primary tool. Location of the survey area in global coordinates is only required to within 100 m, and this can be achieved with today's satellite navigation of the survey ship, presuming that it is simultaneously located relative to the transponder net. Signals to trigger the transponders would be sent from the sound source at the time of every shot and on a similar interval from at least one point on the receiver hydrophone streamer. The resulting replies would be received at several points in the receiving array, including the points of origin of the interrogation signals. With this arrangement the travel times for an adequate number of points to define shot and receiver locations can be obtained. Transponders will have to be of a new type, capable of having a recognition time that is reproducible to within 10^{-4} sec. Sound velocity will probably have to be measured on station, although it may not be necessary to have accuracy of better than 1 part in 10^4 (10 cm in 1 km) since the signals to be combined coherently will only be over an approximately 1-km span, even though the total area may be 10 km or more across. Since these surveys will generally be carried out in less than 1-km water depth, multiple reflections of the acoustic navigation signals can be a problem; however, use of a large number of independent transponder channels can minimize this by assuring that short-range direct-path operation is used. By the time the survey is completed, a large enough number of multiple transponder fix points should be available to provide for calculation of transponder array geometry to match the accuracy requirements.

4.2 MISSILE-FIRING EVALUATION

This mission is currently being carried out by use of acoustic transponder fields and acoustic location systems at both ends of the trajectory for firings from submarines. Location over long ranges is met currently by relating near-surface points determined in the water by transponder and in air by satellite navigation. At present the 10-m accuracy is not met, but it should be feasible with the Global Positioning System (GPS). As one presses for 10-m accuracy in location of a surface craft relative to a deep-seafloor transponder net, a major problem is the determination of the corrections due to refraction and the effective sound velocity through the entire water column. Accuracies of 10 m can currently be achieved, however, if reasonable care is taken in determining the sound-speed profile from top to bottom and calculations are made that take its variability into account.

4.3 RADIOACTIVE WASTE DISPOSAL

The basic requirements for accuracy and area coverage can be met by today's conventional deep-sea systems. Existing operational procedures for replacement of transponders to keep a field alive indefinitely have been developed and used as well.

The principal difficulty here is that it may not always be feasible to return to the disposal sites in a timely manner to replace the active units. This implies that there should be a passive backup system that would have a lifetime of at least thousands of years. The procedure would then be to put down a new transponder net and survey to locate the passive markers relative to it and thus re-establish by map matching the original coordinate system in which the disposal canisters' positions are known.

Four options obviously present themselves: geologic features or man-made assemblages involving optical, acoustic, or magnetic sensing. The principal problem that one must anticipate is the possibility of burial of the marking materials in sediment, either by the normal slow rain from above or by a "turbidity current"—near-bottom mud flow—that might originate far away. This implies that whatever is used it must either be quite large (tens of meters in all dimensions) or be such that it can be viewed in spite of modest sediment cover.

If there are substantial rock outcrops, or small hills with superposed fine-scale relief, or even slightly buried distinctive features, these would suffice. Unfortunately, the requirements usually given for appropriate waste-disposal areas (Hollister *et al.*, 1981) imply a uniform kind of terrain, although a near-bottom survey in the vicinity of one favored mid-North Pacific site being intensively investigated for this purpose does show a nearby hill with steep scarps on some of its slopes that might serve as a base for re-establishing a transponder network.

Any approach using optical viewing (photography, closed circuit TV, or direct observation from submersibles) must involve a large enough object or set of objects that a layer of sediment a meter or so thick would not obscure one's ability to recognize it. This implies primarily that some part of each marker should be quite steep sided and that it should have substantial relief relative to a meter.

Acoustic markers must be similarly large and distinctive enough in shape to be differentiated from any complex geologic reflectors. Here there is a useful tradeoff, however, since if geologic reflectors of a discrete nature are present then the acoustic marker would not be required in the first place. Structures 2 or 3 m in all dimensions would be adequate for detection by near-bottom sonars, particularly if several were placed in a known pattern. Objects substantially larger would have to be used if location with near-surface sonars were desirable.

