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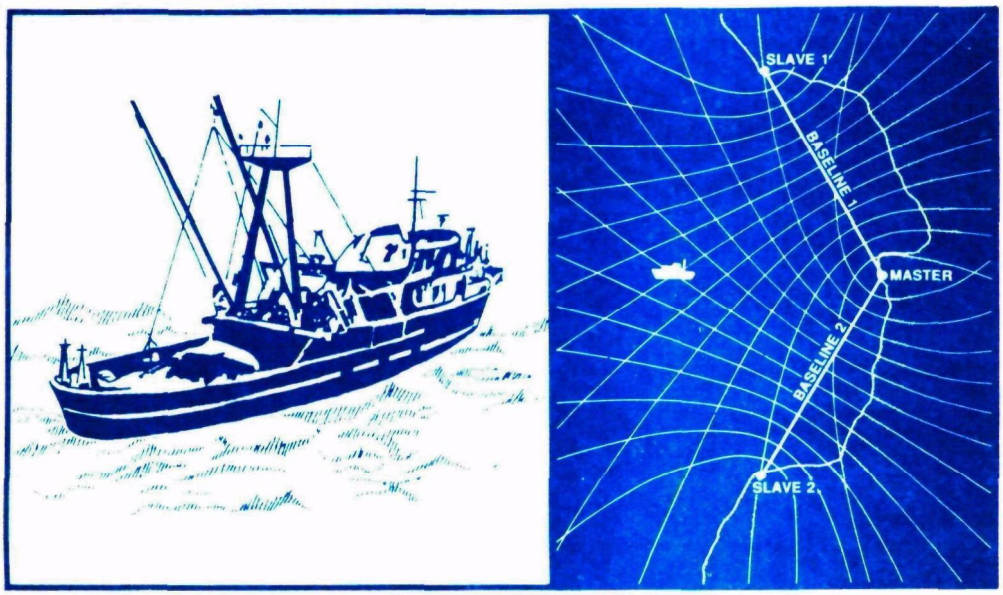
Evaluation of Survey Positioning Methods for Nearshore Marine and Estuarine Waters



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Final Report

EVALUATION OF SURVEY POSITIONING METHODS FOR NEARSHORE MARINE AND ESTUARINE WATERS

for

Marine Operations Division
Office of Marine and Estuarine Protection
U.S. Environmental Protection Agency
Washington, DC 20460

March, 1987

by

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PREFACE

This manual has been prepared by EPA's Marine Operations Division, Office of Marine and Estuarine Protection in direct response to the request from EPA Regional Offices and coastal municipalities with sewage treatment plants discharging into estuarine and marine coastal waters. The members of the 301(h) Task Force of EPA, which includes representatives for the EPA Regions I, II, III, IV, IX and X, the Office of Research and Development, and the Office of Water, are to be commended for their vital role in the development of this guidance by the technical support contractor, Tetra Tech, Inc. Under regulations implementing Section 301(h) of the Clean Water Act, municipalities are required to conduct monitoring programs to evaluate the impact of their discharge on marine biota, to demonstrate compliance with applicable water quality standards, and to measure toxic substances in the discharge. This document provides essential information for the evaluation of operating characteristics (e.g., accuracy, precision, reliability) and system costs of station positioning equipment. Four main types of navigational instruments are considered in this document: optical techniques, electro-optical methods, electronic microwave systems, and satellite positioning equipment.

Positioning for 301(h) monitoring programs is discussed along with the various advantages and disadvantages of each type of positioning system. A system selection procedure is also outlined to enable the designation of an appropriate positioning method to meet the needs of a given monitoring program. Further, methods are suggested to enhance system operational characteristics to minimize positional errors.

The information provided herein will be useful to U.S. EPA monitoring program reviewers, permit writers, permittees, and organizations involved in the design, implementation and review of nearshore monitoring studies. Selection of appropriate station positioning methods from the wide range of

available techniques is an important consideration of all monitoring programs, therefore the guidance developed herein should have broad applicability in the design of marine and estuarine monitoring programs.

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ACKNOWLEDGMENTS

This document has been reviewed by the 301(h) Task Force of the Environmental Protection Agency, which includes representatives from the Water Management Divisions of U.S. EPA Regions I, II, III, IV, IX, and X; the Office of Research and Development - Environmental Research Laboratory - Narragansett (located in Narragansett, RI and Newport, OR); and the Marine Operations Division in the Office of Marine and Estuarine Protection, Office of Water.

This technical guidance document was prepared by Tetra Tech, Inc. for the U.S. Environmental Protection Agency (Marine Operations Division, Office of Marine and Estuarine Protection, Office of Water) under the 301(h) post-decision technical support contract No. 68-01-6938, Allison J. Duryee, Project Officer. This report was prepared under the direction of Dr. Thomas C. Ginn, Project Manager. The primary author was Dr. William P. Muellenhoff. Ms. Theresa M. Wood performed technical editing and supervised report production.

Mention of trade names or commercial products herein does not constitute endorsement for use by U.S. EPA or Tetra Tech, Inc.

1. INTRODUCTION

REPORT PURPOSE

The purpose of this report is to provide information to assist U.S. Environmental Protection Agency (EPA) reviewers of 301(h) monitoring programs, permit writers, permit applicants, and permittees in the process of selection and review of survey positioning techniques which will be used to locate sampling stations in nearshore marine and estuarine 301(h) monitoring programs. It is designed to be a reference document for quickly identifying candidate navigational systems to use in particular situations, based on their operating characteristics and cost. Descriptions and assessments of available locational techniques and equipment, and assistance for minimizing locational error are provided. As such, it complements two other 301(h) program guidance documents that address monitoring program variables, station siting, sampling procedures, sampling equipment, sampling frequency, sample handling, analytical methods, data analysis, and reporting procedures (Tetra Tech 1982a,b).

ORGANIZATION AND USE

The report is arranged to enable users with different levels of familiarity with navigational equipment to access information in the detail needed, and to then proceed through the in-depth selection of one or more systems that will satisfy a particular application. Following a brief summary of available navigational techniques in the next part of the Introduction, Section 2 addresses navigational requirements for monitoring programs conducted near coastal outfalls. Typical discharger locations are discussed along with zone of initial dilution boundaries, types of monitoring stations usually specified, and recommended accuracy limits for positioning at such stations. Section 3 is an overview of available systems, including categories of equipment, typical ranges, advantages and disadvantages, and expected accuracies. A system selection procedure is outlined in Section 4, which includes defining positional requirements, selecting screening criteria,

reviewing candidate systems, and finally selecting a best system for a particular need. Also, the options of renting or leasing systems and daily costs are discussed. Recommended procedures and equipment are presented in Section 5, with a quick reference chart indicating those systems most applicable in coastal areas. The most effective shallow water navigational techniques that are available are also discussed.

Details regarding positioning errors have been appended, along with the design and performance characteristics of representative systems. This enables interested readers to access this material without unnecessarily burdening others not requiring such information. Refer to the Table of Contents Appendix B listing for the particular details of each system considered.

Readers should be alert for advancements in navigational techniques that may have occurred since publication of this document. In particular, users should monitor the development of sufficiently accurate systems that are expected to become available in the near future at reasonable costs (e.g., satellite systems). Manufacturers cited herein, other manufacturers, and government agencies (e.g., the U.S. Coast Guard and the National Ocean Survey) can provide permit writers and monitoring program designers with the most current information on available systems. The 1985 prices quoted herein are for minimum systems that allow range-azimuth, range-range, or hyperbolic positioning. They do not typically include the costs of optional equipment for data processing, position plotting, or guidance control. Where ancilliary equipment is needed, or deemed highly desirable in the future, its availability should be considered in final selection of a system.

Although a number of manufacturers, trade names, and commercial products are cited in this report, their inclusion does not signify endorsement or recommendation for use by the U.S. EPA or by Tetra Tech, Inc. Similarly, the exclusion of a product does not signify disapproval. Recommendations are confined to techniques or categories of equipment for specific applications. Commercial products are mentioned merely as examples, and no

attempt has been made to include all products now available. For such information, document users should contact manufacturer representatives or equipment dealers in their area.

AVAILABLE NAVIGATIONAL TECHNIQUES

Positioning techniques can be classified as mechanical, optical, electro-optical, electronic, or a combination of these. Mechanical distance measuring techniques (e.g., tapes, wire, measuring wheels, and rods) which are not amenable to offshore positioning are not further discussed herein.

The most popular optical techniques include use of theodolites and sextants. A theodolite is an instrument used to measure horizontal and vertical angles. It is used to visually sight on the vessel (usually a target mounted on the mast) to determine the angle between it and a target of known position onshore. Performed simultaneously with another theodolite at a different position onshore, or at a later time with the same instrument at the second position, this sighting enables a geometrical determination of the vessel's position. Alternately a sextant can be used on the vessel to observe the angles between three objects of known position onshore, again enabling a plot of the vessel's position. Range is limited to line-of-sight.

Electro-optical systems include the laser, which enables very accurate distance measurements. In coastal navigation, the most useful electro-optical system measures both the angle to the vessel (siting optically as with a theodolite) and the range using electronic (typically microwave) signals. Referred to as total stations or range-azimuth systems, these systems eliminate the need for more than one shore station. Although many are limited to the visual range, some are now all electronic, permitting operation even with low visibilities.

Electronic systems use the transmission of electromagnetic (EM) waves between two or more shore stations and the vessel to define vessel location. This is accomplished by measuring differences in either time delays or the phases of arriving signals. The systems are based on a knowledge of

the EM wave travel velocity and an ability to predict variations in this velocity as a function of travel path and period of transmission. Most short-range systems operate at microwave frequencies, whereas longer range systems typically operate at much lower frequencies. As indicated in Appendix B, there are a number of systems operating at a variety of ranges, with the longer range systems typically having lower accuracies. The popular Loran-C is one of the systems discussed in detail in Appendix B.

Satellite navigation systems are also long-range, although they do not operate at low frequencies. Positional measurements are based on the Doppler frequency shift which occurs when the distance between the satellite transmitter and vessel receiver changes, and knowledge of the satellite's orbit. The U.S. Navy Transit (NAVSAT) system, the Navstar Global Positioning System, and private satellite systems will soon afford the user, at a reasonable cost, a selection of highly accurate systems usable in most areas.

2. MONITORING REQUIREMENTS

LOCATIONS OF OUTFALLS

Over 200 municipalities from Alaska, Hawaii, Puerto Rico, and eastern and western U.S. coastal areas have applied for variances from the secondary treatment requirements of the Clean Water Act. Due to the large number and diverse geographic locations of the applicants, the offshore distances and the water depths at the proposed monitoring stations vary widely. Some of the smaller applicants in New England and Alaska have proposed outfall locations very close to shore in shallow waters. By contrast, some of the larger applicants have requested discharge locations as far as 8,085 m (26,525 ft) offshore, in typical water depths of 60 m (197 ft). Near Hawaii, discharges have been proposed for waters up to 150 m (492 ft) deep, although offshore distances are small due to the presence of significant bottom slopes. Puerto Rican discharges are 1,000-3,000 m (3,281-9,843ft) offshore in waters 10-40 m (33-131 ft) deep. Because of the diversity in locations of proposed discharges, navigational techniques and error allowances recommended herein apply to a wide range of water depths and distances offshore.

MONITORING STATION LOCATIONS

The U.S. Environmental Protection Agency requires that receiving water quality standards will be met and that water quality conditions will be adequate to ensure the protection and propagation of a balanced indigenous population of shellfish, fish, and wildlife and allow recreational activities in and on the water beyond the boundary of the zone of initial dilution (U.S. EPA 1982). The ZID, as this zone is referred to, is the region of initial mixing surrounding or adjacent to the end of the outfall pipe or diffuser ports. The zone may not, however, be larger than allowed by applicable water quality standards (U.S. EPA 1982). The ZID represents the area within which the critical initial dilutions occur (i.e., the lowest initial dilution

and those which occur when the environment is most sensitive). U.S. EPA uses a simplified method to calculate the size and shape of the ZID. The width is twice the depth of the water plus the width of the diffuser, and the length is twice the water depth plus the length of the diffuser (U.S. EPA 1979). The ZID boundary is centered on the diffuser, and extends from the water surface to the bottom (Tetra Tech 1982a).

To meet the monitoring requirements of Section 125.62 of the Final Rule governing coastal municipal discharges (U.S. EPA 1982), receiving water and sediment sampling stations need to be located at or very near the ZID boundary, at reference sites, and in potential impact areas. ZID boundary stations should be located on both the upcurrent and downcurrent sides of the ZID, with the downcurrent site being occupied at any given time to ensure that the waste field drift flow is intercepted as it is carried across the ZID boundary (Tetra Tech 1982a).

Compliance with conditions of a secondary treatment variance requires monitoring at a site-specific array of sampling locations. The importance of both absolute accuracy (i.e., correct geographical location) and repeatable accuracy (i.e., return capability) is a function of the particular sampling station in question. The types of stations usually specified in 301(h) monitoring programs are depicted in Figure 1. Absolute and repeatable accuracies are most critical for the within-ZID and ZID-boundary stations (Z_0, Z_1, Z_2). Applicants must be able to sample at a specific boundary location on any given occasion, and to return to nearly the same location on subsequent trips. At gradient (G_1, G_2, G_3, G_4) and control or reference (C_1) stations, initial accurate location is not as critical. However, it is important to relocate these stations accurately during subsequent surveys to be able to quantify any temporal changes in the parameters sampled (e.g., benthic community characteristics). This requirement for high repeatable accuracy also applies to stations in or near special habitats (H_1, H_2). The ability to conduct sampling at the appropriate depth contour is also very important.

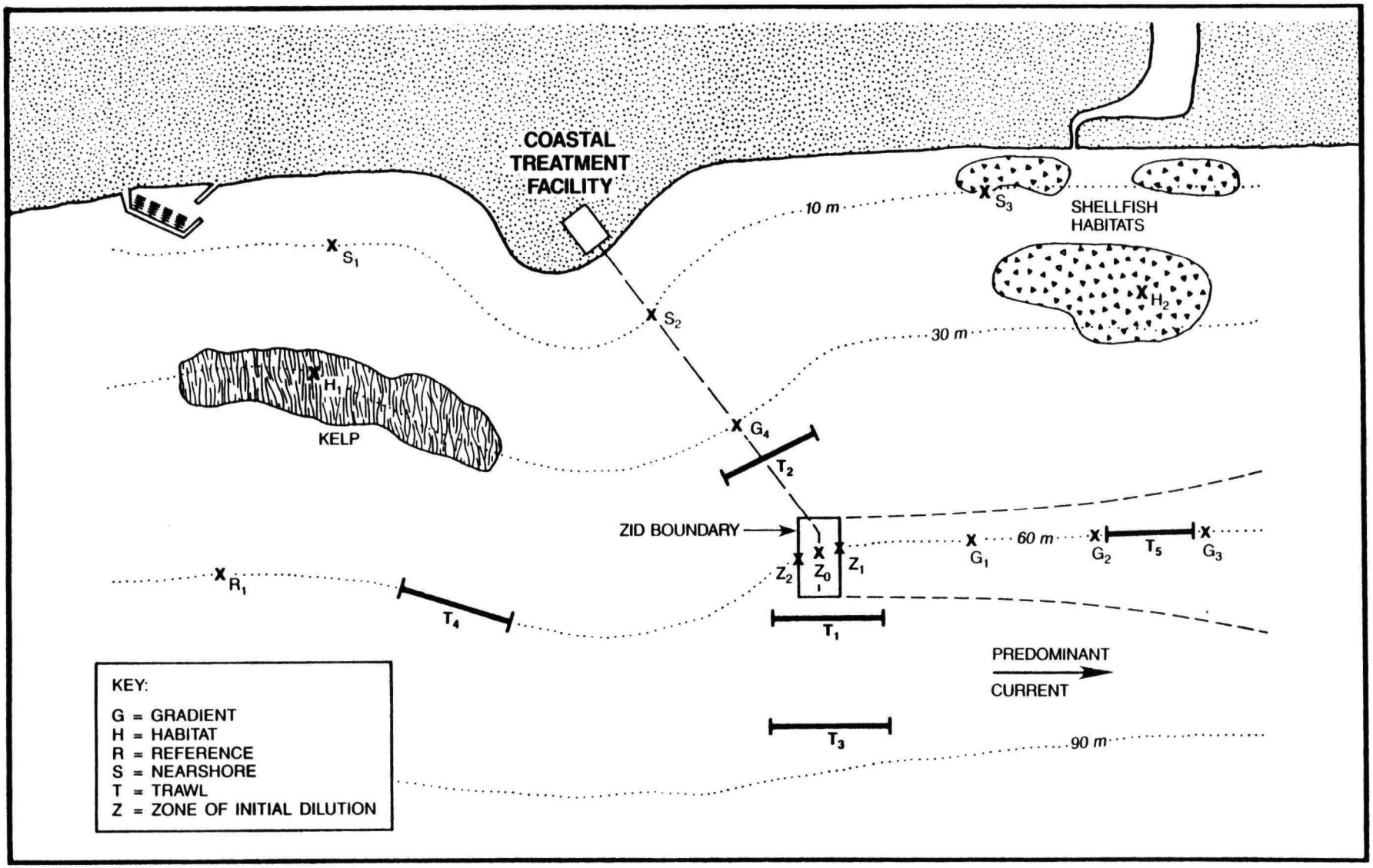


Figure 1. Examples of some key 301(h) monitoring station locations for a medium-large marine municipal discharge.

ACCURACY LIMITATIONS

Both the procedures and equipment used to establish a position contribute errors that determine the overall accuracy of a fix. Absolute or predictable accuracy is a measure of nearness to which a system can define a position by latitude and longitude (Bowditch 1984). Repeatable or relative accuracy is a measure of a system's ability to return the user to a position whose coordinates were previously measured with the same system. The difference between these two accuracies can be quite significant. For example, depending on one's location in the coverage area, Loran-C has a repeatable accuracy in offshore areas from 15 to 90 m (49 to 295 ft), but an absolute accuracy of somewhere between 185 and 463 m (607 and 1,519 ft) (Dungan 1979).

In many instances, repeatable accuracy is more important than absolute accuracy (e.g., retrieval of crab pots, return to desirable fishing grounds, avoidance of underwater obstructions, and locating an important sea buoy). For coastal outfall monitoring, both repeatable and absolute accuracy can be important, depending on the type of sampling site. For within-ZID and ZID-boundary stations, both accuracies are important because sampling stations must be located within or very near the boundary and be repeatedly occupied during the program. For gradient, special habitat, and reference stations, repeatable accuracy is more important than absolute geographic location. Once such a station is established within a special habitat, it is often necessary to return to the same site to identify temporal variations in the previously sampled biological community. Thus, it is important to select navigational procedures and equipment with both the absolute and repeatable accuracies needed to meet the monitoring program objectives. Because repeatable accuracy of navigational equipment is usually at least one order of magnitude better than absolute accuracy, the latter frequently limits the location of a sampling vessel during coastal monitoring programs. Therefore, the following discussion focuses on absolute accuracies that can be achieved by various procedures and associated equipment.

Practical considerations also limit how well an offshore positional fix can be made. Resolution of a position line to better than 1-2 m (3.3-6.6 ft) becomes meaningless when measuring the location of a moving vessel (trawling),

or one which is on station but pitching and rolling. Antenna movement alone usually precludes any higher resolution in position coordinates. Exceptions to this rule can occur when conditions are unusually calm or when the platform is highly stable (e.g., a semi-submersible drilling rig).

POSITIONING ERROR

Many factors contribute to the total error in position of the water column or benthic sampling point. These include movement or drift of the "on-station" vessel, knowledge of the offsets between the navigational system antenna and equipment deployment point and between this point and the subsurface sampling or profiling equipment, and error in the ship's initial location itself. Most of these factors are very site or operationally specific, and can be estimated with varying degrees of confidence. Because the accuracy to which the actual sampling point is known is highly dependent on all such factors, they should be carefully considered in both the design and conduct of monitoring programs. The discussion herein is limited to only one of the overall error components, namely the location of the vessel itself at a desired point on the surface.

One important factor to consider when selecting a navigational location technique is the locational accuracy required of the vessel at each of the candidate stations. Of importance are both the absolute or geographic accuracy, and the repeatable accuracy enabling return to the same stations within desired limits of positional error. The following example method may prove useful as an aid in establishing the error limitations suitable for a particular set of monitoring stations.

In evaluating navigational accuracy requirements during this review, a method was sought to specify the positional error as a function of one or more pertinent parameters. A ZID boundary error proportional to some percentage of the ZID dimension was selected as the controlling parameter. Because ZID size is proportional to the water depth, the allowable error in position would also be proportional to depth. For example, the ZID-boundary stations could be located at a distance from the diffuser axis equal to one-half the ZID width plus 20 percent of the water depth at mean

tide level. The allowable maximum error in the location of these stations would then be ±20 percent of the water depth. As a result, the closest that sampling would occur is at the ZID boundary, and the farthest that sampling would occur is 40 percent of the water depth beyond this boundary. Nominally, however, sampling would be performed within a distance from the ZID boundary equal to 20 percent of the water depth. Example ZID-boundary station locations using this approach for a variety of ZID sizes are listed in Table 1. The ZID-boundary and sampling station locations for discharges at the 100-, 60-, and 20-m (328-, 197-, and 66-ft) depths are shown in Figure 2.

When discharge depths are less than approximately 15 m (49 ft), the example 20 percent error allowance results in a highly restrictive positional error [i.e., less than ±3 m (±9.8 ft)]. Therefore, a positioning error of ±3 m (±9.8 ft) would be more appropriate when sampling station depths are less than 15 m (49 ft). Although the percent error as a function of water depth increases at shallower depths, this minimum error is reasonable given available navigational techniques for small sampling vessels in other than extremely calm waters. Stations beyond the ZID may be similarly located using the 20 percent depth rule to the 15-m (49-ft) contour and using the ±3-m (±9.8-ft) error limitation for shallower locations. As indicated earlier, it is recognized that the ability to reoccupy a given site can be as important as knowing its exact geographical location. However, relocation probably will not be a problem because the same navigational equipment used to absolutely locate ZID-boundary stations will likely be used elsewhere. By using this equipment a repeatability of less than ±2 m (±6.6 ft) can be expected.

This approach may be useful for determining accuracy requirements for equipment selection. However, if this approach is used when specifying allowable positional error, higher accuracy is required at the shallower stations. This would result in more stringent requirements for shorter outfalls, normally associated with municipalities having smaller volumetric flow rates. Such municipalities often have much more limited resources available for monitoring programs than do larger dischargers. Thus, it is important to recognize such a constraint. Fortunately, as discussed

TABLE 1. EXAMPLE ZID-BOUNDARY STATION LOCATIONS

Average Diffuser Depth (m)	Average Diffuser Diameter (m)	ZID Width (m)	Recommended Station Location[a] (m)	Recommended Allowable Error[b] (m)
100	4.0	204.0	122.0	±20
90	3.6	183.6	109.8	±18
80	3.4	163.4	87.7	±16
70	3.2	143.2	85.6	±14
60	3.0	123.0	73.5	±12
50	2.5	102.5	61.3	±10
40	2.2	82.2	49.1	± 8
30	2.0	62.0	37.0	± 6
20	1.8	41.8	24.9	± 4
15	1.5	31.5	18.8	± 3
10	1.5	21.5	13.8	± 3
5	1.0	11.0	8.5	± 3
3	0.5	6.5	6.3	± 3

[a] Distance from the zone of initial dilution centerline to the station, based on 0.5 times the ZID width plus 20 percent of the average water depth of the diffuser when over 15 m (49 ft).

[b] Error magnitude is equal to ±20 percent of the average diffuser depth, when over 15 m (49 ft).