Magnetic phenomena could be used in the form of either permanent magnets or a large structure built of ferromagnetic materials. Objects of this kind have an intrinsic appeal, since they can be detected without appreciable degradation through a thin overlying sediment layer. Permanent magnets detectable at 10-m range represent a reasonable combination of materials and detection devices. An order-of-magnitude larger range would be difficult to achieve. An array of such elements could form a set of lines of known orientation and sufficient horizontal extent to provide both a good target and easily used position information.

The approach of using a large iron structure, however, suggests a method that is both easily implemented and cost-effective (relative to transportation and burial costs for the radioactive material itself)—this is to tow an old iron ship to the disposal area and scuttle it on site. Judging by the instance in which this was done with the SS *Briggs* in 5000 m of water in the Atlantic, the ship should retain its structural integrity during the sinking process. Given the fact that the near-bottom water has only modest oxygen content, oxidation of the steel should take place quite slowly.

Such an object would provide a useful acoustic, optical, or magnetic target and have large enough horizontal dimensions to make it effective on a map-matching basis to relate a new bottom-referenced navigation system to the original acoustic transponders to within 10 m. Since a ship of this kind will have substantial hold spaces, these can be used to pour in a cargo of properly mixed and cured concrete, or even of natural rock, to assure that when the iron structure eventually does disintegrate a distinctive pattern of acoustically and optically observable material will remain.

4.4 GEODYNAMICS—SPREADING CENTERS OR SLUMP ZONES

Strain buildup in spreading centers or slump zones presents a local geodetic problem that can be solved with acoustic transponders and appropriate auxiliary pressure and sound-velocity measuring equipment. Given the small-scale rough nature of the seafloor in the spreading-center regions this can best be approached by putting in the markers and surveying them repeatedly with a near-bottom operating instrument package (an undersea acoustic analog of the proposed Airborne Laser Ranging System—Degnan, 1981). This approach provides a large statistical base, using observations over a large number of acoustic paths so that local sound-velocity anomalies can be either isolated, if they are extreme, or averaged out if they are small. Simultaneous sound-velocity surveys to the level of 1 part in 10^5 will also be required, since hydrothermal activity, whether concentrated or diffuse, can produce changes in the mean value of sound speed that might be mistaken for changes in dimensions of the array of reference markers. Such a system is described by Spiess (1980).

While in the gross sense this type of acoustic system, using precision transponders, can cope with the problem, it is desirable in both the spreading center and slump development contexts to be able to document small-scale details of the pattern of strain accumulation. However, research budgets would be taxed to provide a large enough number of active acoustic units for this purpose. This leads to pressure to develop a complementary laser-ranging or photographic system that would employ much less expensive optical reflectors in considerable numbers in portions of the area that might be of particular interest. The vehicle that would be used to resurvey the larger-scale transponder network at regular intervals, or following an episode of seismic activity that could be detected by other auxiliary instruments, could be equipped to make the photographic observations as well, since its position and motion will be quite accurately known.

Installation of both acoustic and optical markers can be carried out from small submersibles, such as *Alvin*. On the other hand, considerably less operating cost would be incurred if an unmanned machine operating on the end of a conducting wire were built for this purpose. Such a seafloor-supported work vehicle would also be the platform for mounting a laser-ranging transmit-receive unit to complement the multiplicity of fixed, on-bottom retroreflectors. Techniques for securing the units (transponders or reflectors) to the seafloor can be adapted from those already developed for drilling holes and grouting objects to seafloor rock in shallow water.

4.5 GEODYNAMICS–INTERPLATE MOTION AND INTRAPLATE DEFORMATION

Just as in the missile-firing evaluation problem, the long ranges involved dictate the use of electromagnetic/satellite or radio-astronomical systems for the major length determination, with acoustic markers on the seafloor and some means for interconnecting the two systems. In this case, however, the 10-cm accuracy requirement makes every step of the problem much more difficult. Two aspects, however, help to ease the situation somewhat: (1) the surface platforms at the two ends can be positioned relative to the seafloor markers in optimum rather than random fashion, and (2) the positional observations can be repeated many times, thus giving some gain through averaging.