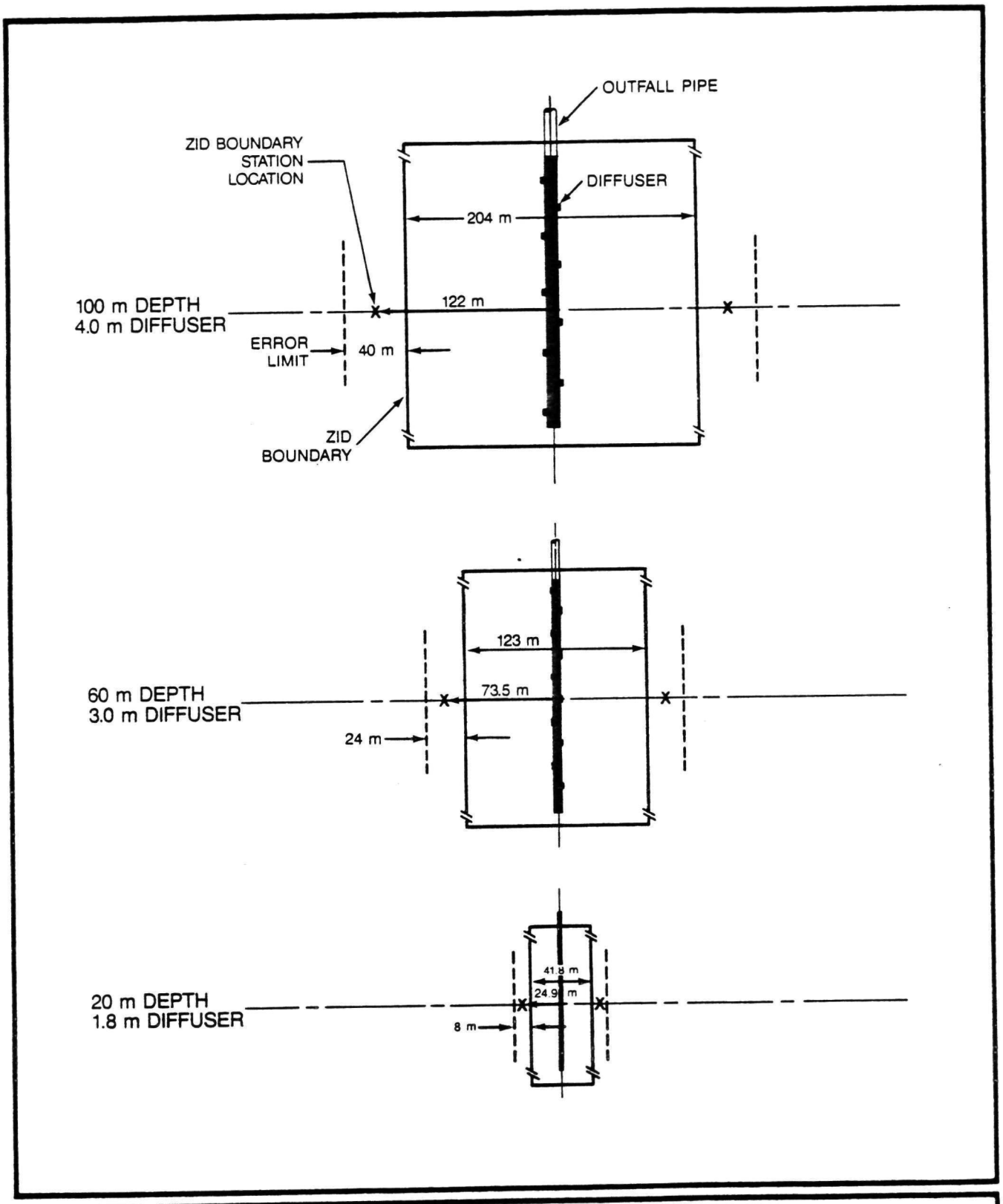


Figure 2. Locations of ZID-boundary stations for selected ZID sizes.

in Section 5 of this report, inexpensive navigational techniques applicable to short-range/shallow-water situations that allow positioning well within a few meters are available. Also, the equipment can be rented for the infrequent use a small discharger will have, as discussed in Section 4.

3. OVERVIEW OF AVAILABLE SYSTEMS

There are many methods for positioning sampling vessels in coastal waters and for returning to previously occupied sampling sites. These methods range from simple extensions of well-established onshore survey techniques using theodolites to highly sophisticated electronic navigation systems. In this section, a number of positioning methods and their associated theoretical accuracies are presented, with emphasis on procedures for consistently meeting the recommended levels of accuracy. Also addressed are site-location errors and ways in which these can be minimized.

OPTICAL POSITIONING TECHNIQUES

Optical positioning requires visual sighting to determine alignment on one or more ranges, or the distances and angles between the vessel and shore targets. Methods most frequently used include:

- Graduated line (tape) or wire
- Intersecting ranges
- Range line and uniform speed or angle
- Vertical angle ranging (subtense bar or stadia)
- Angle and distance to vessel
- Two angles from shore or vessel.

Use of a tape or wire is impractical except in the case of very short distances from shore. Intersecting ranges are used when a number of established landmarks permit easy selection of multiple ranges that intersect at the desired sampling point, and accuracy is not critical. Range line and uniform

speed or angle between the line and an onshore target are more applicable to hydrographic surveys than discrete sampling station locations. Vertical angle ranging requires a graduated shore line target known as a subtense bar. A sextant is set so the individual marks on the bar subtend a given angle at desired distances from shore. This method is limited to extremely confined areas, relatively short distances, and calm waters.

The remaining optical methods are most applicable for offshore positioning. The angle and stadia method was used historically in very calm waters. This method requires vertical positioning of the stadia (or rod) on the vessel and careful measurement of angles to the stadia hairs, enabling a calculation of distance from the observer to the rod. A position fix is made by measuring the azimuth from a baseline of known orientation. Although practical only in calm seas, this same method is now effectively employed by electronically determining the distance using either a total station or a range-azimuth system, such as those discussed later in this report. The traditional optical positioning method involves the observation of two horizontal angles, either from shore using two theodolites, or from the vessel using a sextant. Each of these techniques is discussed in the remainder of this section.

Theodolite Intersection

Position of the sampling vessel can be established using theodolites by two onshore observers who simultaneously measure the angle between a reference object or shore traverse and the vessel (Figure 3). A rod or other aiming point is normally erected on the vessel. Radios, flag signals, or lights are used to set the moment at which angle measurements are made. Using a theodolite with an accuracy of ± 15 sec for single angle measurement at intercept angles near 45° and a range of 5 km (3.1 mi), should yield a position error less than ± 1 m (3.3 ft) (Ingham 1975). A method for calculating expected errors for specific positioning situations is presented in Appendix A.

Although the accuracy of this method appears high, its use in open waters has several distinct disadvantages. Complex arrangements are usually

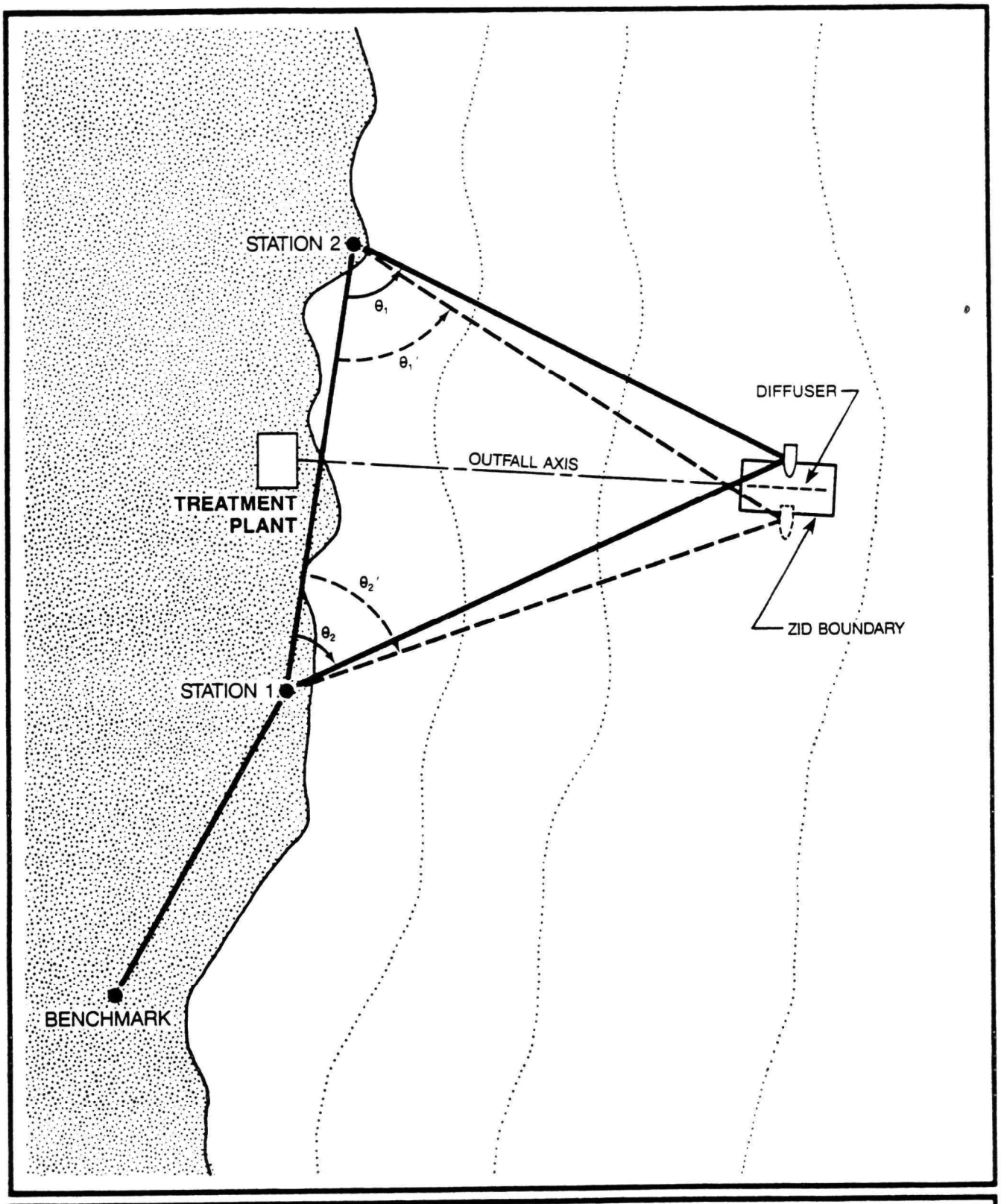


Figure 3. Station positioning by theodolite intersection.

needed to ensure that angles are simultaneously measured by the two onshore observers at the time of the desired fix. Although not a problem when the vessel remains on station for a long period of time, it becomes a problem when the vessel is trawling. Lines from the two theodolites should ideally intersect at nearly right angles at the vessel's location. Weak position fixes or corresponding large positional areas of uncertainty result when the angles measured are less than 30° or more than 150°. To avoid such extreme angles, onshore observers may have to move frequently, resulting in delays of a predetermined sampling schedule. Finally, as with all optical methods, target movement and path interferences (e.g., fog, heavy rain, or heat waves) can confound the measurements. In spite of these disadvantages, the procedure offers relatively high accuracies at low cost and has been successfully applied in small-scale coastal surveys during favorable weather. It is also advantageous in very restrictive areas or in harbors.

Sextant Angle Resection

An offshore position can also be fixed from the vessel by measuring the two horizontal angles between lines-of-sight to three identifiable targets whose positions are known (Budlong 1977). When a vessel is underway, the sextant angles must be measured simultaneously by two observers. The measurement of the first angle between the center and one outside target allows determination of a circle of position (COP) on which the sampling vessel must lie. For example, when the measured angle is 52°, the first circle of position is plotted by subtracting this angle from 90° and drawing lines seaward from the siting targets at the resultant angle of 38° from the baseline (Figure 4). These lines cross at the center of the first COP, which can then be drawn with a compass. This procedure is then repeated using the center and remaining target, resulting in the plot of the second COP. In the example, the second angle is 67°, requiring a plot of radius lines at 23° from the baseline. The intersection of the two position circles marks the vessel's location.

Position fixes are normally plotted using a station pointer or a three-arm protractor (Figure 5). The two measured angles are set by moving and then locking the two outer arms of the protractor. The protractor is then

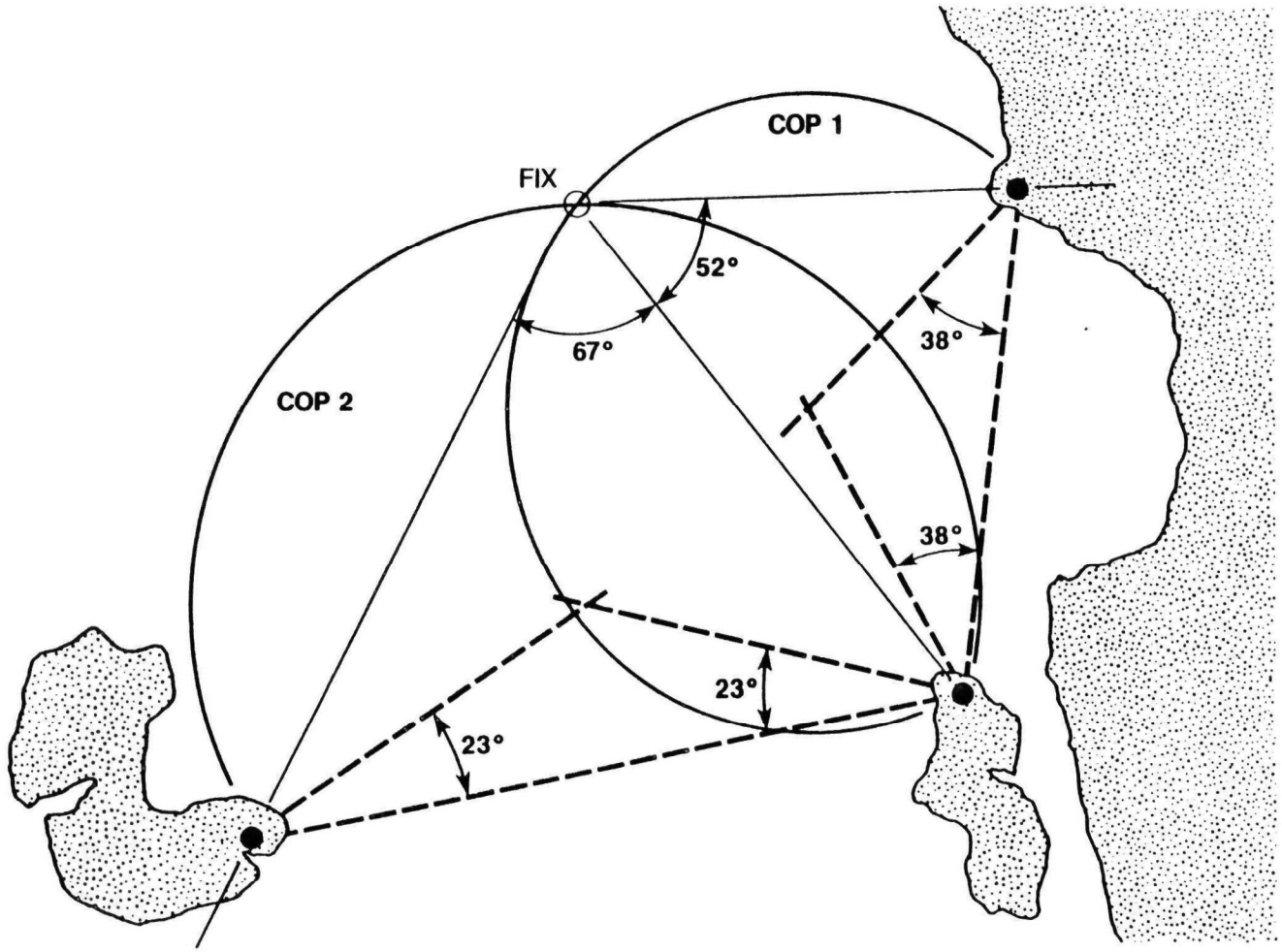


Figure 4. Station fix using position circles.

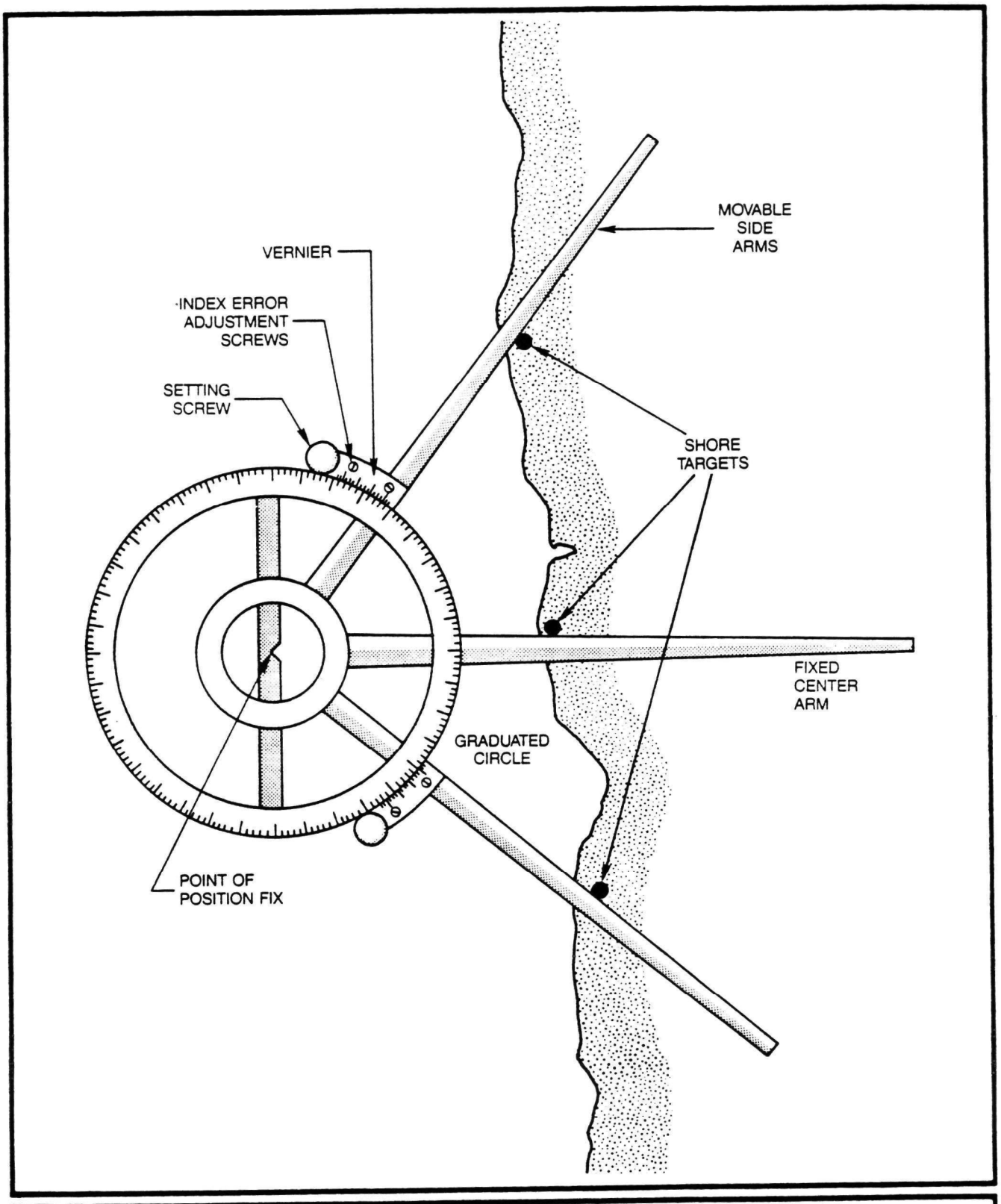
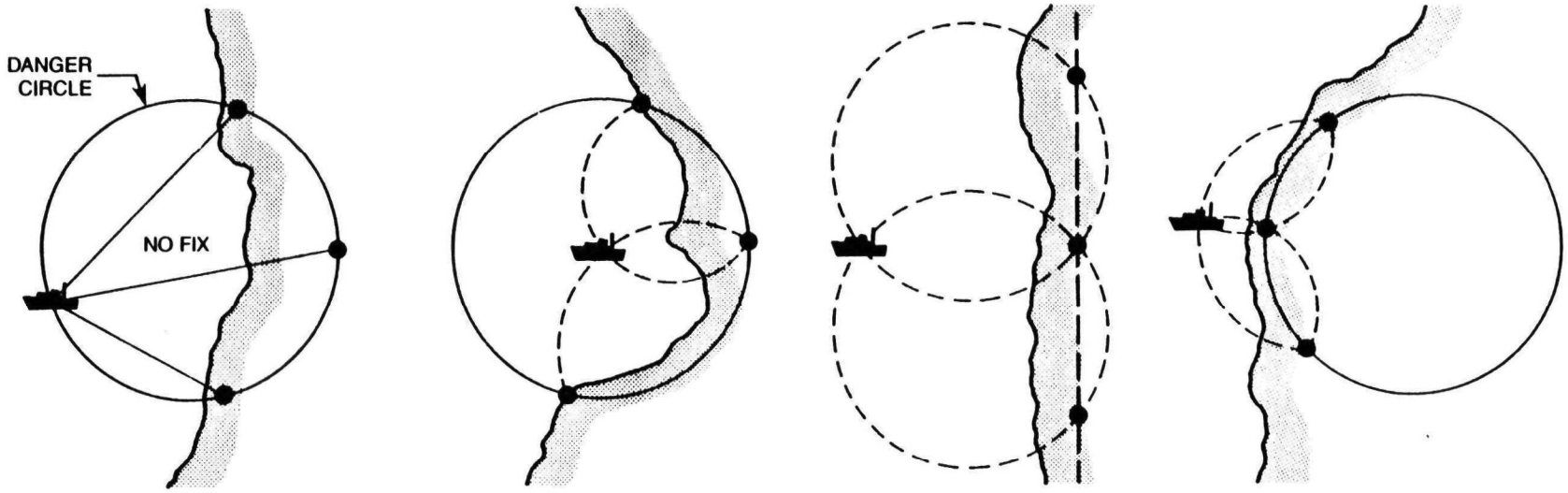


Figure 5. Three-arm protractor for sextant resections.

moved over a nautical chart until all three arms are aligned with the preplotted locations of the shore targets. The vessel's position is then recorded at the center of the protractor. Because this procedure can be implemented in 10–15 sec with some experience, it has been used historically in hydrographic surveys where moving vessel positions are needed. To minimize the parallax error, the two sextant operators should stand as close as possible when making the measurements. Sextant angles can be routinely measured to approximately 1 min of arc or better, depending on the instrument quality and operator ability. Within 5 km (3.1 mi) of shore stations and at acceptable COP crossing angles, the resulting accuracy in position is 1 part in 2,500 or about ± 2 m (6.6 ft) (Ingham 1975).

Sextant angle resection has been the most widely used positioning technique in coastal surveying. This is due to the relatively high accuracies that can be achieved, ease of implementation, and nominal cost of the sextants and the three-arm protractor. Also, no shore party is required. The procedure does have some limiting factors, however. Range is ultimately limited by visibility and by the sizes, elevation, and placement of the shore targets. Also, it is imperative to follow certain rules in locating targets to avoid indeterminate or weak fixes. For example, a fix cannot be obtained when the vessel and all three shore targets lie on a common circle (called the danger circle) as shown in Figure 6. This can be avoided by alignment of the three shore targets along a straight line, which, in effect, causes the radius of the danger circle to become infinite. Other recommended practices to assure strong fixes are placement of targets so that intercepted angles fall between 30° and 150° (ideally between 45° and 60°), thereby maintaining large position circle cut angles. Shore targets may also be placed on a curve convex to the observer, with the middle target nearest the sampling vessel. Alternately, targets may lie on a curve concave to the vessel, provided the anticipated positions are within the triangle formed by them, they are practically equidistant from the vessel, the observed angles are not less than 60°, or the vessel is well outside the circumscribing circle (Clark 1951; Davis et al. 1966). Selected acceptable target configurations and an unacceptable alignment are also depicted in Figure 6.



Adapted from Ingham 1975

Figure 6. Shore target locations to avoid the danger circle.

When at the limits of visibility, sextant angle fixes are likely to be weak because the angles are small. In such cases, large positional errors can be caused by very small errors in the angles themselves (Umbach 1976). This problem can be partially offset by using a telescope mounted on the sextant. Sextants must be in perfect adjustment and angles must be read with extreme care. Also, the sextant must be of superior quality so that the angles may be read to the necessary precision. When working at locations very near shore, the sum of the two angles can approach 180°, with one angle often very large and the other very small. Under such conditions, care must be taken to mark the two angles simultaneously if the vessel is moving, or to make several measurements if the vessel is on station, because the angles change rapidly with little vessel movement.

Split-fixes (no common center object) may be taken when a three-point fix is not possible. The vessel position is at the intersection of two angle loci. A fix is considered strong when the intersection angle is greater than 45°. Split fixes should be used only when absolutely necessary. They are inefficient due to the required recording procedures and plotting time, and they cannot generally be entered into automatic data processing and plotting systems.

Considering the accuracy achievable when the double horizontal sextant angle method is properly implemented, this procedure offers an inexpensive candidate positioning method for limited coastal surveys. However, the method may be ineffective during poor visibility or other periods when monitoring may nonetheless be required. Also important is the need to construct, survey, and maintain a sufficient number of properly located shore targets to provide unambiguous positioning. Overall, the method has merit when the cost of an electronic positioning system cannot be justified.

ELECTRONIC POSITIONING TECHNIQUES

Electronic positioning systems utilize the transmission of electromagnetic (EM) waves from two or more shore stations and a vessel transmitter to define a vessel's location. The systems are based on the EM wave travel velocity of 299,793 km/sec (186,282 mi/sec) and an ability to predict variations

in this velocity as a function of travel path. Position is determined by measuring differences in signal arrival times (range-range mode) or by comparing the phases of received signals to those of the transmitted signal (hyperbolic ranging).

At their respective maximum ranges, electronic positioning methods have higher accuracies than visual methods. Measurements can be obtained regardless of weather and visibility conditions and operating ranges are typically much greater than for optical methods. Range can be extended to 50-100 km (31-62 mi) by simply elevating transmitting and receiving antennae until signal attenuation becomes a limiting factor. Shore stations need not be attended, minimizing personnel requirements. Positional readouts are available as distances or coordinates rather than wavelengths or time delays, and deck units are usually compatible with data processing and automatic plotting equipment. Position information is continuous, enabling maintenance of a desired location by dynamic positioning or by traversing along a predetermined path.

The short-range systems of primary importance in coastal monitoring programs are compact, lightweight, durable, easily calibrated, and relatively stable. Disadvantages of electronic systems can include cost, particularly for smaller monitoring program requirements, the inconvenience of orienting shore and onboard units, vandalism of shore stations, and unknown signal propagation effects (although this should not be a problem over relatively short distances). As discussed later, however, the cost factor can be minimized by sharing among multiple users, by leasing equipment during survey periods, or by contracting for both survey personnel and equipment.

System Classifications

Electronic positioning systems are often classified by range capability, which depends largely on propagation characteristics of the operating signal. Band width and signal power also influence reception distance. For purposes of discussion, electronic positioning systems are herein categorized as short-range, medium-range, long-range, and global or very long-range. Although short-range systems are emphasized, other categories are also

examined because systems such as Loran-C are frequently proposed by coastal dischargers. Satellite navigation systems are also presented, because their system prices are declining and capabilities (i.e., coverage and access time) are expected to increase. Representative commercially available equipment in the various range categories is presented in Table 2.

Short-range [0-40 km (0-25 mi)] microwave systems are portable and best suited for use in the range-range mode (see "Operating Modes," below). Medium-range systems [to 150 km (93 mi)] are also transportable, although components are usually bigger and heavier. They are effective in either the range-range or hyperbolic mode (see below). Long-range [to 2,000 km (1,243 mi)] and global systems transmit from permanently installed, widely dispersed shore stations or satellites for multi-user operation.

Comparative Absolute Accuracies

Although it is difficult to specify the positional accuracies achievable by instruments in each category, some generalizations can be made. Whereas optical methods provide accuracies of ±2 m (6.6 ft) for ranges up to 5 km (3.1 mi) offshore, short-range electronic positioning systems provide accuracies of ±1 to 3 m (±3.3 to 9.8 ft) for ranges up to 40 km (25 mi) from shore stations. Comparable medium-range system accuracies are ±5.0 m (16 ft) up to 150 km (93 mi). Long-range systems typically have accuracies of ±50 to 100 m (164 to 328 ft) within 350 km (217 mi) of shore stations, and over ±100 m (328 ft) at greater ranges.

Operating Modes

There are two principal radio navigation system operating modes: the two-range (or range-range) mode and the hyperbolic mode. Some systems utilize the advantages of each in a combination mode. In the range-range mode, position fixing is accomplished by measuring the extremely small time intervals required for EM signals to travel from a master transmitter onboard a vessel to one or more slave stations onshore, and back (Figure 7). For a known propagation velocity, the time interval is converted to a distance (range) from the slave, defining a single circle of position on which the

TABLE 2. ELECTRONIC POSITIONING SYSTEM CATEGORIES

Category	Range	Representative Systems
Very long range	>2,000 km	OMEGA TRANSIT (NAVSAT)
Very low frequency Satellite		GEOSTAR NAVSTAR GPS SERIES AERO SERVICE GPS
Long range	0-2,000 km	LORAN-C VIEWNAV
Low frequency		LAMBDA
Medium range	0-150 km	SYLEDIS RAYDIST TRAK IV
Medium-high frequency		HYPER-FIX ARGO DM-54 HYDROTRAC
Short range		
Radar	0-100 km	DECCA FURNO U.S.A. KODEN/SI-TEX RAYTHEON MARINE
Microwave	0-40 km	TRISPONDER MINIRANGER MICRO-FIX HYDROFLEX AUTOTAPE AZTRAC POLARFIX ARTEMIS

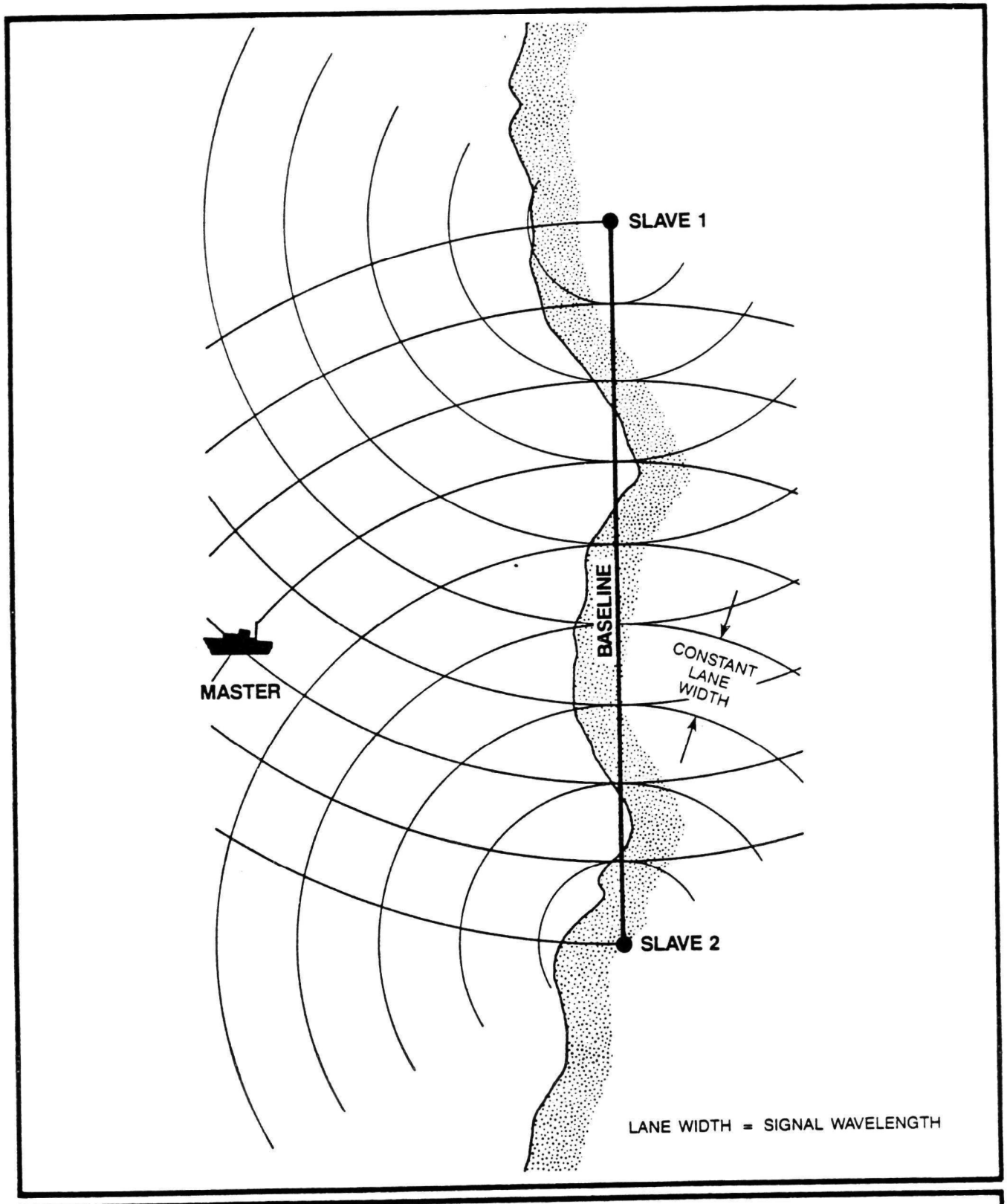


Figure 7. Range-range radio-navigation operating mode.

vessel may lie. The intersection of two or more such circles (based on signal returns from two or more slave stations) results in a position fix. This operating mode is usually restricted to a single user, although single side-band techniques have been employed to allow multi-user operation (Ingham 1975). Lane width remains constant regardless of distance from the system baseline. In effect, the lane-width aspect of system resolution does not increase at increasing ranges from the baseline, as is the case in the hyperbolic positioning mode.

In the hyperbolic mode, the receiver onboard a vessel detects the phase difference of signals arriving from multiple shore-based transmitters. Lines of constant phase between a master and slave transmitters form a hyperbolic pattern of position lines (Figure 8). By measuring the phase difference between arriving signals, the vessel can be located along one of the position hyperbolas. Adding a second master-slave transmitter pair superimposes another hyperbolic pattern, resulting in a grid network with pattern crossings (Figure 9). Measurement of the signal phase difference from the second transmitter pair allows vessel positioning on the second pattern, and therefore "unambiguous" location at the applicable grid crossing point. Phase differences usually are resolved to 1/100 of the lane width. Because of lane widening for increasing range from the baseline, the system resolution decreases with vessel distance from the master-slave transmitter baseline. As indicated earlier, the angle-of-cut of arriving signals also affects the magnitude of position error. In hyperbolic systems, extending the baseline length improves cut-angles of the arriving signals and decreases lane spreading (Ingham 1975).

Short-Range Systems

Electronic Distance-Measuring Instruments--

Electro-optical and microwave distance-measuring instruments (EDMI) are used extensively in land-based surveying. The EDMI master generates a carrier signal which is directed towards a reflector (in the case of light beams) or a repeater (for microwaves). The light or microwave beam is modulated at two or three different frequencies, usually under the control

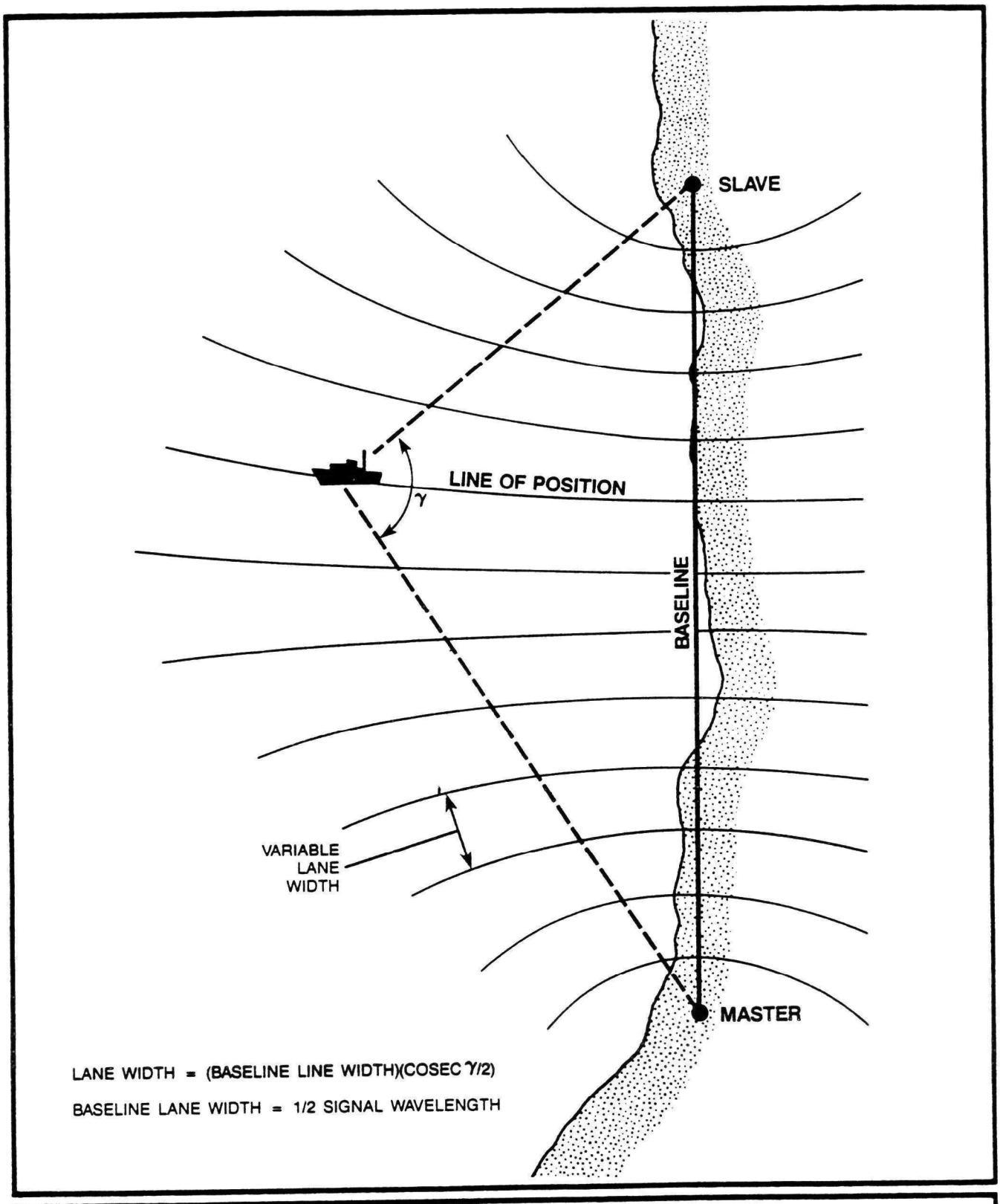


Figure 8. Hyperbolic radio-navigation operating mode.

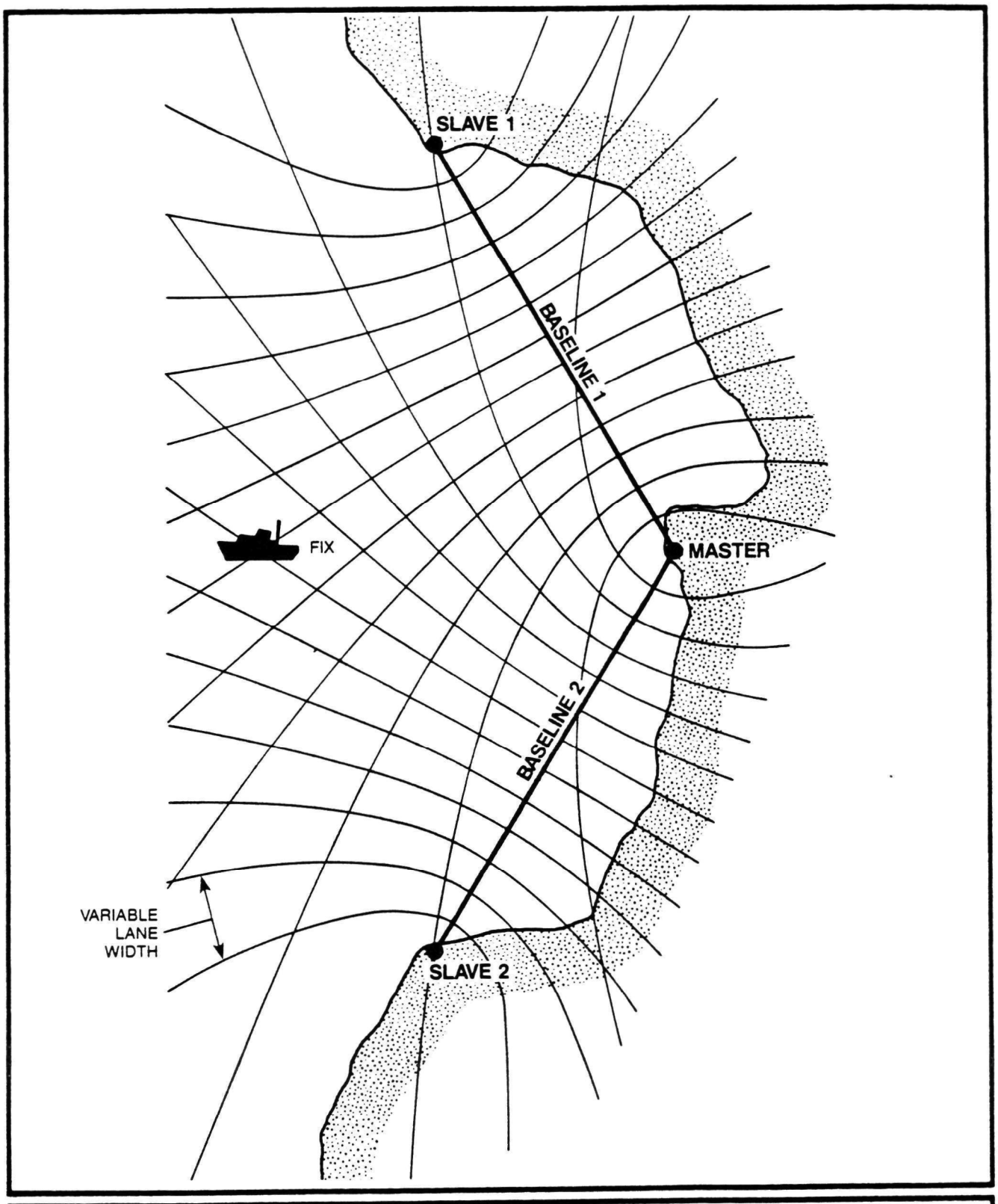


Figure 9. Hyperbolic grid formed by two position line patterns.

of a precision quartz crystal oscillator. A phase comparison of the incoming and outgoing beams at the master enables very accurate distance determinations.

The EDMI is a relatively new development in the field of surveying. The Geodimeter of the early 1950s, which used a modulated light beam, was replaced in the late 1950s by the Tellurometer which used a modulated microwave signal. This improvement increased the range and allowed operation in moderate rain, fog, and darkness. Newer EDMIs have shorter ranges and are much more compact, less power-intensive, and easier to read due to the use of solid-state electronics. The latest EDMIs use highly coherent laser light, have longer ranges, require even less power, are portable, and are easy to operate. The so-called "total station" consists of a theodolite for measuring angles and an EDMI for measuring distances, with outputs recorded on magnetic or paper tape for subsequent analyses. Under favorable conditions, typical EDMI ranges are 1.6 km (1 mi) for light-based systems, 80 km (50 mi) for laser systems, and 150 km (93 mi) for microwave systems.

Properly adjusted and calibrated, an EDMI has very few sources of error. Ground wave reflection can cause error when measurements are made over water, because reflected signals result in faulty distances due to the longer path lengths. The swing, or cyclic manner in which reflections are recorded, must be correctly interpreted. At very close range, EDMI accuracy is limited by a constant of uncertainty. Beyond 0.5-1.0 km (0.3-0.6 mi), accuracies of 1 part in 25,000 are easily achievable. If meteorological conditions over the signal path are sufficiently well known, accuracies of 1 part in 100,000 can be achieved (Moffitt and Bouchard 1982). Most manufacturers report EDMI mean square error (MSE) capabilities at $\pm$ (5 mm + 2-5 ppm). At a distance of 5 km (3.1 mi), this represents distances of from 1.5 to 3.0 cm (0.6 to 1.2 in). It is apparent, therefore, that accuracies achievable with electronic distance measurement devices are more than adequate to meet the positioning requirements for coastal surveys. In fact, the angle-measuring devices used with an EDMI, and not the EDMI itself, limit positional accuracy. Probably the major disadvantage of the EDMI is the irregular motion and resultant misalignment of the reflector (in electro-optical systems). Use of microwave patterns eases directivity requirements.

Total Stations--

An electronic tachymeter, commonly referred to as a total station, is an instrument for determining the range, bearing, and elevation of a distant object. As used in coastal surveys, it is a shore station instrument used to sight the survey vessel reflectors, enabling positional information to be recorded onshore for subsequent communication to the vessel operator. In a manual station, the same telescope optics (co-axial) are used to measure both distance and angles. They are basically theodolites with built-in EDMI units. With such manually operated units, slope reduction of distances is done by optically reading the vertical angle and keying it into a built-in or hand-held calculator (McDonnell, Jr. 1983). A semiautomatic total station contains a vertical angle sensor for automatic slope reduction of distances, while horizontal angles are read optically. With an automatic station, both horizontal and vertical angles are read electronically for use with slope distances in a data collector or internal computer. A theodolite with a mount-on EDMI is not usually classified as a total station. An exception is the modular total station, designed to allow addition of other equipment. Such units are usually built around an electronic (digitized) theodolite such as the Kern E1. Many total stations use hand-held calculators for data storage, computations, access to control registers, testing, calibration, and orthogonal offset determinations. Most manufacturers offer optional data collectors that serve as electronic supplements to field books. This permits a convenient interface with a computer and remote transmission of data using an acoustic modem.

Although some manufacturers report displaying angles or accuracies to 1 sec or less, experienced surveyors know that this level of accuracy requires careful or repeated pointings at good targets. Fortunately, locating coastal monitoring stations does not require such an accuracy out to the 5- or 6-km (3.1- to 3.7-mi) range that is needed in some cases. The range capability of a total station is dependent on the number of prisms available for signal reflection. Such prisms are directional (i.e., must be pointed towards the shore station), as opposed to omnidirectional prism arrangements used for range-azimuth navigation systems described later in this report.

For coastal monitoring programs, single station capability is attractive. Setup and calibration efforts are minimized, and the logistics of station movement are much simpler than with a multi-station net. A total station can be used on many other projects when not in use for periodic monitoring programs. Instrument capabilities and costs are reported in the free, bimonthly journal Point of Beginning [P.O.B. Publishing Company, Wayne, MI (313-729-8400)].

Microwave Navigation Systems--

Short-range electronic positioning systems generally operate at microwave frequencies. These frequencies limit the system ranges to "radio line-of-sight" because any obstructing objects cause a complete loss of signal and can result in undetected erroneous distance readings (Umbach 1976). Typically, such systems are effective between 25 and 100 km (16 and 62 mi) offshore, depending on antenna heights and power outputs. Position measurements are indirect (i.e., by timing the travel of multiple pulsed signals from a master to two or more remote stations and back; alternately, phase differences between arriving signals can be measured). Available systems operate in the range-range mode, the hyperbolic mode, or both. The position fix is defined by the intersection point of two position circles or hyperbolic constant-phase lines. Most systems consist of a receiver-transmitter with antenna on the vessel, and two shore stations also having a receiver transmitter, antenna, and power source. Typically, when the vessel's signal is received at each shore unit, a response signal is triggered. Ranges are then automatically determined based on the time delays of returning signals.

Because microwave systems have nominal accuracies of ±1-3 m (±3.3-9.8 ft) from very short ranges to 25-40 km (16-25 mi), they provide adequate positioning capability for coastal monitoring programs. This is advantageous in large sampling efforts involving more than one vessel, or separate programs in which sponsors share system costs but wish to access the unit at any time.

Medium-Range Systems

Systems in this category typically operate in the medium- to high-frequency bands (i.e., 1.5-400 MHz), achieving greater ranges using EM waves that propagate around the earth's surface. This enables greater spheroidal distances to be measured, limited normally by transmitter power outputs (Ingham 1975). Typical ranges are up to 150 km (93 mi) from base stations, although system modifications in some cases have extended this up to 400 km (249 mi). The need for much longer baselines requires careful selection of station sites and usually results in the establishment of semipermanent master-remote chains. Although the typical operating mode is hyperbolic, some systems allow range-range operation. All systems are capable of lane integration or counting. However, a break in reception may require a vessel to return to a known point to allow the lane count to be reset.

Positional accuracies are very dependent on knowledge of the EM wave propagation velocity over the entire transmission path, which is influenced by the nature of the path. Systems calibrated for over-water transmissions can err when land masses (e.g., islands) are located between the survey vessel and shore stations. Also important is the extent to which transmission path atmospheric characteristics (e.g., temperature, pressure, and humidity) differ from that of the "standard atmosphere." Variations in velocity values can also be caused by differences in the conductivity of the surfaces over which the EM waves travel. Poor conductance results in low propagation velocities, high attenuation, and reduced effective range (Umbach 1976). Manufacturers usually state a system's resolution in terms of a lane-width fraction (e.g., 0.01 lane) or a distance on the baseline. Resolution in this case is a measure of the equipment's precision or ability to detect and display signal changes corresponding to small changes in distances. Positional accuracy, on the other hand, is a function not only of the error in each of the hyperbolic position lines, but the combined error associated with two or more position lines and their associated crossing angles (Appendix A). Positional accuracies of medium-range systems vary from a few meters near the base line to tens of meters at the system's range limits (Ingham 1975).

Medium-range systems must be used with caution in nearshore coastal areas due to the severe landmass attenuation and water-land interface effects. Such effects are usually manifested as large calibration variations within a limited survey area. These systems generally present a less desirable option for coastal monitoring than do the short-range systems because a much higher price is required for a range capability beyond that needed. Also absolute positioning accuracy is generally less than the short-range systems discussed earlier.