For the long-range component, the best approach appears to be through using signals from GPS satellites. This should preserve the 10-cm goal (perhaps even approaching 1 cm–Counselman, 1982a) over the 1000-km range.

The problem of relating points on the deep seafloor to others close to the sea surface with 10-cm accuracy is one for which there is not an immediately available solution. Three options were considered. The first would be to build on the developing technology of inertial systems (see Section 3.3). With this approach a package could be lowered from the near-surface vehicle down into the vicinity of the seafloor transponder net and the position difference established in the same manner as these units might be used to determine the end of a borehole. Requirements on the inertial package would be substantially less demanding than in the borehole tracking application—temperature range would be much less, size constraints could be relaxed, and problems of impact with borehole walls would not exist.

The second approach would be to use underwater acoustic transponders on the bottom to link the surface observation location to a seafloor reference point using a conventional travel-time measurement approach. The slant ranges would be reasonable, about 7 km; thus, timing to within the necessary resolution would be feasible. The real problem is that of knowing the sound-velocity profile from sea surface to bottom with adequate accuracy to be able to convert the travel-time measurements into actual physical ranges. The deep part of the profile (below about 1 km) presents a tractable sound-velocity measuring problem, since its characteristics change quite slowly. The upper part, however, if there is strong internal wave activity, can be expected to contribute to appreciable variations (relative to the desired 1 part in 10^5 accuracy in the effective sound speed over the entire path) in times that could be less than an hour. While methods used in some studies of internal waves (Pinkel, 1975) could be used to make the necessary upper-layer corrections, this would clearly introduce appreciable measurement complexity. In any event this would again give rise to the need for a good sound-velocity measuring device (1 part in 10^5) and for knowledge of its depth to 10 cm.

The third, and most attractive, approach would also use underwater acoustics, but would work in the time-difference measuring mode, rather than using direct travel-time measurement as discussed in the previous paragraph. Systems of this type can take one of two basic forms—a single transponder on the seafloor, with a set of receiving hydrophones on or near the ship to be tracked, or the inverse, with a single transmitter-receiver on the ship and a set of transponders fixed to the seafloor, with the travel-time differences for the various transponder pairs used as the primary data. In either case, if one is nearly directly over, or under, the center of the transponder group or receiving array, one's sensitivity to environmental parameters is substantially reduced.

The type of system in which the receiving elements are located on the ship (short-baseline system—Section 3.1) has been used in a number of contexts. Unfortunately, in order to achieve subdecimeter accuracy in deep water, the arrival angle of the sound relative to the vertical must be measured to 0.01 mrad. With a 20-m baseline this implies resolving acoustic path-length differences of about 0.2 mm or travel-time measurements of approximately 0.2 μsec as well as quite precise knowledge of the vertical. Given that the sound absorption over expected path lengths will limit one to frequencies below about 50 kHz, and ship motion will complicate any averaging process, it does not appear that short-baseline systems can be effective in this context.

The alternative in which the hydrophones are on the seafloor and the point to be tracked is on the ship, however, offers the possibility of working with much larger array dimensions than could be held rigidly together at the sea surface. This approach, using time-difference measurements among the various pairs of seafloor units has not been tried at sea and would be a practical means for implementing the phase-difference measuring approach proposed by Bender (Committee on Geodesy/Committee on Seismology, 1981) but using transponders to eliminate the effects of currents and the need for maintaining a common time base at pairs of points separated by several kilometers. The simplest configuration to consider is a square, in which one would measure the travel-time differences for two approximately orthogonal pairs of hydrophones. It should be feasible to hold an appropriate ship (e.g., one with good on-station maneuvering capability such as *Knorr*, *Melville*, or *Glomar Challenger*) for a prolonged period or moor a buoy (e.g., *Flip*) within 100 m of the point at which the travel-time differences for the two pairs are both zero and to use the time differences to establish the location of the ship's reference hydrophone to within 1-10 cm.