Long-Range Systems

Long-range and global navigation systems generally operate at low (30-300 kHz) or very low (less than 30 kHz) frequencies. As in the case of medium-range systems, EM waves at such frequencies travel for very long distances, limited typically by transmitter power. Onshore station chains are usually permanent, for use with an appropriate vessel receiver and published hyperbolic lattice charts (Ingham 1975). Because long-range systems are designed primarily for general navigation rather than accurate positioning, achievable accuracies are typically much lower than those of shorter-range systems. Long-range systems included in this category are OMEGA and Loran-C units, the Decca Lambda, and satellite systems. All these systems are described further in Appendix B. Particular emphasis is on Loran-C which is commonly used for coastal navigation and provides 15-90 m (50-300 ft) repeatable accuracy at a cost of $1,000-$2,000. Improved performance can be achieved using the differential mode with the expense of another Loran-C receiver and communication system for transmitting offset corrections. In addition, satellite systems are detailed in Appendix B because the developing positional accuracies and costs appear promising for future use in coastal navigation.

HYBRID POSITIONING TECHNIQUES

A number of hybrid positioning systems combine positional data from various sources to obtain fixes. Such systems usually involve the intersection of a visual line-of-position with an electronic line-of-position (Umbach 1976). Visual data may be in the form of sextant angles or theodolite azimuths. Electronic positional data are normally obtained from a microwave system.

Of particular interest to coastal monitoring programs are dynamic positioning systems that require only a single shore station and that use the simultaneous measurement of angle from a known direction and range to the survey vessel. This range-azimuth method has the advantage of circular coverage around the shore station (Figure 10). A single station minimizes logistical requirements and geometric limitations. Line-of-position intersections are the ideal 90° everywhere within the coverage area. Because it is independent of the absolute azimuth angle, growth in the error ellipse is due only to distance from the shore station. Accuracy improves as range decreases, even fairly close to the shore station, and only one unobstructed line-of-sight is needed. However, such systems allow only a single user.

Characteristics of three representative range-azimuth systems are summarized in Appendix B. Two have fully automatic shore stations, requiring attendance only during setup and alignment. The third requires an onshore operator at all times. For multiple-day surveys, an automatic station eliminates the tedium of continuously tracking the survey vessel. The systems described offer much greater flexibility than range-range or hyperbolic systems with multiple onshore stations. Where positioning requirements extend into ports, estuaries, or up rivers, the single-station system offers distinct advantages in covering restricted or congested survey areas and in establishing an unobstructed signal path. Each system described is unique in either its operating medium (optical, microwave, laser) and/or procedure (i.e., manual or automatic tracking). The higher costs of these systems compared to standard microwave systems may be justified where the system can also be used for onshore work during non-survey periods.

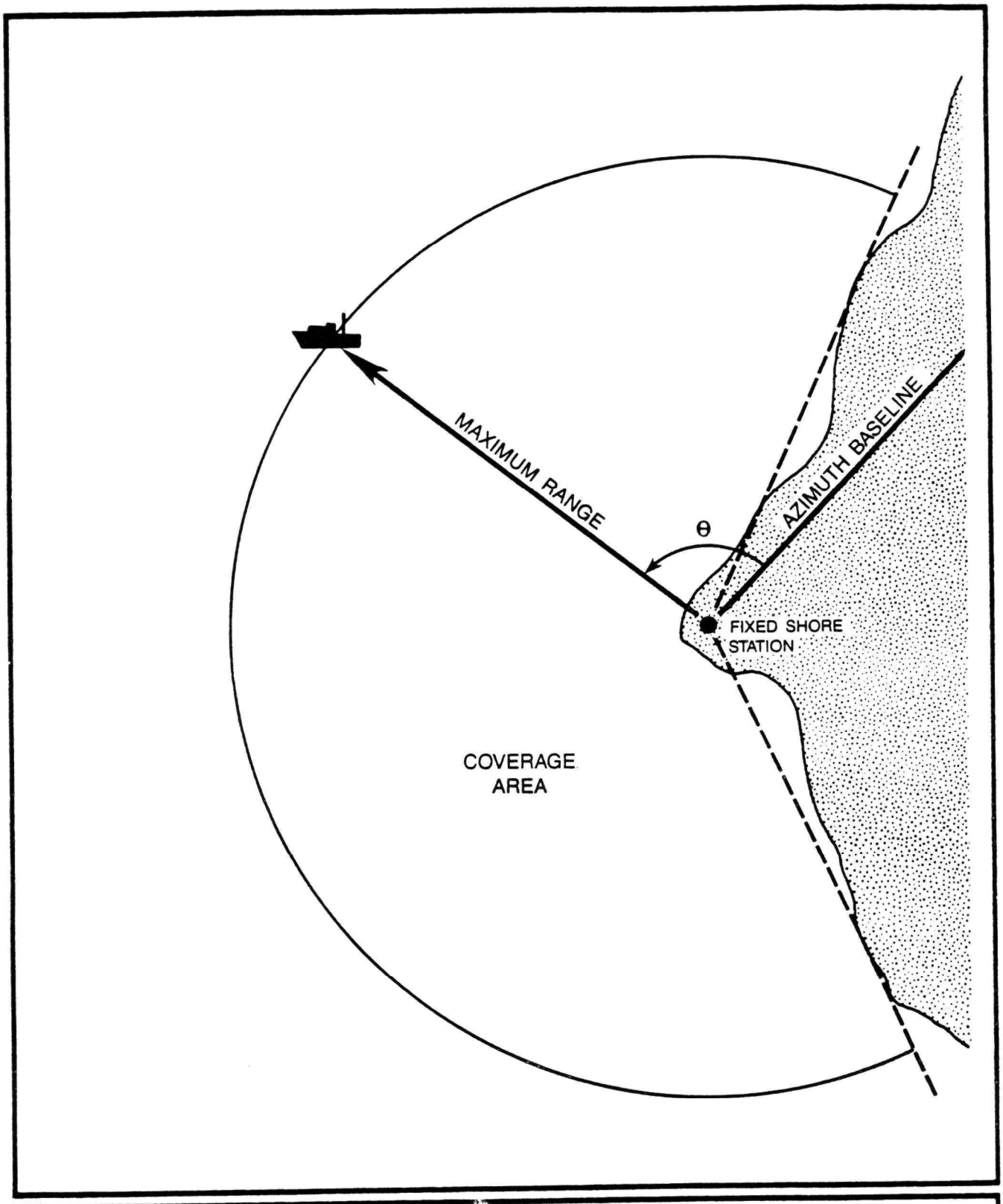


Figure 10. Range-azimuth positioning system area of coverage.

4. SYSTEM SELECTION PROCEDURE

The major steps in selecting a navigation system include design of the overall monitoring program, definition of specific positioning requirements, and evaluation of available systems. Actual implementation of the system involves approval and procurement of the selected system, assembly and installation of shore stations, and equipment calibration and field-testing.

DEFINING POSITION REQUIREMENTS

The maximum allowable positional error of the selected navigational system is based on the required absolute positional accuracy at each proposed monitoring station (e.g., within-ZID, ZID-boundary, near-ZID, gradient, reference, and nearshore stations). To determine the needed accuracy for position locations, a variety of information can be used. For example, defining the characteristics of each station by type, location, water depth, estimated time on-station, and frequency with which it will be occupied would be useful for determining accuracy requirements. Using the depth criterion selected, such as that described in Section 2 of this report, the maximum recommended positional error can be calculated for each station. Using this method, either the ZID-boundary or a shallower station away from the ZID could result in the most stringent accuracy requirement. Additional error allowances for non-ZID boundary stations and state agency requirements (e.g., mixing zone limitations) may also be determined. Ranges to each station from the midpoint and extreme upcoast and downcoast limits of the sampling area can be determined from a nautical chart. Biological trawl paths and navigational hazards can also be indicated on a monitoring station diagram which depicts the outfall, ZID, special habitats, potentially impacted areas, and the fixed monitoring stations.

Based on a general knowledge of available systems (i.e., range-azimuth, azimuth-azimuth, range-range, or hyperbolic), candidate locations for onshore stations should be examined. Estimates of positional errors should be

based on anticipated LOP or angle errors expected at each station. Alternate shore station locations should be examined to define one or more locations that will provide coverage of the entire sampling area using different types of systems. A summary of limiting factors within the survey area and at individual sites should be developed, based on an inspection of each candidate shore station site. Line-of-site obstructions, traffic frequency, competing transmitters, air-water boundary irregularities, accessibility, and security should be evaluated. Having established accuracy requirements and survey area characteristics, the planner can then proceed with selection of appropriate screening criteria.

ESTABLISHING SCREENING CRITERIA

It is important to establish a set of screening criteria appropriate for the intended uses of the navigational equipment. Possible screening criteria include achievable range compared with the distance to the farthest monitoring station, equipment accuracy compared to the levels specified for each station, availability of equipment, and initial cost relative to available funds. Systems surviving the initial screening may be examined further. Categories of positioning systems, and the effect of applying such criteria are presented in Figure 11.

Range Considerations

Eight equipment categories are shown as input to the Level I range screening. Visibility and infrared limitations may eliminate theodolites, EDMIs, total stations, and two of the range-azimuth systems, depending on distance capability needed. Use of multiple prisms and possible directional clusters must be considered at this step. Screening effects are shown here only graphically as dashed lines going into Level II. However, in an actual screening, a number of specific instrument models in each of these categories may be dropped from further consideration due to inability to operate at the distances needed. Fortunately, sea conditions conducive to sampling are coincident with relatively high visibilities. The desire to continue sampling under other than ideal conditions may be balanced against the inconvenience of resampling on a better day. The presence

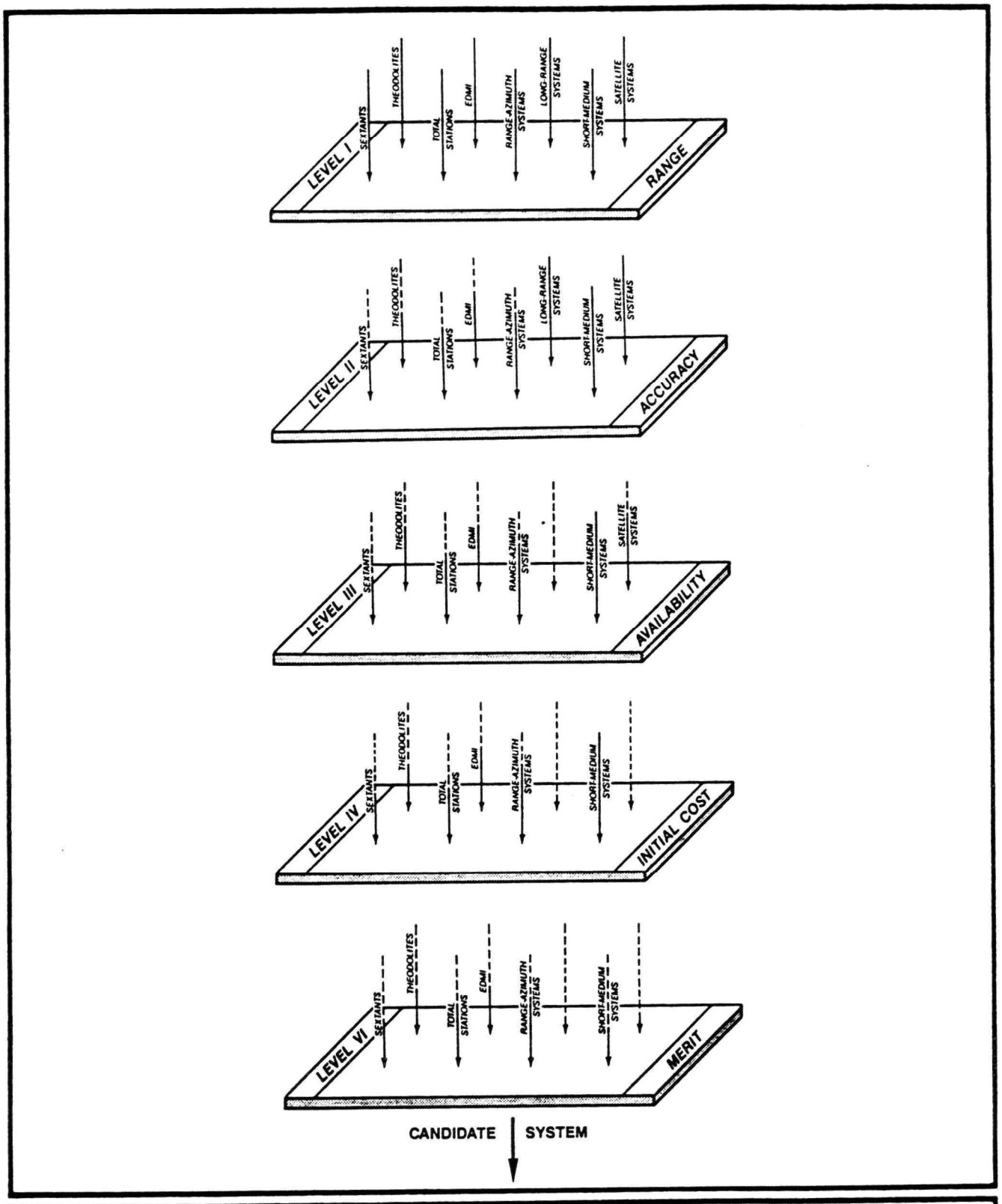


Figure 11. Navigation system preliminary screening criteria.

of navigational hazards or the difficulty in returning to port may preclude sampling under low-visibility conditions.

Accuracy Capability

At the accuracy levels used in the earlier example, long-range positioning systems may virtually be dropped from further consideration. Even when operated in a differential mode, such systems do not provide the selected positioning accuracy. They have been designed for navigating or distant positioning in open seas, where absolute accuracy is usually unimportant. An exception might be to retrieve oceanographic equipment. Even then, to be within 50 m (165 ft) is usually sufficient to sight the resurfaced package, which is normally equipped with a radar antenna. Some of the medium-range systems and all of the short-range systems pass the screening at the selected accuracy level. In this example, the number of candidate satellite systems is reduced by this screening because Transit-based systems cannot achieve accuracy requirements in the required relatively short time frame. All other systems provide the absolute accuracies selected, and thus are not further eliminated at Level II.

Availability

Assuming that a monitoring program must be implemented by mid-1986, virtually all candidate satellite systems that can provide the required accuracy would have to be dropped from further consideration. Several are early in the planning stage (e.g., GEOSTAR). For others, the manufacturers do not anticipate full operation before the end of 1986 or mid-1987 (e.g., ISTRAC SERIES and Aero Service Marine GPS). All other systems are available, limited only by the procurement period.

Capital and Operating Costs

Remaining medium-range systems, except Syledis, exceed $100,000. Microwave systems typically cost $40,000-$65,000, with one (Autotape) at $90,000. The three range-azimuth systems (which may offer greater flexibility for other work and reduced logistical problems) range from $64,500 for

an AZTRAC plus Falcon 484 to $100,000 for POLARFIX. ARTEMIS is intermediate in cost, at $70,000. Remaining systems (total stations for $9,000 manual, $15,000-$25,000 automatic; EDMI and theodolites for $10,000-$12,000; a pair of sextants for $8,000 maximum; two theodolites for $4,000-$8,000) are all significantly lower in initial cost. However, these are typically much more labor-intensive and complicated logistically. It may be necessary to factor these additional "costs" in over the life of the system. Thus, all but one of the medium-range systems and one of the short-range systems might be dropped from further consideration. However, representatives from each category passing Level III may remain after the Level IV screening based on initial cost alone. Further cost-benefit analyses are appropriate at this step. The option of renting or leasing the selected system might also be considered.

REVIEW OF CANDIDATE SYSTEMS

The initial screening process eliminates systems without the required range or accuracy capabilities (as described in the previous section). Systems surviving this initial cut may then be carefully examined for capability and cost. Important additional factors include compatibility with any existing equipment, ability to accommodate future system expansion, and availability of ancillary items (e.g., data logger, plotter, tracking monitor, or computer). Flexibility to use the system for other work may also be relevant. For example, street improvement projects or dredging of a navigation channels may also require use of the navigation equipment. Such projects may be in high-traffic areas, near signal interference sources, near tall structures that block line-of-sight, or perhaps up a sinuous river. In such cases, attributes of a particular system type (e.g., range-azimuth) may warrant more careful examination of available systems in that category.

PURCHASE/LEASE OPTION EVALUATION

Short-term rental or long-term leasing of equipment may be considered as an alternative to purchase of a positioning system. A short-term rental limits costs to the actual surveying periods only and avoids maintenance

responsibilities. Long-term leasing affords continued access for applications other than coastal surveying, at reduced daily or monthly rates. These two options may be particularly attractive to smaller municipalities unable to justify or fund the initial cost of surveying equipment. These arrangements are also attractive during periods of rapid navigation system development if such developments indicate that adequate systems will be available in the near future at lower capital costs. Current efforts in the satellite navigation field are an example of such development.

Three principal sources of rental equipment are manufacturers (usually only lease/purchase option plans), companies with a large pool of surveying and navigation equipment devoted exclusively to equipment rentals, and service firms that normally provide staff and equipment to support a field survey. Some environmental consulting firms also maintain equipment lease pools, since equipment is used routinely in the conduct of field work. The monthly rental cost of equipment is often set at 10 percent of the suggested retail cost. However, short-term rates for many items are categorized by the number of rental days (e.g., 1-10, 11-90, and 91 plus). Rent/purchase options are available, enabling ownership transfer to the renter for a nominal amount at the end of a fixed rental period. In some cases, eventual purchase of a rented item is optional, with a set amount of the rental fee (e.g., 50-80 percent) applied to the purchase price when the option is exercised.

Typical 1985 rental costs for candidate positioning systems are shown in Table 3. As indicated, a theodolite/EDMI pair can be rented for approximately $50-$85 per day for short periods, or $20-$35 for periods over 3 months. Total stations rent for $40-$100 per day on a short-term basis, depending on how elaborate (e.g., automatic) the station is. For longer periods, the daily rate drops to $15-$60. Hydrographic systems range from approximately $175 to $200 per day (e.g., Trisponder 202, Mini Ranger III, or Cubic Autotape). Monthly rates are typically $3,000 for basic systems, but can exceed $15,000 for more elaborate systems.

Although the cost information presented herein will change, the range of costs indicated should enable the potential user to consider rent/lease

TABLE 3. TYPICAL 1985 EQUIPMENT RENTAL COSTS

Category		Daily Cost (Dollars) 1-10 Days	11-90 Days	91+ Days	Monthly
Theodolites	1"	25-35	18-21	12-15	
	6-10"	22-25	13-15	9-12	
	20"	15-18	10-13	7-10	
EDMIs	1.0-2.0 km	25-30	15-19	10-13	
	2.0-6.0 km	25-65	18-39	15-20	
	>6.0	40-50	25-30	16-22	
Total Stations	Automatic	75-110	45-70	30-60	
	Manual	40-50	25-45	16-20	
Hydrographic Systems					
Trisponder 202	175				2,750
Cubic Auto Tape (3 range)	200	105	90		
Motorola Mini Ranger II (including 2 transponders)	200	105	90		3,750
(additional transponders)	36	18	12		

as well as procurement when evaluating the cost-effectiveness of applicable systems. It may also be appropriate to include the cost of one or more equipment technicians or operators (typically at $300 per day plus expenses) to provide reliable navigation data for each survey.

5. SUMMARY OF RECOMMENDED PROCEDURES AND EQUIPMENT

Based on this evaluation, the systems recommended for coastal positioning include theodolite, sextants, EDMIs, total stations, and microwave and range-azimuth systems. Although satellite systems offer adequate accuracy, they require further development. However, satellite systems should be considered in future applications. This final discussion is a summary of the recommended positioning techniques for coastal navigation.

CANDIDATE SYSTEM SELECTION

Positioning techniques and associated equipment were described in previous sections of this report. No single system is best for all coastal monitoring purposes, as needs will vary according to size and complexity of the planned monitoring program, nature of the immediate and surrounding areas, and other navigational or surveying requirements of a municipality.

Positioning techniques fall into three principal measurement categories:

- Multiple Horizontal Angles

  Theodolite Intersection
  Sextant Angle Resection

- Multiple Electronic Ranges

  Distance-Measuring Instruments
  Range-Range Mode
  Hyperbolic Mode
  Satellite Ranging

- Range and Angle

  Theodolite and EDMI
  Total Station
  Range-Azimuth Navigation Systems.

Systems within these categories which will meet or exceed the positional accuracy levels recommended herein are summarized in Table 4.

Multiple Horizontal Angles

In the first category, theodolites were found to have the angular accuracies required, out to the maximum ranges anticipated. Their costs range from $1,000 to $4,000 (30-sec vs. 10-sec accuracy) and are readily available due to general use as a surveying instrument. At least two theodolites, two operators, a vessel siting target, and a three-way communications link to coordinate fixes are required. Visibility can be a limiting factor.

By comparison, sextant angle resection can be performed using one instrument if the vessel is stationary, or using two instruments simultaneously if the vessel is moving. Achievable angular accuracy of ±10 sec is adequate and relatively inexpensive sextants ($1,000-$2,000) are readily available. Again, visible range can be limiting. Shooting an accurate fix from a nonstationary platform in any significant sea or swell could be more difficult than shooting with theodolites from shore. A distinct advantage of sextant angle resection is location of the navigators on the survey vessel. The method generally requires highly visible shore targets and a three-arm protractor for plotting positions.

Multiple Electronic Ranges

Positioning using multiple ranges can be accomplished with two staffed EDMI stations. Accuracies were found to be more than adequate but ranges were found to be marginal [if needed beyond 3 km (1.9 mi)] unless multiple prisms were used. Because such prisms are directional, procurement of multiple clusters for more than one direction could result in a significant

TABLE 4. SUMMARY OF RECOMMENDED SYSTEMS

Category	Representative Equipment	Accuracy	Cost	Advantages	Disadvantages
Theodolite	Table B-1 Table B-2	10-30 sec ± 1 m (3.3 ft)	$1,000-$4,000	Traditional method. Inexpensive. High accuracy. Successfully applied. Restricted areas.	Line-of-sight. Two manned shore stations. Simultaneous measurements. Limits on intersection angles. Area coverage; station movement.
Sextant	Table B-3	± 10 sec ± 2 m (6.6 ft)	$1,000-$2,000	Rapid. Easy to implement. Most widely used. Low cost. No shore party. High accuracy.	Simultaneous measurement of two angles. Target visibilities, location, maintenance. Line-of-sight. Best in calm conditions. Limits on acceptable angles.
EDMI	Table B-4	1.5-3.0 cm	$3,500-$15,000	Extremely accurate. Usable for other surveying projects. Cost. Compact, portable, rugged.	Motion and directionality of reflectors. Visibility, unless microwave. Two shore stations. Ground wave reflection.
Total Stations	Table B-5	5-7 cm	$8,000-$30,000	Single onshore station. Other uses. Minimum logistics.	Reflector movement and directionality. Prism costs.
Microwave Navigation Systems	Table B-6	± 1-3 m	$40,000-$90,000	No visiblity restrictions. Multiple users. Highly accurate. Radio line-of-sight.	Cost. Multiple onshore stations. Logistics. Security.
Range-Azimuth Systems	Table B-10	0.01° and 0.5 m	$65,000-$100,000	High accuracy. Single station. Circular coverage.	Single user. Cost.
Satellite Systems	Table B-9	1-10 m	$150,000-$300,000 (initial units)	High accuracy. Minimum logistics. Use in restricted/congested areas. Future cost. No shore stations.	Current coverage. Initial development cost.

cost beyond the initial investment of $3,500-$5,000 each for the two shorter-range units, or $8,000-$15,000 each for the two longer-range units. Several microwave navigation systems with more than adequate range and sufficient accuracy are available in the $40,000-$90,000 range. Limitations include geometry of shore stations, position of the vessel in the coverage area (i.e., crossing angle limitations), and possible interferences due to line-of-sight obstructions, sea-surface reflective nulls, and land-sea boundaries. The hyperbolic mode provides multiple user capability, but at the cost of an additional shore station.

Satellite ranging holds promise because required accuracies should be achievable in the near future. Transit satellite-based systems do not offer sufficient accuracy, except with multiple passes, and multiple passes are impractical when a given sampling station is occupied only briefly. Accuracies needed will undoubtedly be achievable in the future using differential GPS techniques ($10,000-$40,000 for first units; as low as $1,000 for subsequent production models). Commercial geosynchronous satellite networks, such as GEOSTAR, may become available at a proposed system interrogator cost of $450 plus a monthly fee. However, this system is in the very early stages of planning, having only recently received FCC approval of requested frequencies. Finally, the codeless GPS systems (SERIES or Aero Services Marine GPS System) currently under development could be used, but at a current cost of over $250,000.

Range and Angle

Systems in the range-azimuth category show great promise. Required angular and range accuracies are available, only one shore station is needed, and costs depend on system refinements. At the low end of the scale, an EDMI and theodolite could be paired with a communication link for approximately $10,000-$12,000. Total stations developed specifically for this requirement range in cost from $8,000 for a manual station to $15,000-$30,000 for a fully automatic station. Optical and infrared range limitations apply to these systems. Finally, the three range-azimuth navigational systems examined provide sufficient positional accuracy with a single station at

costs ranging from $65,000 for manual tracking to $70,000-$100,000 for fully automatic tracking.

SHALLOW-WATER POSITIONING METHODS

When sampling stations are located in relatively shallow water, they can be identified by relatively inexpensive methods (in addition to those discussed earlier in this report). Provided the center of the ZID over the outfall can be located (e.g., by diver-positioned surface float) an optical range finder may be used to establish the required distances to nearby water quality or biological sampling stations. An optical range finder is used by simply focusing a split-image on the target float, enabling the slant distances to the target to be read off the instrument scale. When combined with a careful compass reading, this distance reading allows positioning of the sampling vessel. Positioning in this way enables profiling of the water column or collection of grab samples of bottom sediments.

A survey of accuracies claimed for commercially available instruments suggests that the ±3 m (9.8 ft) recommended minimum accuracy can be achieved within approximately 100 m (328 ft) of the surface target. The Lietz Model 1200, for example, provides an accuracy of ±1 m (3.3 ft) at 100 m (328 ft). Beyond this distance, instrumental errors increase rapidly. For the instrument cited, a ±9 m (29.5 ft) accuracy is quoted at 300 m (984 ft). The suggested U.S. list prices of optical range finders vary from $35 to $120 (Folk, L., 21 March 1985, personal communication).

An acceptable alternate method of collecting bottom samples from desired locations in shallow water is to use divers. Provided visibility is adequate, divers may measure radial distances to desired locations by holding a tape at the outfall and traversing the appropriate distance over the bottom in the proper direction.

Visual ranges have sometimes been used to establish a station position. This method requires that a minimum of two objects are in alignment, enabling the vessel to be placed on a common axis extending to the vessel's position. Simultaneous siting on a second set of at least two objects places the

vessel at the intersection of the two common axes. The accuracy of each visual range is highly dependent on the quality of the visual range (e.g., alignment), the distance from the alignment objects to the vessel, and the angle between each range. Also, the number of visual ranges used affects the magnitude of the positional error. Although this technique is frequently used for positioning single sampling stations in bays and harbors or otherwise where a number of convenient alignable targets can be selected, the method is not considered acceptable for coastal monitoring at ZID boundary stations. Even when a desired sampling station has been accurately located using one of the previously discussed methods, and at that location at least three aligned target-pairs are visible, it is not likely that sufficient alignment target-pairs will be present for all other desired locations. Also, the unpredictability of positional error each time a station is reoccupied detracts from the value of this method.

Permanent installation of a marker buoy at the outfall terminus or midpoint of the diffuser allows easy return to this point on subsequent sampling trips. Using the previously discussed range-finder technique or a line of desired length enables positioning at desired distances from the marker buoy. However, it is not uncommon to lose such a buoy due to vandalism, impact, or severe wind and wave forces which cause its release and movement from the site. Therefore, it is necessary that the sampling party be prepared to relocate the outfall station (e.g., by diver, sonar, or pinger mounted on the outfall itself), if location of other stations are dependent on locating this station first.

Because the techniques described here are inexpensive to implement (as are use of the sextant resection or theodolite intersection methods), they are attractive to small coastal municipalities. However, as discussed in Section 4, use of more sophisticated and less labor-dependent techniques may be achievable at moderate costs by renting or leasing, rather than buying such equipment. Such options may be considered, provided the recommended absolute positional accuracies can be achieved by the technique selected.

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APPENDIX A

POSITION ERROR ANALYSIS

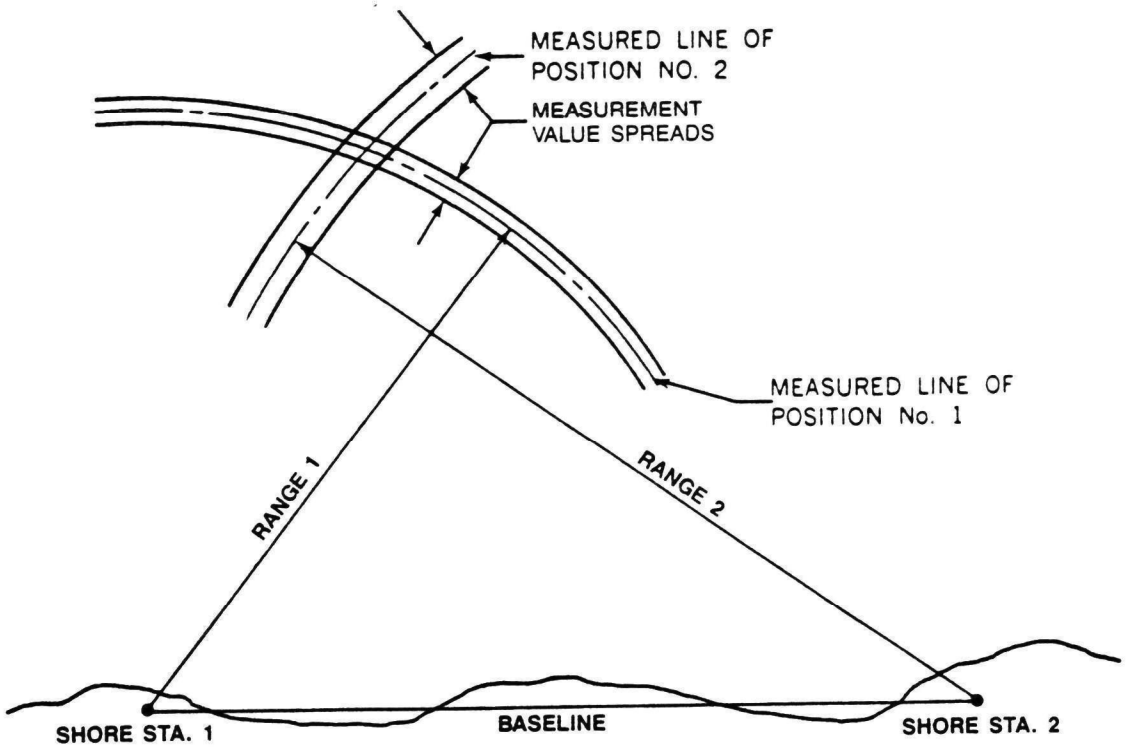
APPENDIX A

ANALYSIS OF POSITION ERROR

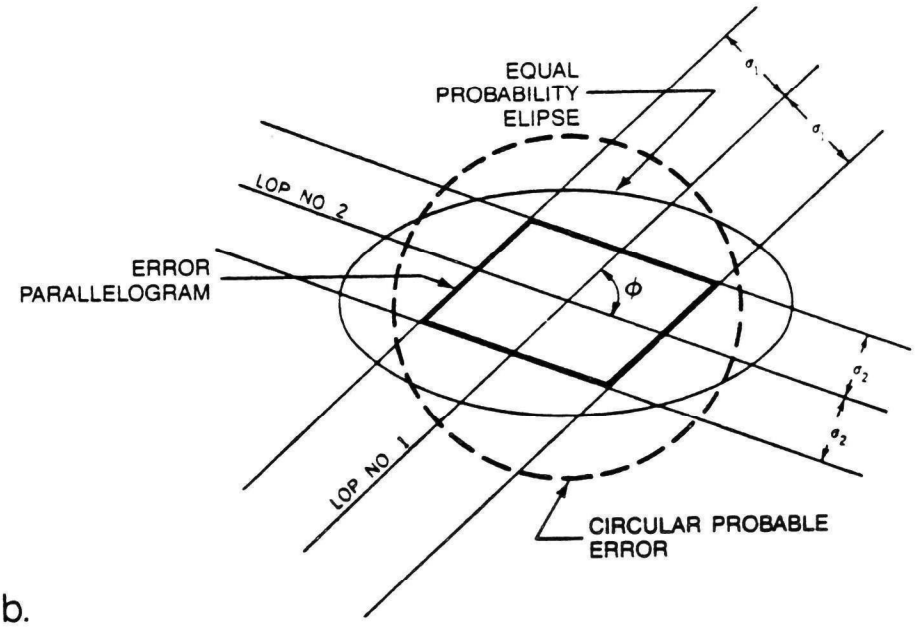
Traditionally, position errors have been classified into three categories: gross, systematic, and random (Mikhail and Gracie 1981). Gross errors are mistakes due to observer carelessness and must be detected and eliminated from positional measurements. Systematic errors occur due to a deterministic system, in this case the sextant, range finder, or electronic positioning equipment. Such errors can be expressed by functional relationships and can therefore be corrected for in the final measurement. Random errors reflect variations in measurements that remain after eliminating gross errors and allowing for systematic errors. As their name implies, such observational errors are random and have no known functional relationship. Random errors, the subject of the following discussion, are dealt with on a statistical basis using probability models.

All positional fixes are in error to some extent. This is true even if the transmitting stations have been very accurately located and bias or systematic errors in position coordinates have been eliminated. Random errors will still cause a variable displacement of position lines about their computed positions.

Positional accuracy is usually stated in terms of the probability of being within a certain distance of a desired geographical location. The uncertainty in each line of position can be described by its standard deviation (σ), which is the square root of the sum of the squares of deviations from the mean line-of-position (LOP) value, divided by one less than the number of repetitive measurements. The LOP can therefore be considered a strip whose width is a function of the LOP uncertainty, or standard deviation (Figure A-1a). Because a fix involves at least two LOPs, each having an uncertainty, the LOP crossing boundary forms a parallelogram (Figure A-1b).



a.



b.

SOURCE: MODIFIED FROM BOWDITCH 1984

Figure A-1. Line of position measurements from two shore stations, depicting LOP uncertainty (a), and associated error indicator (b).

The parallelogram area is dependent on the size of the standard deviations of the two LOPs and the angle at which they cross. The parallelogram area is given by:

$$A = (2\sigma_1)(2\sigma_2) \csc = 4\sigma_1\sigma_2 \csc\phi \qquad \text{(A-1)}$$

where σ_1 and σ_2 are the LOP measurement standard deviations. As the cosecant function becomes large for angles less than 30° and more than 150°, so too does the size of the error parallelogram (Figure A-2). Thus, to reduce positional uncertainties, shore station locations should be located such that very large or very small cut angles do not occur within the survey area.

Probability theory indicates a 68.3 percent chance of being within $\pm 1.0\sigma$ of the mean of a set of normally distributed measurements. However, the probability that the measured position is within the parallelogram is less. For two sets of measurements, the joint or product probability is $(0.683)^2 \times 100$ or 46.6 percent. A probable parallelogram is defined as one for which the probability of a measurements being within its boundary is 50 percent. This occurs at distances slightly larger than $\pm 1.0\sigma$ (i.e., $\pm 1.05\sigma$). Using $\pm 2.0\sigma$ results in a parallelogram within which it is 91 percent probable that the positional location occurs. A parallelogram constructed to reflect a specific probability that the actual position will lie within its boundaries, is easy to overlay on a nautical chart. The principal drawback is that the error parallelogram is not a curve of equal probability. The chance of being located in a small area adjacent to the midpoint of one of the sides is greater than the chance of being in an equal size area located in one of the corners.

An equal probability contour from a two-LOP fix is an ellipse centered on the LOP intersections (Figure A-1b). This can be seen by examining the density function of two jointly distributed random variables, called a bivariate normal distribution. The joint distribution has the form of a bell-shaped surface as shown in Figure A-3 (Mikhail and Gracie 1981). Any plane parallel to the x,y coordinate plane cuts the bivariate density surface in an ellipse. As with the parallelogram, the area and configuration

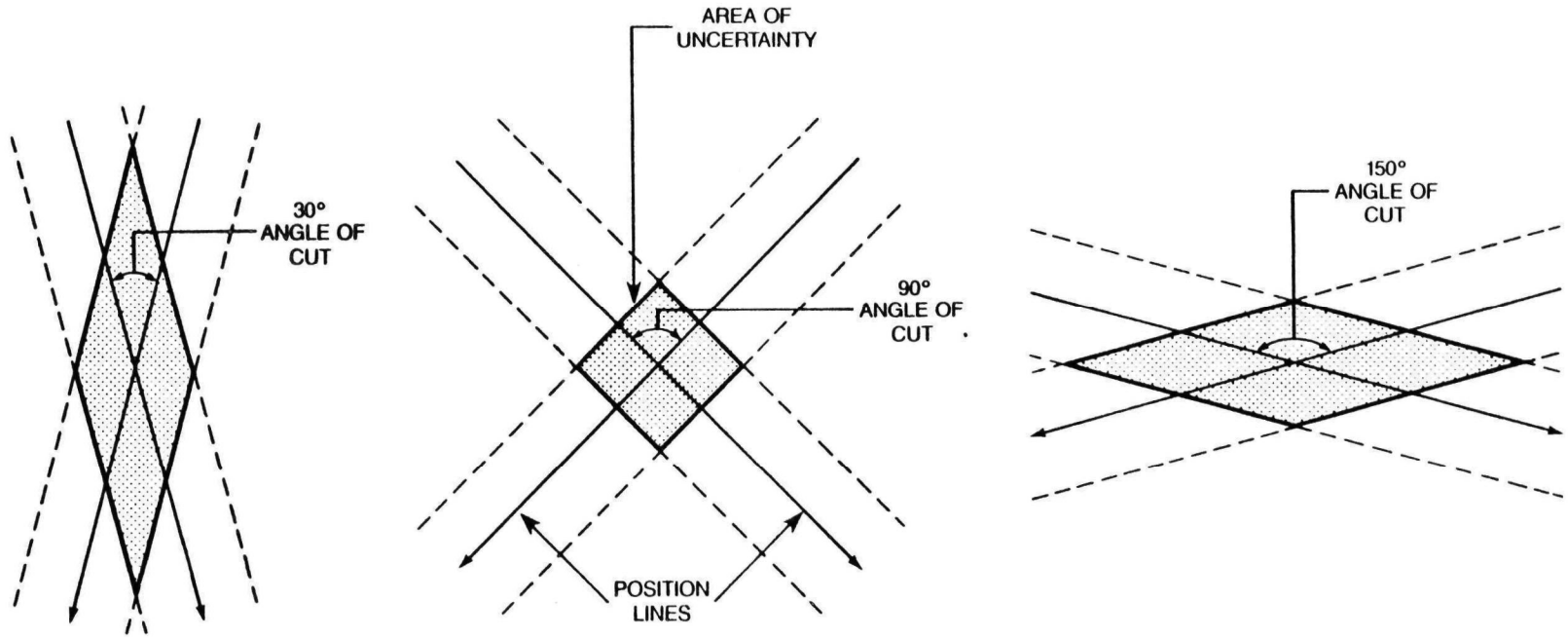
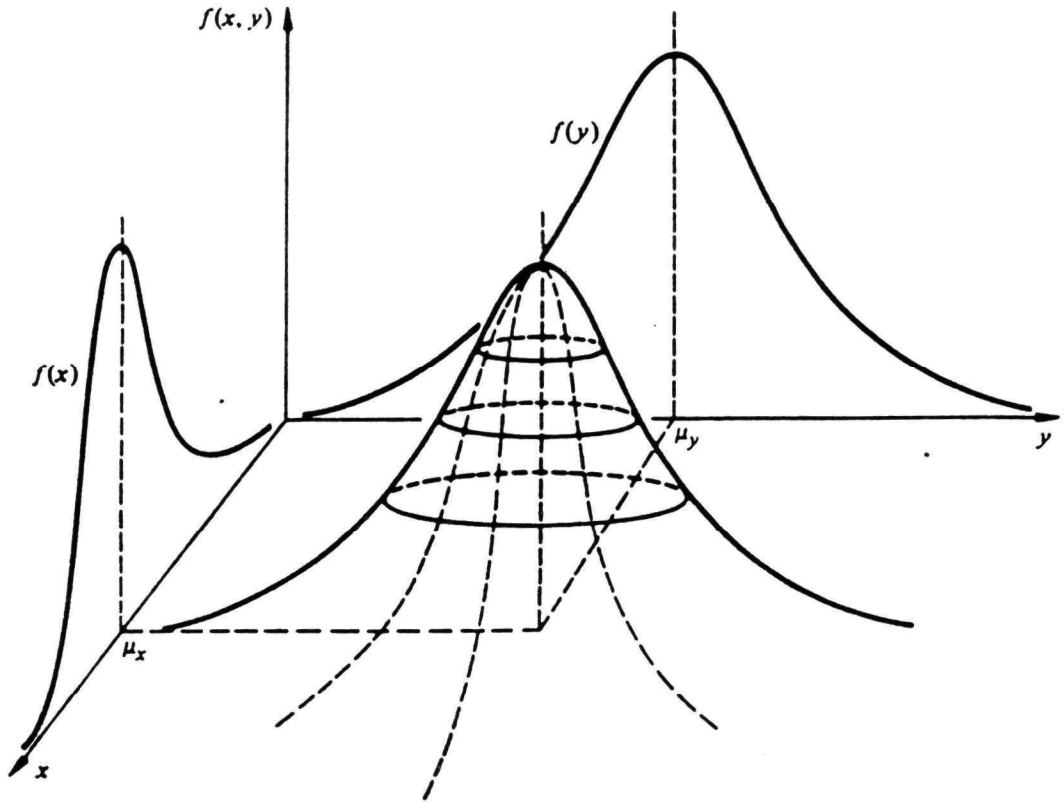


Figure A-2. Angle-of-cut effects on fix accuracy



SOURCE: MIKHAIL AND GRACIE 1981

Figure A-3. Density function of two jointly distributed random variables.

of the error ellipse are dependent on the crossing angle and standard deviations in each set of measurements. The ellipse in which 50 percent of the expected measurements lie is referred to as the probable ellipse. The major axis of the ellipse will pass through the true position and lie within the LOP acute crossing angle. Techniques for determining the orientation and the magnitudes of an error ellipse for various probability levels are presented by Mikhail and Gracie (1981).

When the error density distributions of two sets of measurements are equal and the cut angle is 90°, the error figure becomes a circular normal distribution. At a radial distance from the true position equal to 1σ, there is a 39.9 percent chance of being located within the circle. A 50 percent probability occurs for a circle with a 1.18σ radius and a 90 percent probability occurs for a circle with a 2.2σ radius. These probabilities change as the cut angle varies from 90°, and as the two LOP standard deviations differ from each other. For example, if $\sigma_1 = \sigma_2$ and the cut angle is 40°, the circle having a radius of 1σ corresponds to a 26 percent probability. A 50 percent probability occurs at 1.62σ. A radius greater than 3.4σ is needed to achieve a 90 percent probability that the position lies within the circle boundary.

It is more common to establish the probability that a position is located within a circle of a particular radius than to define an error ellipse. The resultant circular probable error (CPE or CEP) is the radius of a circle within which 50 percent of the fixes should be located (Figure A-1b). Bowditch (1984) provides two methods for determining the sizes of error circles at a desired probability level, given the standard deviation in each LOP measurement and the associated pattern crossing angle. Alternately, the probability that the measured position is within a circle of a selected radius can also be determined.

As the cut angle approaches 90°, the probability of measurements being within a circle of given radius increases. Or, alternately, the radius within which a certain percentage of all measurements will fall decreases. Table A-1 can be used in the special case where the σ values of the two fix measurements are equal. For example, for a circle error radius (R)

TABLE A-1. PROBABILITY VERSUS R/σ FOR ELLIPTICAL BIVARIATE DISTRIBUTIONS WITH TWO EQUAL STANDARD DEVIATIONS

R/σ \ θ	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
0.0																		.000
0.1																		.005
0.2	.001	.004	.006	.007	.009	.011	.011	.012	.014	.015	.016	.017	.018	.018	.019	.019	.019	.020
0.3	.005	.009	.012	.015	.019	.022	.025	.028	.031	.034	.036	.038	.040	.041	.042	.043	.044	.044
0.4	.008	.014	.021	.027	.033	.039	.045	.050	.055	.059	.063	.067	.070	.072	.074	.076	.077	.077
0.5	.009	.019	.029	.039	.048	.057	.066	.074	.083	.090	.096	.102	.106	.110	.114	.116	.117	.118
0.6	.014	.029	.043	.057	.070	.082	.095	.106	.117	.127	.135	.143	.150	.156	.159	.162	.164	.165
0.7	.020	.039	.057	.075	.093	.110	.126	.141	.155	.168	.179	.189	.198	.205	.211	.215	.217	.217
0.8	.025	.048	.072	.095	.117	.138	.158	.177	.195	.211	.226	.238	.249	.258	.265	.270	.273	.274
0.9	.031	.060	.088	.116	.143	.169	.196	.217	.238	.257	.275	.290	.303	.314	.322	.328	.332	.333
1.0	.035	.070	.104	.137	.169	.199	.228	.256	.281	.305	.326	.343	.358	.371	.381	.388	.392	.393
1.1	.040	.080	.120	.158	.196	.231	.265	.296	.325	.352	.366	.396	.414	.428	.440	.448	.452	.454
1.2	.046	.092	.136	.181	.224	.264	.302	.337	.370	.400	.426	.449	.469	.485	.497	.506	.512	.513
1.3	.053	.104	.155	.204	.251	.296	.339	.378	.414	.446	.475	.501	.522	.540	.553	.563	.569	.570
1.4	.058	.115	.171	.226	.278	.327	.374	.417	.456	.491	.523	.550	.573	.582	.606	.617	.623	.625
1.5	.063	.126	.188	.247	.304	.358	.408	.455	.497	.535	.568	.597	.621	.641	.656	.667	.673	.675
1.6	.069	.138	.204	.269	.330	.388	.442	.491	.536	.576	.611	.640	.666	.686	.702	.713	.720	.722
1.7	.074	.148	.220	.289	.355	.417	.471	.526	.573	.615	.650	.682	.707	.728	.744	.756	.762	.764
1.8	.079	.159	.236	.310	.380	.445	.505	.559	.608	.651	.688	.719	.745	.766	.782	.793	.800	.802
1.9	.084	.169	.251	.329	.403	.471	.536	.591	.641	.685	.722	.754	.780	.800	.816	.827	.833	.836
2.0	.089	.179	.266	.349	.426	.498	.563	.621	.672	.716	.753	.785	.810	.832	.846	.856	.862	.865
2.1	.093	.189	.280	.367	.448	.523	.589	.649	.700	.744	.780	.812	.837	.857	.871	.881	.887	.890
2.2	.099	.199	.295	.386	.470	.546	.615	.675	.727	.771	.808	.838	.861	.880	.894	.903	.909	.911
2.3	.104	.209	.309	.404	.490	.570	.639	.700	.752	.795	.831	.860	.883	.900	.913	.922	.927	.929
2.4	.109	.219	.324	.422	.512	.592	.663	.724	.775	.818	.852	.880	.901	.918	.930	.938	.942	.944
2.5	.115	.229	.338	.440	.532	.614	.686	.746	.797	.838	.871	.897	.918	.933	.943	.951	.955	.956
2.6	.119	.239	.352	.457	.551	.634	.706	.766	.816	.856	.888	.912	.931	.945	.954	.961	.964	.966
2.7	.124	.248	.366	.474	.570	.654	.726	.786	.835	.873	.903	.926	.943	.955	.964	.969	.973	.974
2.8	.129	.258	.379	.490	.589	.674	.746	.805	.851	.888	.916	.937	.953	.963	.971	.976	.979	.980
2.9	.134	.268	.393	.507	.607	.692	.763	.821	.867	.902	.928	.947	.961	.971	.978	.982	.984	.985
3.0	.139	.277	.406	.522	.624	.710	.781	.837	.880	.914	.938	.956	.968	.976	.982	.986	.988	.989
3.1	.144	.287	.419	.538	.641	.727	.797	.852	.893	.924	.947	.963	.974	.982	.986	.989	.991	.992
3.2	.149	.296	.432	.553	.657	.743	.812	.865	.905	.934	.955	.969	.979	.985	.990	.992	.993	.994
3.3	.154	.306	.445	.568	.673	.759	.826	.878	.916	.943	.962	.975	.983	.989	.992	.994	.995	.996
3.4	.159	.315	.458	.583	.688	.773	.840	.889	.925	.951	.968	.979	.986	.991	.994	.996	.997	.997
3.5	.164	.324	.470	.597	.703	.788	.852	.900	.934	.957	.973	.983	.989	.993	.995	.997	.998	.998
3.6	.169	.333	.482	.611	.717	.801	.864	.910	.942	.963	.977	.986	.991	.995	.997	.998	.998	.999
3.7	.174	.343	.494	.625	.731	.814	.875	.919	.949	.968	.981	.990	.993	.996	.998	.998	.999	.999
3.8	.179	.352	.506	.638	.744	.826	.886	.927	.955	.973	.984	.991	.995	.997	.998	.999	.999	1.000
3.9	.183	.360	.518	.651	.757	.838	.895	.935	.961	.977	.987	.993	.996	.998	.999	.999	1.000	1.000
4.0	.189	.370	.529	.664	.770	.848	.904	.942	.966	.980	.989	.994	.997	.998	.999	.999	1.000	1.000
4.1	.193	.378	.541	.676	.781	.859	.913	.948	.970	.983	.991	.995	.998	.999	.999	1.000	1.000	1.000
4.2	.198	.387	.552	.688	.793	.869	.920	.954	.974	.986	.993	.996	.998	.999	.999	1.000	1.000	1.000
4.3	.203	.396	.564	.700	.804	.878	.927	.958	.978	.988	.994	.997	.999	.999	1.000	1.000	1.000	1.000
4.4																		1.000

Reference: Bowditch 1984.

equal to 1σ (i.e., the ratio of $R/\sigma=1$), the probability of measurements being within a circle this size varies from 3.5 percent at a 5° cut angle to 39.3 percent at a 90° cut angle, with a 26 percent probability occuring at 40° as mentioned earlier. At a given cut angle, as the R/σ ratio or error circle increases, so too does the probability that measurements will fall within the circle. At an angle of 40°, for example, as R/σ varies from 0.2 to 4.3, the probabilities vary from 1.2 to 95.8 percent. Thus, Table A-1 can be used to estimate the size of the error circle, for a given cut angle, when the two measurement standard deviations are equal. For example, when σ_1 and σ_2 = 20 m (66 ft) and the cut angle is 50°, the radius at which 50 percent of all measurements will be contained is determined by interpolating in Table A-1 between $R/\sigma = 1.4$ at a $P = 0.491$ and $R/\sigma = 1.5$ at $P = 0.535$ resulting in an $R/\sigma = 1.42$ at $P = 0.50$. Thus, the desired radius $R = 1.42\sigma$ or 28.4 m (93.2 ft).