The choice of baseline lengths is driven toward large distances by the fact that the time-difference measurement requirement is eased as the baseline grows. On the other hand, the inherent environmental limit to this approach lies in the horizontal variations in sound-velocity profile, and this risk is minimized by use of as short a baseline as possible. A reasonable compromise is to use a length about twice the water depth. This gives centimeter accuracy in the local coordinates near the center of the net if time differences are good to 10 μsec and presuming that the effective sound speeds on the several paths are the same within a part in 10^5. In most deep areas this will be a good assumption because the path geometry is favorable. In the deep part of the water column the paths are separated by kilometers but the water is quite uniform in any horizontal plane. Near the surface, where the presence of internal waves in association with the vertical variations in temperature lead to appreciable horizontal gradients of sound speed, the paths are quite close together, thus minimizing inequalities between the several paths. During any series of position determinations the near-surface temperature profile should be measured repeatedly to allow selection of observation times in which the horizontal gradients are minimal, as inferred from the related vertical motions of the temperature structure.

The actual sound speed, baseline lengths, and transponder depths all enter as linear factors relating the travel-time differences to the horizontal displacement of the observation point from a spot directly over the acoustic center of the seafloor array. Thus, if one is within 100 m of the center, one can achieve centimeter accuracy with knowledge of these parameters to 1 part in 10^4. These geometric control requirements can be achieved in most open-ocean areas on the basis of a careful survey using the same approach as in the local geodetic case treated above and with enough of a time series of on-bottom pressure measurements to allow prediction of the tides to within about 20 percent.

It should be noted that in the above discussion the individual measurement criteria are pointed at 1-cm accuracy, even though 10 cm would be quite useful. The reason is that there are quite a few such quantities to be measured and each will make its own independent contribution, thus trying to hold each to 1 cm should result in an overall system achieving about a 5-cm goal.

This approach will require measurement of the sound-velocity profile locally and appears to provide, potentially, the appropriate means for solving the problem of tying surface reference points to the seafloor. It may be that in many areas, once we have more experience with detailed repeated measurements of the sound-velocity profile, one can fall back on the simpler direct use of the individual travel times and thus relax the position-keeping restrictions on the surface platform to a kilometer or so, which would allow use of any research ship or of single-point moored buoys rather than the tight three-point moorings or good on-station maneuverability that the 100-m radius of action implies.

4.6 GENERAL CONSIDERATIONS

In connection with each of the above systems it will be necessary to develop and apply appropriate algorithms and related software in order to obtain the desired navigational positions and the locations of reference points. While in most instances some advantage can be taken of pre-existing computer programs (particularly for acoustic transponder navigation and baseline-length determinations based on very-long-baseline interferometry or the GPS), neverthelsss, the overall data processing will in each case involve elements not previously implemented. This will be particularly true for aspects that involve appreciable sound-velocity variation along the ray path.

In most land geodetic situations it is possible to delay carrying out full data reduction until the survey group has returned to its base. While in principle this could be done for seagoing operations as well, it is desirable to carry out as much of the computational work as possible while the party is still on site. This allows a critical evaluation of the data while there is still time to reoccupy stations to check any equipment or environmental questions that might arise.

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Appendix A: Attendees at Meetings of the Panel on Ocean Bottom Positioning

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J. William Grady, Del Norte Technology, Inc., Bethesda, Maryland
Earl E. Hays, Woods Hole Oceanographic Institution
P. S. Montgomery, Ametek, El Cajon, California
Hyman Orlin, National Research Council
Donald W. Perkins, Marine Board, National Research Council
Robert P. Porter, Nippon Schlumberger, Tokyo, Japan
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Robert Rowland, U.S. Geological Survey
Phil Schwimmer, Defense Mapping Agency
Fred N. Spiess, Scripps Institution of Oceanography
Sam Stein, Sonatech, Inc., Goleta, California
Patrick J. Taylor, National Aeronautics and Space Administration