Error circles about a measured position can be constructed for different LOP standard deviations and cut angles. This can be done by first calculating σ_x and σ_y, the standard deviations along the major and minor axes of the error ellipse (discussed later in this section), knowing the crossing angle and the standard deviations in each measurement (σ_1 and σ_2). Table A-2 is then used to provide probabilities as a function of c, the ratio of the smaller to larger of σ_x and σ_y, and K as the ratio of the error circle radius to the larger of σ_x or σ_y. For example, for a 50° angle of cut, a σ_1 = 15 m (49 ft) and σ_2 = 20 m (66 ft), the probability of location within a circle of 30 m (98 ft) is:

$$(\sigma_1)^2 = 225 \text{ m}^2$$
$$(\sigma_2)^2 = 400 \text{ m}^2$$
$$\sin^2\phi = 0.5868$$

Substituting into equations A-4 and A-5 (given in the following discussion on error ellipses), σ_x is 29.9 m (98.1 ft) and σ_y is 13.1 m (43.0 ft).

TABLE A-2. CIRCULAR ERROR PROBABILITIES AS A FUNCTION OF MEASUREMENT STANDARD DEVIATION RATIOS AND ERROR CIRCLE RADIUS

K \ c	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.1	.0796557	.0443987	.0242119	.0164176	.0123875	.0099377	.0082940	.0071157	.0062299	.0055400	.0049875
0.2	.1585194	.1339783	.0884533	.0628396	.0482413	.0390193	.0327123	.0281415	.0246824	.0219757	.0198013
0.3	.2358228	.2213804	.1739300	.1318281	.1039193	.0851535	.0719102	.0621386	.0546598	.0487639	.0440025
0.4	.3108435	.3010228	.2635181	.2139084	.1742045	.1451808	.1237982	.1076237	.0950495	.0850326	.0768837
0.5	.3829249	.3755584	.3481790	.3003001	.2532953	.2152880	.1857448	.1626829	.1443941	.1296280	.1175031
0.6	.4514938	.4457708	.4255605	.3846374	.3357384	.2914682	.2548177	.2251114	.2009797	.1811783	.1647298
0.7	.5160727	.5115048	.4960683	.4633258	.4170862	.3699305	.3280302	.2925654	.2629373	.2381583	.2172955
0.8	.5762892	.5725957	.5604457	.5349387	.4941882	.4474207	.4025628	.3627122	.3283453	.2989700	.2738510
0.9	.6318797	.6288721	.6191354	.5993140	.5651564	.5213998	.4759375	.4333628	.3953279	.3620135	.3330232
1.0	.6826895	.6802325	.6723586	.6568242	.6291249	.5900953	.5461319	.5025790	.4621421	.4257553	.3934693
1.1	.7286679	.7266597	.7202682	.7079681	.6859367	.6524489	.6116316	.5687467	.5272462	.4887873	.4539256
1.2	.7698607	.7682215	.7630305	.7532175	.7359558	.7079973	.6714269	.6306168	.5893494	.5498736	.5132477
1.3	.8063990	.8050648	.8008554	.7929968	.7793550	.7567265	.7249673	.6873122	.6474394	.6079822	.5704428
1.4	.8384867	.8374049	.8340018	.8277048	.8169851	.7989288	.7720889	.7383089	.7007900	.6623035	.6216889
1.5	.8663856	.8655127	.8627728	.8577362	.8493071	.8350816	.8129287	.7833962	.7489500	.7122546	.6753475
1.6	.8904014	.8897008	.8875060	.8834914	.8768644	.8657559	.8478393	.8226246	.7917194	.7574708	.7219627
1.7	.9108691	.9103102	.9085619	.9053766	.9001746	.8915536	.8773116	.8562471	.8291137	.7977882	.7462539
1.8	.9281394	.9276964	.9263125	.9237989	.9197275	.9130680	.9019110	.8846624	.8613238	.8332175	.8021013
1.9	.9425669	.9422182	.9411299	.9391586	.9359855	.9308615	.9222277	.9083609	.8886731	.8639149	.8355255
2.0	.9544997	.9542272	.9533775	.9518415	.9493815	.9454546	.9388418	.9278799	.9115762	.8901495	.8646647
2.1	.9642712	.9640598	.9634011	.9622127	.9603170	.9573205	.9522999	.9437668	.9305013	.9122714	.8897495
2.2	.9721931	.9720304	.9715237	.9706109	.9691597	.9668845	.9631017	.9565522	.9459386	.9306821	.9110784
2.3	.9785518	.9784275	.9780408	.9773450	.9762419	.9745239	.9716934	.9667306	.9583739	.9458085	.9289946
2.4	.9836049	.9835108	.9832180	.9826918	.9818594	.9805703	.9784661	.9747495	.9682698	.9580804	.9438652
2.5	.9875807	.9875100	.9872900	.9868953	.9862720	.9853112	.9837569	.9810035	.9760522	.9679136	.9570631
2.6	.9906776	.9906249	.9904612	.9901674	.9897045	.9889934	.9878527	.9858331	.9821023	.9756969	.9659525
2.7	.9930661	.9930271	.9929062	.9926894	.9923483	.9918260	.9909944	.9893268	.9867530	.9817837	.9738786
2.8	.9948897	.9948612	.9947727	.9946141	.9943649	.9939842	.9933821	.9923249	.9902888	.9864876	.9801569
2.9	.9962684	.9962477	.9961834	.9960684	.9958878	.9956126	.9951798	.9944246	.9929482	.9900803	.9850792
3.0	.9973002	.9972853	.9972391	.9971564	.9970266	.9968294	.9965205	.9959854	.9949274	.9927925	.9888910
3.1	.9980648	.9980542	.9980212	.9979622	.9978699	.9977296	.9975109	.9971348	.9963851	.9948168	.9918113
3.2	.9986257	.9986182	.9985949	.9985533	.9984880	.9983892	.9982356	.9979733	.9974478	.9963105	.9940240
3.3	.9990332	.9990279	.9990116	.9989824	.9989368	.9988677	.9987607	.9985792	.9982147	.9974004	.9956822
3.4	.9993261	.9993225	.9993112	.9992909	.9992593	.9992115	.9991376	.9990129	.9987626	.9981868	.9969113
3.5	.9995347	.9995323	.9995245	.9995105	.9994888	.9994559	.9994053	.9993204	.9991502	.9987480	.9978125
3.6	.9996818	.9996801	.9996748	.9996653	.9996505	.9996281	.9995938	.9995364	.9994218	.9991442	.9984662
3.7	.9997844	.9997832	.9997797	.9997733	.9997633	.9997482	.9997251	.9996867	.9996102	.9994208	.9989352
3.8	.9998553	.9998545	.9998522	.9998478	.9998412	.9998311	.9998157	.9997902	.9997396	.9996119	.9992682
3.9	.9999038	.9999033	.9999018	.9998989	.9998945	.9998878	.9998776	.9998608	.9998276	.9997426	.9995020
4.0	.9999367	.9999363	.9999353	.9999334	.9999305	.9999261	.9999195	.9999085	.9998870	.9998309	.9996645
4.1	.9999587	.9999585	.9999578	.9999566	.9999547	.9999519	.9999475	.9999404	.9999266	.9998900	.9997763
4.2	.9999733	.9999732	.9999727	.9999720	.9999707	.9999689	.9999661	.9999616	.9999527	.9999292	.9998523
4.3	.9999829	.9999828	.9999826	.9999821	.9999813	.9999801	.9999783	.9999754	.9999698	.9999548	.9999034
4.4	.9999892	.9999891	.9999889	.9999886	.9999881	.9999874	.9999863	.9999845	.9999809	.9999715	.9999375
4.5	.9999932	.9999932	.9999931	.9999929	.9999925	.9999921	.9999914	.9999902	.9999881	.9999822	.9999599
4.6	.9999958	.9999957	.9999957	.9999955	.9999954	.9999951	.9999947	.9999939	.9999926	.9999889	.9999746
4.7	.9999974	.9999974	.9999973	.9999973	.9999971	.9999970	.9999967	.9999963	.9999955	.9999932	.9999840
4.8	.9999984	.9999984	.9999984	.9999983	.9999983	.9999982	.9999980	.9999977	.9999972	.9999959	.9999901
4.9	.9999990	.9999990	.9999990	.9999990	.9999990	.9999989	.9999988	.9999986	.9999983	.9999975	.9999939
5.0	.9999994	.9999994	.9999994	.9999994	.9999994	.9999993	.9999993	.9999992	.9999990	.9999985	.9999963
5.1	.9999997	.9999997	.9999997	.9999996	.9999996	.9999996	.9999996	.9999995	.9999994	.9999991	.9999978
5.2	.9999998	.9999998	.9999998	.9999998	.9999998	.9999998	.9999998	.9999997	.9999997	.9999995	.9999987
5.3	.9999999	.9999999	.9999999	.9999999	.9999999	.9999999	.9999999	.9999998	.9999998	.9999997	.9999992
5.4	.9999999	.9999999	.9999999	.9999999	.9999999	.9999999	.9999999	.9999999	.9999999	.9999998	.9999995
5.5	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	.9999999	.9999999	.9999999	.9999997
5.6								1.0000000	1.0000000	.9999999	.9999998
5.7										1.0000000	.9999999
5.8											1.0000000
5.9											
6.0											

Reference: Bowditch 1984.

Therefore:

$$c = 13.1/29.9 = 0.44$$

and

$$K = 30/29.9 = 1.003$$

Entering Table A-2 for values K = 1.0 and c = 0.4 gives a probability of 62 percent.

The error circle approach has the advantage of being able to designate positional accuracy with a single number (namely radius). As with the error parallelogram, however, the error circle is not an equal probability contour. Also noteworthy is that the area of the CEP circle becomes greater than the corresponding basic ellipse as the ratio of ellipse minor to major axes decreases from 1.0 (Bowditch 1984).

Positional accuracy is often quoted using radial error, root mean square (rms) error, or d_{rms} (also written DRMS), all of which have the same meaning. As with CEP, the error figure is a circle having a radius equal to:

$$d_{rms} = (\sigma_x{}^2 + \sigma_y{}^2)^{1/2} \qquad \text{(A-2)}$$

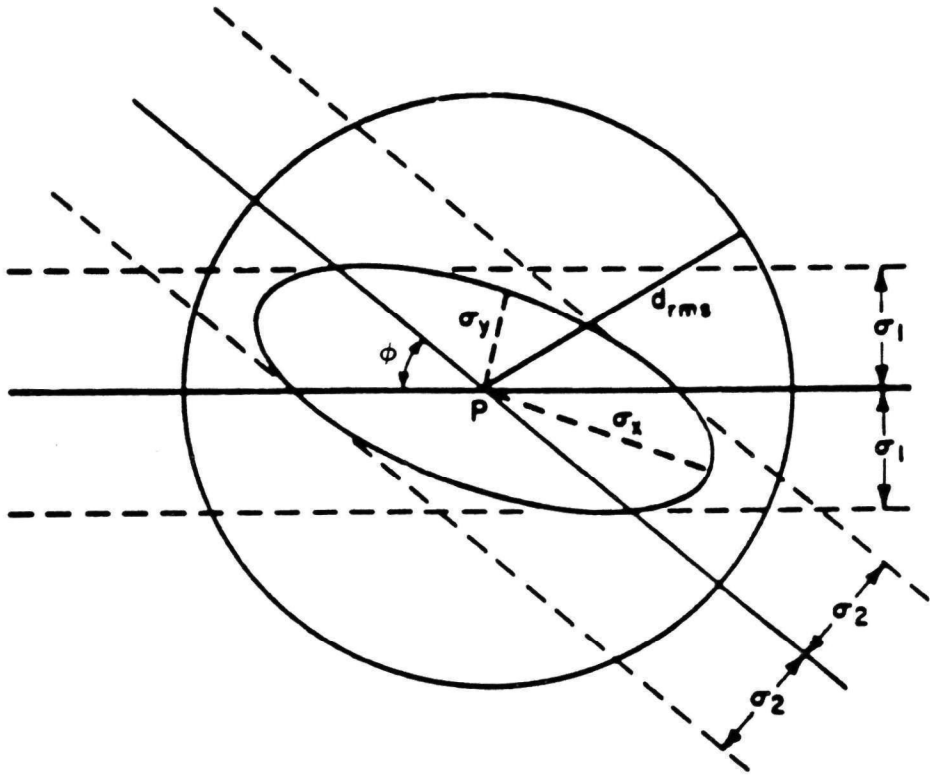
where σ_x and σ_y are the 1σ error components along the major and minor axes of the probability ellipse (Figure A-4). This is often referred to as the $1d_{rms}$ or 1σ fix accuracy. Similarly, a 2σ fix is given by:

$$2d_{rms} = [(2\sigma_x)^2 + (2\sigma_y)^2]^{1/2} \qquad \text{(A-3)}$$

Given the LOP standard deviations σ_1 and σ_2, the standard deviations along the basic ellipse axes can be determined by:

$$\sigma_x{}^2 = [1/(2 \sin^2\phi)] \{ \sigma_1{}^2 + \sigma_2{}^2 + [(\sigma_1{}^2 + \sigma_2{}^2)^2 - 4(\sin^2\phi)\, \sigma_1{}^2\sigma_2{}^2]^{1/2}\} \qquad \text{(A-4)}$$

and



SOURCE: BOWDITCH 1984

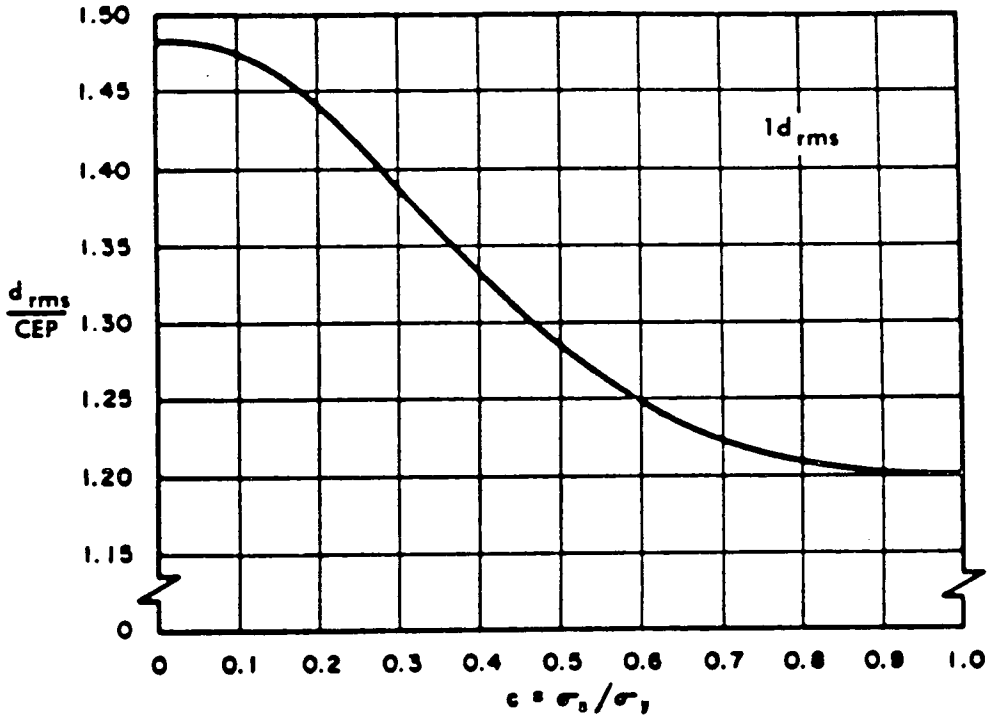
Figure A-4. Illustration of radial error.

$$\sigma_y^2 = [1/(2 \sin^2\phi)] \{ \sigma_1^2 + \sigma_2^2 - [(\sigma_1^2 + \sigma_2^2)^2 - 4(\sin^2\phi)\ \sigma_1^2\sigma_2^2]^{1/2}\} \quad \text{(A-5)}$$

The probability of being within a $1d_{rms}$ circle varies from 63 to 68 percent depending on the ellipticity of the error ellipse. For a $2d_{rms}$ circle, the probability varies from 95 to 98 percent.

Equipment manufacturers quote accuracy probabilities using various terminology. Most commonly, CEP and d_{rms} values are provided. The relationship between these two particular accuracy measures is shown in Figure A-5. For equal standard deviations ($\sigma_x/\sigma_y = 1$), the d_{rms} is 1.2 times the CEP. Thus, quoting the CEP would be more advantageous to a manufacturer than quoting a d_{rms} value.

It is common to describe two-dimensional error distributions by two separate one-dimensional standard deviations along each error axis (σ_1 and σ_2). However, when system accuracy is given as 100 m (328 ft) at the 2σ level, two clarifications are needed: 1) whether absolute or repeatable accuracy is being quoted; and 2) whether σ measures linear or circular error. If the error is circular, the number describes an 86 percent probability level, whereas if a 2σ d_{rms} is referred to, then the probability of the positioning being within the circle is between 95 and 98 percent, depending on error ellipse axis lengths. Therefore, unless the basis of an accuracy figure is very explicitly stated, it may be necessary to clarify its meaning. Only then can the accuracy performance of competitive systems be compared.



SOURCE: BOWDITCH 1984

Figure A-5. Ellipticity versus d_{rms}/CEP.

APPENDIX B

SYSTEM CHARACTERISTICS

APPENDIX B

SYSTEM CHARACTERISTICS

Characteristics of the kinds of systems described in the report are provided in this appendix in the following order:

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Hyper-Fix	
Argo DM-54	
Hydrotrac	
• Long-Range Systems	B-22
Loran-C	
Viewnav	
Lambda	
Omega	
• Satellite Systems	B-28
Transit (Navsat)	
Geostar	

Navstar GPS
Series
Aero Service GPS

- Hybrid Positioning Techniques B-38
  - Aztrac
  - Polarfix
  - Artemis

This more detailed information is provided to enable quick-reference review by document users interested in the performance characteristics and costs of systems representative of each class.

THEODOLITES

A theodolite is an instrument designed to measure horizontal and vertical angles. Two rather distinct theodolite classes exist. Those having verniers or scale divisions are less accurate than those having micrometer or digitized readouts. As indicated in Table B-1, the former can typically be read to the 10- to 30-sec angular increment, whereas the more sophisticated units can be read between 0.1 and 1.0 sec (Table B-2). Corresponding price ranges are $650 to $4,000 for vernier models; $1,900 to $16,000 or more for digital models. As discussed in the text, reading accuracies in the 15 sec range should be adequate for most purposes.

SEXTANTS

Sextants are classified as vernier or micrometer drum models, the latter being preferred by most users. A well-constructed metal marine sextant is capable of measuring angles with an instrument error not exceeding 10 sec or 0.1 min of arc (Bowditch 1984). However, as indicated earlier, positional error will be highly dependent on operator ability. For accurate work, a sextant having an arc radius of 162 mm (6.4 in) or more should be selected. Characteristics of representative sextants are presented in Table B-3. As indicated instruments with sufficient accuracies are available in the $600 to $1,600 price range.

TABLE B-1. SUMMARY OF VERNIER TRANSIT AND SCALE-READING THEODOLITE CHARACTERISTICS

COMPANY	MODEL	VERNIER MICROMETER OR SCALE DIVISION	READABLE TO:	U.S. SUGGESTED LIST PRICE*
Benchmark	JENA 020	20"	10"	$2495
Berger	Bronze 65/45	20"/1'	20"/30"	$2125/3850
	Aston 67	20"	20"	$1835
	Project 100	1'	30"	$1100
	ST-1/6	1'/20"	30"/20"	$699/1499
	ST-8/9	20"	10"	$1699/1899
Kern	K1-S/ST	30"	6"	$3895/3995
Leitz	BT20/10C	20"	10"	$1695/1995
	115	1'	30"	$795
	TS20A/S6	1'	20"/6"	$2495/3695
Nikon	NT-2S MK III	1'	0.2'	$3195
	Schneider 700/400	20"/1'	6"/20"	$1235/650
Pentax	GT-4B/6B	20"		$1695/1895
	TH-60S/60E	1'	6"	$2500/1895
Teledyne	OP 107/100-A-20	20"	20"	$1295/1185
	G-15	20"	20"	$1350
	400W	1'		$650
Topcon	AG-30B	30"	15"	$1595
	TL-60SE	1'	20"	$2100
Warren-Knight	10-2220/3200	20"/1'	10"/30"	$2695/1295
White	TR-300	1'		$749
	TR-303/303PM	20"		$1879/1995
	T-307AT/309T	1'/20"	6"/10"	$2695/2350
Wild	T-16		12"	$1895
	T-05	20"	10"	$3950
Zeiss	Th-42/43	20"	10"	$3950

*January 1985

TABLE B-2. SUMMARY OF MICROMETER AND DIGITIZED THEODOLITE CHARACTERISTICS

COMPANY	MODEL	VERNIER MICROMETER OR SCALE DIVISION	READABLE TO:	U.S. SUGGESTED LIST PRICE*
Benchmark	JENA 010A JENA 015B	1" 6"	0.1" 1"	$4295 $3495
Kern	DKM2-A/T DKM3/DKM3-A	1" 0.5"	0.1" 0.1"	$5890 $12295
Lietz	DT-20E TM6/10E/20H TM-1A	20" Accuracy 6"/10"/20" 1"	10" Display 2"/5"/10" 0.1"	$2995 $3995/3695/3295 $5995
Nikon	NT-1/5A NT-4D/3D/2D	20"/1" 6"/10"/20"	6"/0.25" 1"/2"/4"	$1895/5950 $3695/3595/3095
Pentax	TH-20D/10D/06D TH-01W	20"/10"/6" 1"	5"/2"/1" 0.5"	$2850/3500/3690 $4900
White	TH 10-20/10 T-308AT/208AT TH 10-1	20"/10" 20"/10" 1"	2"/1" 10"/5" 0.1"	$2850/3500 $2995/3495 $5500
Topcon	DT-20 TL-20DE/10DE/6DE	LCD Readout 20" 20"/10"/6"	- 10"/5"/3"	$2695 $2859/3500/3690
Wild	T-0/T-1 T-2/T-3 T-2000	20"/6" 1"/0.2" 0.5"	20"/3" 0.1"/0.1" 0.1"	$3995 $5995/11995 $13995
Zeiss	Th-2 ITh-2	1" 0.6"	- -	$5950 $16500

*January 1985

TABLE B-3. MARINE SEXTANT CHARACTERISTICS

SPECIFICATIONS	C. PLATH NAVSTAR CLASSIC	NAVSTAR PROFESSIONAL	TAMAYA SPICA	TAMAYA JUPITER UNIVISION	TAMAYA VENUS	WEEMS& PLATH
Arc Range	-5 to +125°	-5 to +125°	-5 to +125°	-5 to $\pm$125°	-5 to +125°	-5 to +125°
Instrument Accuracy	< $\pm$10"	< $\pm$10"	< $\pm$10"	< $\pm$12"	< 18"	< $\pm$10"
Vernier Scale	0.2'	0.2'	0.2'	0.2'	0.2'	0.2'
Arc Radius (mm)	162	162	162	162	138	162
Telescope	4X40 6X30	4X40	4X40(7°) 7X35(6.5^{o})	4X40(7°) 7X35(6.5^{o})	3X26	4X40 6X30
Brightness			100/25	100/25	75	
Index Mirror (mm)	57X41	57X30	57X42	57X42	45X30	57X41
Horizon Mirror Dia. (mm)	57	57X30	57	57	45	57
Illumination	Arc & Drum	Yes	Arc & Drum	Arc & Drum	No	Arc & Drum
Frame Material	Brass/Alloy	Makrolon	Aluminum	Aluminum	Aluminum	Brass
Arc Material	Brass/Alloy	Al. Alloy	Bronze	Bronze	Bronze	Brass
Case	Mahogany	Plastic	Plastic	Plastic	Wood	Mahogany
U.S. Suggested List Price (1/85)	$1270	$965	$919	$715	$585	$1674

ELECTRONIC DISTANCE-MEASURING INSTRUMENTS (EDMIs)

Electro-optical and microwave EDMIs are commonly used in land surveying where very small cumulative errors are acceptable. As indicated in Table B-4, the range of an instrument is highly dependent on its signal characteristics and number of reflectors on the target. Optical range is on the order of 1.6 to 6 km (1 to 3.7 mi), whereas microwave units can reach 14 km (8.7 mi). Accuracies at 5 km (3.1 mi) are in the low centimeter range. Costs are from $3,500 to as much as $15,000, and a laser unit, which can operate to 25 km (15.5 mi), is available for $20,500. For most coastal outfall survey work, two units would be required at approximately $5,000 to $6,000 each.

TOTAL STATIONS

Total stations are instruments capable of measuring not only horizontal and vertical angles, but also distance to the target object. Some units operate manually, requiring slope reduction of distances to be done by optically reading a vertical angle and keying it into a calculator. Semi-automatic units contain a vertical angle sensor for automatic slope reduction, but horizontal angles are read optically. Automatic stations read horizontal and vertical angles, and distance, electronically. At a 5 km (3.1 mi) distance, single measurement range error is typically 3 cm (1.2 in); angular error is typically ±2-3 sec or 5-7 cm (2-2.8 in). As shown in Table B-5, costs range from $8,000 for a manual unit to as high as $30,000 for a fully automatic station.

MICROWAVE SYSTEMS

Due to relatively high demand and fairly common usage, there are many commercially available microwave systems. Representative systems described in Table B-6 have nominal absolute accuracies of ± 1 m (3.3 ft), and cost from $39,000 to $90,000. Ranges extend between 40 and 150 km (25-93 mi), well beyond required accuracy for coastal monitoring programs. Some systems offer a multiple user option. Because of their common usage, the characteristics of representative systems are described in the following paragraphs.

TABLE B-4. ELECTRONIC DISTANCE MEASURING INSTRUMENTS

COMPANY	MODEL	RANGE(m) SINGLE PRISM TRIPLE PRISM MAXIMUM(prisms)	ACCURACY MEAN SQUARE ERROR	U.S. SUGGESTED LIST PRICE
Benchmark Orlando, FL (305)281-5000	Surveyor III-X	1600 3000 3500(6)	±(5 mm + 5 ppm)	$3,495
Geodimeter, Inc. Novato, CA (415)677-1256	Geodimeter 14-A	6000 8000 15000	±(5 mm + 3 ppm)	$11,300
	Geodimeter 112/122	2500 3600 6000(8/16)	±(5 mm + 3 ppm)	$6,250(112) $10,950(122)
	Geodimeter 220	1600 2400 3200(8)	±(5 mm + 3 ppm)	$8,850
Kern Instruments Brewster, NY (914)279-5095	DM 503	2000 3500 4500(7)	±(3 mm + 2 ppm)	$8,995
Keuffel & Esser, Co. Morristown, NJ (201)285-5000	Ranger V-A (HeNe Laser)	8000 16000 25000	±(5 mm + 2 ppm)	$20,561
	PulseRanger	1000 3000	±(30 cm + 30ppm)	$7,500
The Lietz Company Overland Park, KS (913)492-4900	RED 2A/2L	2000/3800 2800/5000 ----/7000(9)	±(5 mm + 5 ppm)	$4,695(2A) $5,795(2L)
MK Electronics, Inc. Littleton, CO (303)795-2060	MK-III, MK-III VS	1600 3000 4000	±(5 mm + 2 ppm)	$5,950(III) $7,950(III-VS)
Nikon, Inc. Garden City, NY (516)222-0200	ND 31	1900 3200	±(5 mm + 5 ppm)	$5,885
Pentax, Corp. Englewood, Co (303)733-1101	PM-81	1400 2000	±(5 mm + 5 ppm)	$4,790
Teludist, Inc. Mastic Beach, NY (516)399-5843	Tellemat CMW20 (microwave)	25000	±(5 mm + 3 ppm)	$16,500
Topcon Instrument Corp. Paramus, NJ (201)261-9450	DM-S3	2000 2500 2900(9)	±(5 mm + 5 ppm)	$5,390
Wild Heerbrugg Farmingdale, NY (516)293-7400	Citation-450	1600 2300 4000(11)	±(5 mm + 5 ppm)	$3,995
	D1-4L Distomat	2500 3500 7000(11)	±(5 mm + 5 ppm)	$8,995
	D1-20 Distomat	6000 7000 14000(11)	±(3 mm + 1 ppm)	$14,995

TABLE B-5. TOTAL STATION CHARACTERISTICS

COMPANY	MODEL	TYPE	RANGE* (km) L	RANGE* (km) M	RANGE* (km) H	PRISMS	ACCURACY RANGE	ACCURACY ANGLE	U.S. SUGGESTED LIST PRICE
Carl Zeiss, Inc.	RMS3	Semi-Auto	-	1.5[a]	-	1	±5-10 mm + 2ppm	±2"	$8,260
Thornwood, NY			-	2.0[b]	-	3			
(914)848-1800			-	3.0[c]	-	9			
	Elta 3	Automatic	-	1.6	-	3	±10 mm + 2ppm	±2"	$18,725
			-	2.5	-	6			
			-	3.0	-	18			
	Elta 46R	Automatic	-	2.0	-	3	±10 mm + 2ppm	±3"	$12,820
Geodimeter, Inc.	140	Automatic	1.2	2.2	3.0	1	±(5mm + 5 ppm)	±2"	$19,950
Novato, CA			1.8	3.0	4.0	3			
(415)883-2367			2.4	3.8	5.5	6			
			3.6	4.8	6.0	8			
Kern Instruments	E1/DM503	Automatic	1.5	2.5	3.0	1	±(3 mm + 2 ppm)	±2"	$19,175
Brewster, NY	E2/DM503		2.0	3.5	4.5	3	±(3 mm + 2 ppm)	±0.5"	$22,375
(914)279-5095			2.4	4.5	5.5	7			
Lietz	SMD-3	Manual	-	0.8	1.2	1	±(5 mm + 5 ppm)	10" digital	$8,800
Overland Park, KS	SDM-3ER	Semi-Auto	-	1.4	1.8	3		5" direct	$10,800
(913)492-4900	SET-10	Automatic	-	-	2.5+	9			$14,000
MK electronics	MK-III	Automatic	-	3.0	-	3	±(5 mm + 2 ppm)	6"	$12,950
Littleton, CO	MK-IV		-	4.0	-	3	Stationary		$14,950
(303)795-2060	MK-HYDRO		-	3 or 4	-	3	±(20 mm + 5 ppm) Moving		$16,950
Nikon Instruments	NTD-4	Manual	-	1.2	1.6	1	±(5 mm + 5 ppm)	6" digital	$8,595
Garden City, NJ			-	1.8	2.3	3		3" subdivision	
(516)222-0200	NTD-1	Automatic	-	1.2	1.6	1	±(5 mm + 5 ppm)	1"	$15,985
			-	1.8	2.3	3			
Pentax	PX-10D	Manual	-	1.4	-	1	±(5mm + 5 ppm)	10" digital	$8,450
Englwood, CO			-	1.7	-	3		5" direct	
(303)773-1101								2" estimation	
	PX-06D	Manual	-	1.4	-	1	±(5 mm + 5 ppm)	6" digital	$8,765
			-	1.7	-	3		1" estimation	
Topcon	GTS-2B	Manual	-	1.4	1.7	1	±(5 mm + 5 ppm)	6"	$7,990
Paramus, NJ			-	2.0	2.4	3			
(201)261-9450			-	2.6	3.0	9			
	ET-1	Automatic	-	1.4	1.7	1	±(5 mm + 5 ppm)	2"	$14,250
			-	2.0	2.4	3			
			-	2.6	3.0	9			
Wild Heerbrug	T2000+	Automatic	1.2	2.5	3.5	1	±(5 mm + 5 ppm)	0.5"	$24,000
Farmingdale, NY	DI4L or		1.5	3.5	5.0	3	±(3 mm + 2 ppm)		$25,000
(516(293-7400	DI5		1.7	4.5	6.0	7			
			1.8	5.5	7.0	11			
	T2000+	Automatic	2.0	6.0	9.0	1	±(3mm + 1 ppm)	0.5"	$30,000
	DI20		2.3	7.0	11.0	3			
			2.6	8.0	13.0	7			
			2.7	9.0	14.0	11			

* Atmospheric visibility: a. low = hazy, 5km b. medium = clear, 15km c. high = very clear, 30km

TABLE B-6. MICROWAVE POSITIONING SYSTEM CHARACTERISTICS

SYSTEM	RANGE (km)	FREQUENCY (MHz)	NOMINAL ABSOLUTE ACCURACY (m)	USER CAPABILITY	ANTENNA Vessel	ANTENNA Shore Station	COST
TRISPONDER (520/540 DDMU) DEL NORTE Technology, Inc Euless, TX (817)267-3541	5 80 80	9320-9500(261) 9329-9500(217E) 8800-9000(218E)	±1	up to 8 (more optional)	360°H 20°V	87°/180°H 6°/50°V	$40,000
FALCON 484 Mini-Ranger Motorola, Inc. Tempe, AZ (602)897-4376	37	5410-5600	±2	up to 20	360°H 25°V	70°H 15°V	$39,300
MICRO-FIX Racal DECCA Survey, Inc. Houston, TX (713)783-8220	80	5480 5520 5560	±1	up to 16	360°H 20°,30°V	90°H 6°/30°V	$43,000
HYDROFLEX Teludist, Inc. Mastic Beach, NY (516)399-5843	100	3000	±1 plus $3x10^{-6}$ distance(m)	single multiuser option	360°H 18°V	Long-range 24°H, 22°V Fan Beam 18°V,60°H	$63,500
AUTOTAPE DM-40A/DM-43 Cubic Western Data San Diego, CA (619)268-3100	150	2900-3100	±0.5 ±1:100,000 range	single	360°H 10°V	30°-120°H 10°V	$90,000

*January 1985

Trisponder

The Del Norte Trisponder is an X-band (8,800-9,500 MHz) positioning system composed of a digital distance-measuring unit (DDMU), a master station (usually on the vessel), and two remote stations located at known geographic positions. Each station is a combined transmitter and receiver. The master station antenna is omnidirectional and each remote station has a directional antenna. Distances to remote stations are observed on the DDMU using the range-range mode. A time-sharing feature allows up to eight users.

The manufacturer quotes a typical range accuracy of ±1 m (±3.3 ft), with an instrument resolution of 0.1 m (0.3 ft). In The Hydrographic Manual, Umbach (1976) cites a range error for this system of ±3 m (±10 ft) under good field conditions based on the Trisponder Basic Operation Manual published in 1974. Also cited are tests conducted by the National Ocean Survey (date unknown) which indicated that temporal electronic drift may cause variations in measurements. Recalibration is suggested over a measured base line after every 200 h of operation. However, the tests were conducted on a Model 202 Trisponder Surveyor System for which the manufacturer claimed a resolution of 3 m (10 ft) and a positional accuracy of ±3 m (±10 ft), after field calibration.

The currently available microwave system operates with Model 217/218E transponders and Model 520 or 542 DDMUs. The Model 261 transponder, usable as a master or remote, has a 5-km (3.1-mi) line-of-sight range. The Model 217/218E transponders operate up to 80 km (50 mi) from shore due to higher output power. The transponders are designed for use with either model DDMU. The Model 520 will collect four ranges and display two. The Model 542 interrogates four remotes, outputs four sets of data, and also provides a positioning guidance capability. The cost of a compete system including a Model 520 DDMU, a master and two remote 217/218E transponders, and antenna is $40,000 (Buchanan, C., 31 December 1984, personal communication). For the additional guidance capability of the Model 542 DDMU, the system cost is $44,500. A less expensive "black box" version of the DDMU (Model 562) is available for use with an existing shipboard computer system, allowing

more than eight users. Cost of the Model 562 and other required components is $39,500.

Falcon 484 Mini-Ranger

The Motorola Falcon 484 is a C-band (5,410-5,600 MHz) microwave ranging and positioning system that operates in the two-range mode from 100 m (328 ft) to 40 km (25 mi). The system consists of a vessel receiver-transmitter assembly with an omnidirectional antenna, a range console, and shore-based radar transponders with directional antennae. Pulsed radar from the survey vessel transmitter interrogates radar transponder reference stations located at geographically known points. Elapsed time between transmitted interrogations and the reply from each transponder is used as the basis for range determinations. Two ranges are used for trilateral positioning. If three or four ranges are available, range residuals, sum of squared residuals, and error circle radius data are output for the least squares position solution. The manufacturer claims a range accuracy of ±2 m (±6.6 ft). Up to 20 users can operate in the same area.

A basic Falcon 484 system, including a range processor control display, receiver/transmitter with omnidirectional antenna, two reference stations with directional antenna, miscellaneous cables, and manuals currently costs $39,300 (Jolly, J., 31 December 1984, personal communication). In an effort to eliminate one of two major problems with most microwave positioning systems (i.e., magnatron failures and the need to service beacons), Motorola is currently developing a solid-state beacon using a gun diode. The associated increase in long-term reliability may also result in decreased range. However, range capability should remain adequate for positioning needs of coastal monitoring programs. Costs of the modified transmitters were not available at time of publication.

Micro-Fix

The Racal Survey Micro-Fix is a range-range microwave positioning system. With line-of-sight to shore-based transmitters, it is capable of operating up to 80 km (50 mi) offshore. The system normally operates

at 5,480 MHz, with options at 5,520 and 5,560 MHz. The master station can interrogate up to eight remote stations (from a possible 32), with each remote transmitter/receiver unit (T/R) preset to recognize its own unique station code. Up to four separate station groups can be deployed in the same area without interstation interference. Multi-user capability allows a maximum of 16 users for each deployed chain. Master and remote units are interchangeable.

The basic system consists of a master station with a Control Measurement Unit (CMU), a T/R unit, and two tripod-mounted remote T/R stations. The vessel's master station interrogates the remote stations sequentially, triggering reply pulses received by the master T/R and processed by the CMU to display the corrected ranges. The CMU capabilities include automatic and continuous self-calibration, track guidance, plotter drive, x-y conversion (full spheroid and multi-range solution), and slant range correction. Nominal accuracy is stated by the manufacturer to be ± 1 m (± 3.3 ft). The cost of a basic Micro-Fix system, including training, is $43,000 (Harris, E., 3 January 1985, personal communication).

The manufacturer is developing the capability to use the system in a hyperbolic mode, a combination range-range/hyperbolic mode, or a range-azimuth mode, but this capability is not yet available. The system also uses circular polarization techniques to avoid reflective (water surface) signal cancellation nulls, thereby eliminating the need for a second antenna on the vessel. This has been accomplished by an antenna design that prevents signal entrance from reflective angles.

Hydroflex

Hydroflex is a short- to medium-range microwave navigation system designed for survey applications where a high degree of accuracy is required in fixing or tracking the position of a moving vessel. The system operates at frequencies of 2,920-3,300 MHz and has a range of 100 m to 100 km (328 ft to 62 mi). It consists of a master unit controlled by an HP85 computer with a customized software package, an omnidirectional antenna, and connecting cables. Each remote unit consists of a transceiver and either a large

range or fan-beam antenna for mounting on a customer-provided tripod. Accuracy is claimed to be 1 m (3.3 ft) $\pm 3 \times 10^{-6} D$, where D is the distance measured in meters. The system can be operated in either a two- or three-range mode. Although single-user is the normal operating mode, a multi-user option is available. The cost of a master and two remote stations is $63,500 (Baker, W., 11 January 1985, personal communication).

Autotape DM-40A/DM-43

The Cubic Western Autotape is an S-band range-range microwave positioning system that operates at ranges of up to 150 km (93 mi). System components include a shipboard interrogator and range responders at each fixed onshore station. The DM-43 is capable of working with three geographic sites. Range information is computed by comparing the phase shift of the modulated signal transmitted between the interrogator and responder phase unit to an interrogator reference signal. An Automatic Position Computing System (APCS) is available for steering information, real time analog plot of the vessel's track, and magnetic data recording. The system does not accommodate multiple users. The manufacturer claims a range accuracy of 0.5 m plus 1:100,000 times the range distance. This error is due to internal random errors, systematic errors, temperature variation bias errors, signal strength, component aging, and initial calibration errors. External errors are said to far exceed internal noise, systematic, and bias errors. Index of refraction error, which can approach 5 m (16.4 ft) at 100 km (62 mi), is usually small enough at short ranges to be ignored. Multipath errors (dependent on orientation of reflective objects near and behind the interrogator omnidirectional antenna) have been observed from 0 to 3 m (0 to 9.8 ft). The manufacturer states that internal averaging plus external data smoothing will reduce the effect on Autotape to a small fraction of a meter, provided the antenna is moving. For this reason, the system is best suited to applications where the interrogator is on a moving vehicle.

The cost of a basic Autotape system including an interrogator, two range responders, and associated antennae is $90,000. The same system with the DM-43 and three shore stations is $124,000 (Hempel, C., 10 January 1985, personal communication).

VARIABLE RANGE RADAR

Using variable range radar (VRR) a position can be fixed by measuring the distances to three identifiable targets on the radar screen. A variable range marker is used to measure the distance to the object (as identified by its radar reflection). This distance is then drawn with a compass as a line of position on the nautical chart. The intersection of the multiple LOPs establishes the vessel's position.

Most commercial vessels are equipped with radar for safety and navigation purposes. Coastal vessel radar usually have ranges from 26 to 116 km (16 to 72 mi). A variable range marker (VRM), whether built-in or an add-on, removes a large portion of operator error in estimating distances. For positioning at accuracies less than 300 m (984 ft), a VRM is almost always needed. Range accuracies with the VRM are usually 1 to 2 percent of the range scale, or $\pm$25 m (82 ft) at 0.5 km (0.3 mi), the smallest scale. Accuracy decreases as the range scale is increased. Bearing accuracy is usually less than 1°. Characteristics of representative VRRs are presented in Table B-7. Generally, analog systems have better resolution than digital systems, but are not as versatile.

Each position fix relies on the resolution and identification of the radar reflection. Resolution will depend on target position and alignment. The location of the reflection is not always easy to identify. Placement of the cursor away from the actual reflection surface will introduce error into the fix. Estimation of the location of the radar target in relation to the mapped structures on the chart is important. Misidentification of a reflection source will result in the plotting of a position at the wrong coordinate, but will not affect repeatable accuracy. Certain regions, such as sloped headlands and tidal flats, give inaccurate reflection because it is impossible to relate the reflection to a map location. The most accurate radar range fixes are obtained from solid reflections between 0.16 and 6.4 km (0.1 and 4 mi). This keeps the range scale low resulting in higher accuracy and avoids erroneous readings that can be caused from very close reflections.

TABLE B-7. VARIABLE RANGE RADAR (VRR) SYSTEM CHARACTERISTICS

Systems	Model	Type	Variable Range Markers	Range (km)	Nominal Accuracy Range (m)	Nominal Accuracy Angle	U.S. Suggested List Price[a]
DECCA Racal DECCA Marine Redmond, WA (206) 885-4713	RD170 VRM/VP3	Digital	1 (add-on)	77	-	±0.5°	$3,990
	RD170 BT	Digital	1	77	±30 at 0.4 km	±0.5°	$6,000
Furuno U.S.A. San Francisco, CA (415) 873-9393	FR-360 MKII	Analog	add-on	58	±25 at 0.5 km	<±1°	$4,400 without VRM
	FR-810	Digital	2	116	±36 at 0.5 km	<±1°	$7,400
	FR-1011	Analog	1	77	±25 at 0.5 km	<±1°	$8,300
KODEN/SI-TEX Norwell, MA (617) 871-6223	T-100	Digital	1	26	±22 at 0.5 km	±0.5°	$2,200
Raytheon Marine Seattle, WA (206) 285-6843	3604	Analog	1	58	-	±1°	$4,900
	3610	Analog	1	116	-	±1°	$5,400

[a] December, 1985.

Many vessels are already equipped with VRR and, if necessary, variable range markers can be added for $1,000 to $2,000. The newer digital systems offer multilevel processing for better target pickup (a problem with earlier digital models) and map plotting ability on the screen for $5,000 to $10,000.

MEDIUM-RANGE SYSTEMS

Characteristics of representative medium-range systems are presented in Table B-8. As indicated, absolute accuracies of less than 10 m (33 ft) are reportedly achievable for ranges well beyond those needed for coastal positioning. The additional costs, typically between $100,000 and $200,000, are not justified unless a much longer range system is needed for other navigating or surveying work.

Syledis

The Sercel Syledis is a short- to medium-range radio positioning system that operates in the 420-450 MHz frequency range at distances of up to 300 km (186 mi) from shore. Through the use of long-coded pulses, the system reportedly retains the advantages of short-duration pulses (i.e., accuracy and multipath discrimination) without corresponding limitations. The technique is used to increase the amount of transmission energy available, enabling range extension well beyond line-of-sight at moderate transmitting powers. At operating frequencies, the system is said to be free of velocity variations over ground paths or due to sky waves, and the effects of surface reflected waves are reduced. The system can be operated in an active range-range mode with up to three users in the same network, in a passive (hyperbolic) mode with an unlimited number of users, or in a combined mode (hyperbolic network and single range) with up to 11 users. The last mode has the advantage of retaining range-range accuracy while minimizing transmit times for each user.

The basic system includes a mobile onboard interrogator and an array of accurately positioned beacons along the coastline. Absolute accuracy is claimed to be ±1 m (±3.3 ft) at distances less than line-of-site, ±3 m

TABLE B-8. MEDIUM-RANGE POSITIONING SYSTEM CHARACTERISTICS

SYSTEMS	RANGE (km)	FREQUENCY (MHz)	ABSOLUTE ACCURACY (m)	USER CAPABILITY	ANTENNA VESSEL	ANTENNA SHORE	COST*
SYLEDIS Sercel, Inc. Houston, TX (713)492-6688	300	420-450 406-434	±1 LOS ±3 2X LOS	Up to 4 (Range-range) Unlimited (Hyperbolic)	Not Provided		$ 51,350
RAYDIST Hastings-Raydist Hampton, VA (804)723-6531	278 night 740 day	1.5-2.5	±3	4/net (Range-range) Unlimited (Hyperbolic)	Omnidirectional		$102,200
HYPER-FIX Racal DECCA Survey Houston, TX (713)783-8220	700 day 250 night	1.6-3.4	5-10 0.01 lane display resolution	Up to 6 (Range -range) Unlimited Hyperbolic	Omnidirectional		$113,000
ARGO DM-54 Cubic Western Data San Diego, CA (619)268-3100	740 day 370 night	1.6-2.0	4-5 0.05 lane display resolution	Up to 12 (Range-range) Unlimited (Hyperbolic)	Omnidirectional		$188,00
HYDROTRAC Odom Offshore Surveys Baton Rouge, LA (504)769-3051	300 day 200 night	1.6-4.0	1.5-4 0.01 lane display resolution	Single (Range-range) Unlimited (Hyperbolic)	Omnidirectional		$100,000

*January 1985

($\pm$9.8 ft) up to two times line-of-site, and $\pm$3 m x 10^{-5}D (in meters) beyond this point.

For purposes of coastal monitoring programs, the most likely system configurations are range-range or hyperbolic. In the range-range configuration, components include an SR3 receiver, SD3 power duplexer, two B2 (two-user limit) or B4 (four-user limit) beacons, and shipboard/shore-base antennae. Excluding the antennae (estimated at $1,000 each by the system manufacturer), the basic system cost is $51,350 (including two B2 beacons). To operate in the passive pseudoranging mode, hyperbolic geometry dictates the need for a third shore station. Assuming three B2 beacons, the system would cost $70,185. Use of B4 beacons ($1,210 each) would result in an additional cost for the range-range system of $2,420 and an additional cost for the hyperbolic system of $3,630 (Weems, L., 2 January 1985, personal communication).

Raydist Trak IV

With a Teledyne Hastings-Raydist radio navigation system, users can identify geographic positions within $\pm$3 m ($\pm$9.8 ft) at distances up to 278 km (173 mi) from land-based transmitters during the night and 741 km (460 mi) during the day. A major attribute of this 1.5-2.5 MHz system at medium ranges is improved accuracy over Loran-C. In the range-range mode, Raydist can accommodate four users with a vessel receiver/transmitter (R/T) and two shore R/Ts. Alternately, the hyperbolic mode can be used by relocating the vessel transmitter to a third suitable location on shore and adding a vessel receiver. This mode allows an unlimited number of users. A Radist-T configuration involving a fourth onshore transmitter is available to increase the area of coverage having good line-of-position intersections. In this configuration, an unlimited number of users can be accommodated in the range-range mode (Comstock and Rounion 1982). The system offers elliptical and halop grid patterns in addition to hyperbolic nets. Halop grids assure right-angle intersections throughout the coverage area. The Radist system has a stated resolution of approximately $\pm$0.75 m ($\pm$2.5 ft) and repeatability of $\pm$2 m ($\pm$6.6 ft).

The minimum system for range-range operation consists of an onboard TA100 transmitter, 10.7-m (35-ft) whip antenna, RA89 navigator receiver, and GA62 two-dimensional position indicator. Latitude-longitude readouts require an additional KA18-23 Radist director. Position can be plotted with a PB22B 12-in flatbed plotter. Analog signals can also be retained with an RB15-1 strip-chart recorder. Onshore components consist of two AA77 base stations and two medium-range 14-m (46-ft) antennae. Excluding the KA18-23 Raydist Director, PB22B plotter, and the RB15-1 recorder, the system cost is $102,181. Additional components for hyperbolic mode operation (i.e., QB66B active probe mobile unit antenna and two antenna extensions) cost $1,200. The KA18-23 Raydist Director costs $44,533; the PB22B plotter costs $5,752; and the RB15-1 position signal recorder costs $4,085 (Gibbs, F., 2 January 1985, personal communication).

Hyper-Fix

The Racal DECCA Survey Hyper-Fix is a 1.6-3.4 MHz positioning system that operates at distances from shore up to 700 km (435 mi) in daylight hours and 250 km (155 mi) at night (temperate latitudes). Actual operating range depends on location. In the Gulf of Mexico, for example, 24-h operation is quoted up to 250 km (155 mi)]. The system is operable in the range-range, hyperbolic, or a combined mode using additional shore stations.

As with any 2-MHz system, accuracy is a function of geometry (i.e., distance off baseline and pattern crossing-angle). The receiver/controller is capable of a 0.001 lane resolution, rounded to 0.01 lanes on display. This is equivalent to less than 1 m (3.3 ft) on the baseline. Positional accuracy is said to be on the order of 1 m (3.3 ft) in the hyperbolic mode with optimal geometry and 1.5 m (5 ft) in the ranging mode.

Vessel and onshore station components for range-range operation consist of a power amplifier, receiver/controller, and an antenna tuning unit. In the hyperbolic mode, the same onshore components are needed for each shore station. Only a receiver/controller and an active antenna are required on the vessel. The manufacturer reports relatively complete area coverage in the Gulf of Mexico. Where multiple user demand exists, Racal Decca

Survey, Inc. will establish a chain of shore stations and lease accessibility to them. Users then need only a receiver/controller and an antenna. Based on a comprehensive evaluation of several mid-range systems available, the manufacturer reports wide acceptance of the system by the U.S. Navy (Harris, E., 3 January 1985, personal communication).

A range-range mode system costs approximately $113,000, including $32,276 for a 90515 mobile Receiver/Controller, 90512 Power Amplifier/Battery Charger, and 90516 Antenna Tuning Unit; $715 for a 90538 shipboard antenna; and $40,000 for each of two short-range shore transmitter stations. The hyperbolic mode requires an additional shore station at $40,000. In the Gulf of Mexico, users may purchase the mobile receiver/controller and shipboard antenna for approximately $33,000, and lease access to shore stations for an initial monthly cost of near $12,000. Training in the optimal use of shipboard equipment in conjunction with the established onshore chain is included. Monthly costs decline over time to approximately $9,500 (Harris, E., 3 January 1985, personal communication).

ARGO DM-54

The Cubic Western ARGO DM-54 is a medium-frequency positioning system that operates between 1.6 and 2.0 MHz, and at an additional frequency 10 percent higher when lane identification is used. The system determines mobile station range from each of the fixed stations by accumulating whole-lane counts and computing fractional lane distances. The ARGO uses a multiplexing sequence and a shortened radio frequency pulse to service up to 12 vessels in the two-range mode, or an unlimited number of vessels in the hyperbolic mode. Up to 16 frequency pairs can be factory-programmed for alternate use. Maximum system range is 740 km (460 mi) in daylight and 370 km (230 mi) at night. Range accuracy is given as 0.02 lanes instrumental and 0.05 lanes achievable field accuracy. With lane widths of 74-94 m (243-308 ft), this represents accuracies of 3.7-4.7 m (12-15 ft). Overall position accuracy is stated to be on the order of tens of meters by the manufacturer (Hempel, C., 10 January 1985, personal communication).

The standard ARGO DM-54 configuration consists of four fixed land-based stations and multiple mobile or vessel stations. Each fixed station includes a Range Processing Unit (RPU) and an Antenna Loading Unit (ALU). In addition, mobile stations have a Control and Display Unit (CDU). Options include a two-range strip-chart recorder, a digital printer, tilting yoke mount, power supply, cables, and various antennae. The cost of a basic onshore station (RPU and ALU) is $54,075, not including the antenna [$4,160 for a 30-m (100-ft) model]. In addition, the CDU for the mobile unit costs $14,960, excluding the antenna [$2,500 for a 11-m (35-ft) whip]. A range-range system consisting of two shore stations and a mobile station with antennae costs approximately $188,000.

Hydrotrac

The ODOM Offshore Survey's Hydrotrac is an over-the-horizon medium-range positioning system that operates in the 1.6 to 4 MHz range. The system is capable of operating up to 300 km (186 mi) during the day and 200 km (124 mi) at night in the Gulf of Mexico. Range in other operating areas (e.g., Alaska) may be greater. The system can be operated in either the range-range mode with two shore stations or the hyperbolic mode with a master and two slave stations. By incorporating a third slave station, network coverage can be tripled. Existing U.S. station coverage is primarily in the Gulf of Mexico, where 12 Hydrotrac systems have been operating since 1973.

With ideal crossing angles and predictable signal path conditions, the claimed system accuracy is 2 m (6.6 ft) out to 300 km (186 mi). However, in the hyperbolic mode, land expansion and nonideal crossing angles may result in a lower accuracy. The random errors in the receiver are said to be less than 0.01 lane. A special filter limits the amount of additional error from fluctuation in propagation conditions and incidence of sky waves.

In the range-range mode, vessel system components include a Model 700 Receiver ($25,625), a Model 1000 Amplifier ($6,875), a Model 610 Antenna Coupler ($2,045), a cable set ($812), DC power supply ($468), and a 9-m (30-ft) tilt-base center-loading antenna ($2,034). Each of the two shore stations consists of a Model 701 Slave Drive Unit ($16,250), a Model 1000

Slave Power Amplifier, ($6,875), a Model 610 Antenna Coupler, a cable set, and an antenna of appropriate height for the station location and desired maximum operating range. [A 30-m (100-ft) Texas tower type antenna would cost approximately $5,000; a 9-m (30-ft) whip antenna would cost less than $2,000.] The overall system, including the larger antennae onshore, would cost $99,823 (Apsey, B. 10 January 1985, personal communication).

LONG-RANGE SYSTEMS

Characteristics of selected long-range and global systems are shown in Table B-9. Most of the systems listed do not provide the absolute accuracies recommended herein for coastal monitoring when operated in a normal mode. Of significance, however, are the characteristics of differential Loran-C and proposed satellite systems, as discussed below.

Loran-C

Loran, an acronym for long range navigation, is a pulsed low-frequency electronic navigation system that operates at 90 to 110 kHz in the hyperbolic mode. Loran-C receivers match cycles to measure time differences between arriving master (M) and secondary (W, X, Y, Z) signals, which are pulse- and phase-coded to enable source identification (Panshin 1979). The microsecond arrival time differences are displayed and can be plotted on a special Loran-C latticed chart as lines-of-position. Fully automatic Loran-C receivers simultaneously process signals from two master-secondary station pairs, displaying LOP information to permit course tracking.

Because Loran-C stations radiate peak powers of 250 kW to 2 MW, range capability varies. Due to the use of low frequencies and large baseline distances [i.e., 1,850 km (1,150 mi) or more], Loran-C can provide positional information of reasonable accuracy out to 2,225 km (1,380 mi) with sky waves (Maloney 1978). Range achievable at a particular station is dependent on transmitter power, receiver sensitivity, noise or interference levels, and signal path losses (Canadian Coast Guard 1981).

TABLE B-9. LONG-RANGE POSITIONING SYSTEM CHARACTERISTICS

SYSTEM	RANGE (km)	FREQUENCY (KHz)	NOMINAL ABSOLUTE ACCURACY (m)	USER CAPABILITY	COST
OMEGA Multiple Receiver Manufacturers	Global	10-14	1800 day 3700 night	Unlimited	$4,000-10,000
LORAN-C Multiple Receiver Manufacturers	2500 day 1850 Night	90-110	185-460 15-90 repeatable	Unlimited	$1,000-2,000
LAMBDA DECCA Survey, Ltd. England	400-800	100-200	137 day 730 night	Single 2-range Unlimited-hyperbolic	Call Agent
VIEWNAV Navigation Sciences Bethesda, MD (301)952-5225	Some Coastal Areas	90-110	±10	Multiple	$40,000 and $2,000 annual fee
TRANSIT Multiple Receiver Manufacturers	Global	150 & 400 MHz	90, 1 pass/1 freq. 37-46, 1 pass/2 freq. 3-5, Multiple pass and 2 freq.	Unlimited	$2,500-10,000 basic $30,000-45,000 elaborate
GEOSTAR Geostar Corporation Princeton, NJ (609)452-1130	U.S. Land & Coastal Areas	5117-6533 1618-2492	1-7	Unlimited	Transceiver $450 and link Rental $10-30/mo. (Estimated)
NAVSTAR/GPS Mulitple Receiver Manufacturers	Global	1575 MHz 1228 MHz	40, C/A, CEP 8-9, P, CEP	P-Military C/A Commercial Foreign	$10,000-140,000 initial $1,000 eventually
SERIES ISTAC, Inc. Pasadena, CA (818)793-6130	Global	1575 MHz 1228 MHz	< 1 m diff. Mode	Unlimited	$287,000
AEROSERVICE Houston, TX (713)784-5800	Global	1575 MHz 1228 MHz	< 1 m (1/2 hour)	Multiple	$235,000

At best, the absolute accuracy of Loran-C over short distances using the ground wave varies from 185 to 460 m (607 to 1,509 ft), whereas repeatable accuracy varies from 15 to 90 m (49 to 295 ft) depending on the vessel's location within a given coverage area (Dungan 1979; U.S. Coast Guard 1974). Over longer distances, the nominal ground wave mode accuracy is 0.1 percent of the range, and sky wave accuracies vary from 5.6 to 9.3 km (3.5 to 5.8 mi) (Umbach 1976). Achieving the short-range accuracies cited above requires proper installation, maintenance, and operation of high-quality equipment (Canadian Coast Guard 1981). Available equipment varies from simple receivers and indicators to fully automated receivers with self-tracking capabilities that can interface with a vessel's computer. Coverage in U.S. waters is generally good, with the exceptions of Puerto Rico and some locations off Alaska.

Although Loran-C is frequently proposed for coastal monitoring programs, this application has potential problems. Inland location [up to 160 km (100 mi)] of Loran-C chains requires overland transmission of signals. This results in phase shifts that have been difficult to predict. Such shifts can cause an erroneous position location fix. There are also anomalies associated with land-water interfaces and large structures such as bridges and tall buildings. Crossing-angles can also vary widely from one geographic area to another. In some cases, lines of position are almost parallel, making an accurate fix difficult to impossible. Noise and interference (e.g., from engines and other electronic equipment) can also cause problems. However, most Loran-C receivers are equipped with factory-set or tunable notch filters to minimize such problems.

In an effort to improve navigational capability using the Loran-C system, the U.S. Coast Guard completed a one-time survey of the east and west U.S. coasts in which Loran-C positions were compared with those from a calibrated microwave system. Corrections were obtained for the Defense Mapping Agency nautical charts, whose LOPs were based on theoretical transmission over water paths only (Ryan, R., 11 January 1985, personal communication), but these corrections do not include seasonal or diurnal signal effects.

The land transmission-path effect (known as the additional secondary phase factor) is currently being evaluated in a multiyear U.S. Coast Guard study at approximately 100 locations where signal variations are being recorded daily (Blizard and Slagle 1985). Study results indicate that annual variations in positional minimum errors are highly dependent on geographical location. The minimum 2 d_{rms} error (normal rather than differential Loran-C) for various U.S. coastal areas were found to be the following:

	2 d_{rms} Accuracy (m)		
Area	Lowest	Highest	Location
East Coast	30		Boston
		176	Miami
Gulf of Mexico	58		New Orleans
		179	Corpus Christi
West Coast	42		Seattle
		194	San Diego

Stated otherwise, repetitive measurements at a geographically known site would vary these amounts over a 1-yr period. Thus, they represent the minimum accuracy in absolute position achievable at each location indicated with a calibrated Loran-C having no other error sources.

Loran-C units may be used in a differential mode, substantially reducing the temporal and spatial variances from a predicted position (U.S. Department of Defense and U.S. Department of Navigation 1984). In this mode, a Loran-C receiver is located at a surveyed point onshore near the area to be monitored. Signals observed at this location are compared to signals predicted for this position to calculate offsets of differential corrections. The offsets are transmitted to the monitoring vessel, enabling normally incoming signals to be corrected according to transmission path anomolies. In examining the adequacy of differential Loran-C to meet an 8-20 m (26-66 ft) accuracy requirement of U.S. harbors and harbor approaches, the U.S. Coast Guard

found that a 20 m (66 ft) 2 d_{rms} absolute position accuracy is feasible in some U.S. coastal locations (Doughty and May 1985). Accuracies somewhat higher than this may even be achievable using various methods to predict time difference offsets (i.e., instead of a Sample Mean Method of the U.S. Coast Guard, using Least Squared Error, Alpha-Beta Filter, or a Linear Regression model) (Bruckner 1985).

Absolute and repeatable accuracies achievable with normal Loran-C are not sufficiently accurate to meet the accuracy limits recommended herein. Repeatabilities of approximately ±40 m (131 ft) appear optimal unless using a differential mode when this figure might be reduced to ±20 m (66 ft). This would be acceptable for sites beyond 100 m (328 ft) depths, where ±20 percent of the depth exceeds this value. However, almost all U.S. coastal outfall sites are located in more shallow waters.

Viewnav

To improve upon the positioning accuracy achievable with standard Loran-C receivers, Navigation Sciences has developed Viewnav, an interactive computer system that uses differential Loran-C to position a vessel with a claimed repeatable accuracy of 4.6 m (15 ft). Absolute accuracy of the system is on the order of ±10 m (±32.8 ft) at the 90 percent confidence level, and ±5 m (±16.4 ft) at the 20 percent confidence level (Newcomber K., 21 January 1985, personal communication). Loran-C offsets are obtained by interrogating onshore monitors established by the company. In addition, a land-based microwave system is used to calibrate a vessel's initial position or track. The system is particularly effective in ports and harbor areas where large buildings or the land-water interface may alter Loran-C readings.

A unique feature of the system is an electronic display of the survey area based on digitized nautical charts. As the vessel moves, its position on the display moves relative to depth contours and land boundaries. Other waterborne radar images in the area are also indicated.

A full system presently costs approximately $40,000, with a supplementary annual service fee of $2,000 for chart corrections and equipment maintenance.

The base price includes a mainframe Ai-M16 computer with 512KB of main memory, a flexible disk drive with 1MB capacity, and a Winchester hard disk of 10MB capacity. The basic system provides 5MB of chart storage, which equates to approximately 650 charts depending on scale selected. Additional charts can be stored on floppy disks. The manufacturer was to complete charts and install Loran monitors along the U.S. east coast in 1985 and along remaining U.S. coastal areas by the end of 1986.

If all survey stations were beyond a 50-m (164-ft) depth, then the ±20 percent of depth positioning accuracy could be attained with Viewnav. However, the need for gradient stations toward shore or shallow stations in special habitat or recreational areas will probably require accuracies beyond the system's present capability.

Lambda

The Decca Lambda is a low-frequency hyperbolic navigation system that operates in the 100-200 kHz frequency range, up to 400-800 km (249-497 mi) from shore stations. Lambda, an acronym for low ambiguity Decca, is a version of the Decca Navigator System originally introduced in 1944 (Ingham 1975). It compares phases to determine distances from the transmitters, with a master and three (purple, red, and green) or four (orange) slave stations. A typical receiver includes an identical unit for each frequency and internal circuits for signal phase comparison. Decometers provide readings of position lines, whose intersections on Decca charts provide the vessel's location. Lambda coverage includes Western Europe, the Persian Gulf, the Indian subcontinent, the Far East, Australian waters, and the Canadian maritime provinces. Because U.S. coastal water coverage is not available, the system will not be further discussed in this report.

OMEGA

OMEGA is a time-shared, continuous wave, radio-navigation system operating in the very low frequency range from 10 to 14 kHz. The system offers global coverage from eight stations having 10-kW transmitters on baselines of approximately 9,660 km (6,000 mi). Because sky waves provide line-of-position

data, corrections must be applied to observed values (e.g., from meteorological conditions and solar activity) for ionospheric disturbances. Although the normal operating mode is hyperbolic with at least three shore stations, a circular mode is possible with only two shore stations and a precision oscillator. Receivers count lanes automatically. However, it is necessary to initialize them to within ±0.5 lane width. If the signal is lost, an external fix may be needed to re-establish the lane count.

System accuracy is directly related to the accuracy of propagation correction constants, which are still being refined. The U.S. Navy designed the system to achieve an rms accuracy of 1.6-3.2 km (1-2 mi). However, without propagation predictions, rms accuracy is on the order of 8 km (5 mi). Differential OMEGA uses signal corrections from a fixed receiver located within 320 km (200 mi) to correct receiver readings. This mode theoretically enables an accuracy of approximately 400 m (0.25 mi) within this range (Kasper and Hutchison 1979). Composite OMEGA involves the analysis of information from signals at two or more frequencies to minimize the effect of sudden ionospheric disturbances on position accuracy. However, this approach has not yet been validated.

System costs vary due to the broad user spectrum and associated system components. Prices range from a few thousand dollars for a manual single-frequency receiver to over $25,000 for an automatic receiver that operates at three frequencies and interfaces with complex avionics. The cost of an automatic marine receiver is approximately $10,000. Due to OMEGA's reasonable cost and global coverage, it is an attractive method of general positioning and tracking at sea. However, its low achievable accuracies preclude its use as a coastal monitoring navigational tool.

SATELLITE SYSTEMS

Characteristics of representative government and privately-owned satellite systems are also presented in Table B-9. TRANSIT is the system currently available, although daily coverage is highly dependent on location. Multiple pass inputs are required to achieve the positional accuracies recommended herein. Navstar GPS should provide adequate coverage by 1988-89, but accuracies

achievable will be dependent on code availability to commercial users and the extent to which the signal is detuned in the interest of national security. Initial unit costs will be high, but will decrease rapidly. Some private systems (using government satellite signals, or their own satellites) are also described. In as much as the reported accuracies are adequate, further development of such systems should be monitored carefully.

Transit (Navsat)

The U.S. Navy Navigation Satellite System (originally Project Transit) consists of a group of satellites in 106-min circular polar orbits at altitudes of approximately 1,411 km (877 mi). The system also includes ground tracking stations, a computing center, an injection station, U.S. Naval Observatory time signals, and vessel receivers and computers. Positional measurements are based on the Doppler frequency shift that occurs when the relative distance between the satellite transmitter and vessel receiver changes (i.e., frequency increase upon closure and frequency decrease upon separation). Provided the satellite orbits are very accurately known, it is possible to locate the receiver. The nature of the Doppler shift depends on the exact location of the receiver relative to the satellite path (Maloney 1978). The system operates at frequencies of 150 and 400 MHz so that ionspheric corrections can be made through signal comparison techniques. Ground tracking stations in Hawaii, California, Minnesota, and Maine continuously monitor and provide orbital information to the computing center. Using these data, best-fit orbital and time information are supplied to the injection station for transmission to the satellites every 12 h. The vessel's position is then determined based on "known" orbital positions during satellite passage and measured frequency shifts.

As originally designed, at least one satellite would be within line-of-site every 35 to 100 min. However, at U.S. east and west coast latitudes the acceptable fix window is approximately every 90 min (Driscoll, C., 15 January 1985, personal communication). This is caused, in part, by the requirement that a satellite's maximum altitude be between 15° and 75° of the horizon before a fix can be considered valid. Another problem occurs when two satellites being tracked have approximately the same closest

approach, whereupon it becomes difficult to know which one is being monitored. Typically each satellite provides four fixes per day on two successive orbits spaced by 12 h. Because one satellite is currently inoperative and another has weakened batteries, it may take longer (e.g., several hours at the equator) to gain a valid fix (Booda 1984).

A static position fix with Transit using single-channel equipment can be made with an accuracy of approximately 90 m (295 ft). Dual-channel receivers improve single-pass accuracy to 37-46 m (121-151 ft) (Hoerber 1981; Maloney 1978). With multiple passes, an rms accuracy of 3-5 m (9.8-16.4 ft) is claimed by some equipment manufacturers. Using translocation (i.e., simultaneous measurements at two fixed locations, one of which is accurately known), estimated positional measurement accuracies are in the range of 0.5-1.5 m (1.6-4.9 ft) (Driscoll, C., 15 January 1985, personal communication; Moyer, C., 15 January 1985, personal communication). Magnavox has developed a satellite surveying program (MAGNET) that is reportedly capable of simultaneous location of up to 10 sites with a point-to-point accuracy of 30 cm (1 ft) or better. However, this system is designed for coordinated geodetic studies over wide areas using 3-10 MX 1505 receivers and recording data from ten or more satellite passes (Anonymous 1981).

Transit receiver costs range from $2,500 to $10,000 for basic single frequency units (Murphy, W., 15 January 1985, personal communication). More elaborate multiple-channel systems, sometimes in combination with OMEGA, cost from $30,000 to $52,000 (Jolly, J., 15 January 1985, personal communication; Driscoll, C., 15 January 1985, personal communication).

Use of the Transit system is generally not appropriate for coastal monitoring programs due to the inaccuracy of the system for fixes from either a moving vessel or from one occupying offshore stations for a relatively short time. A fix must be based on a single pass. With satellite passes at 1- or 2-h intervals, multiple-pass data acquisition is impractical. Therefore, only the best single-pass accuracy of 37-46 m (121-151 ft) can be achieved. Because translocation is designed for two fixed stations rather than one on a moving sampling vessel, and because MAGNET applies to land surveying only, neither method will provide the recommended minimum

accuracy of ±3 m (±9.8 ft) during the limited time the vessel will be at any one station. It is also noteworthy that the U.S. Navy intends to phase out Transit (as well as Loran-C and OMEGA) over a 15-yr period (U.S. Department of Defense and Department of Transportation 1984).

GEOSTAR

GEOSTAR is a pulse radio transmission system. It will provide satellite information for positions within the continental U.S. and its coastal waters by 1988. Three geosynchronous satellites (and a fourth as backup) will orbit the earth at 37,000 km (22,991 mi) at 70°, 100°, and 130° W longitude. System components include transceivers, satellites, and computers in a ground station. The links between the ground station and the satellites will operate at 5,117-5,183 MHz and 6,533 MHz, while user-satellite links will be at 1,618 and 2,492 MHz (Whalen 1984). Should a satellite fail, the backup would be moved into a proper orbit by telemetry command from the ground computer facility.

The system user will send a command through the transceiver, which relays the message through the satellites to a central computer at the ground station, reportedly in less than a second. The signal-arrival times from each satellite are used by the ground computer to calculate the position of the specially coded transceiver. The information is then transmitted back to the satellites and relayed back to the transceiver in a similar amount of time.

GEOSTAR will enable a typical single-shot positioning error of 2-7 m (6-23 ft), according to the developer. When needed, accuracies down to 1 m (3.3 ft) reportedly will be achieveable using two-way interaction, signal analysis, and averaging. Users at a known elevation (e.g., sea level) will be afforded the greater accuracy due to much smaller geometrical dilution of precision where only two rather than three coordinates are required. Continuous operations in a differential mode should also enable correction inputs for such errors as ionospheric delays, satellite position drift, and drifts in satellite electronic delays.

System designers estimate that the cost of a basic hand-held transceiver with a typewriter keyboard and LCD display will be well under $1,000 by the time the system is operable. A monthly service charge in the range of $10 to $30 is also anticipated (Howarth, C., 16 January 1985, personal communication). At publication, FCC reportedly had completed its review and approval of GEOSTAR Corporation's application for use of the requested frequencies. Candidate users are urged to verify the latest satellite/ground station operating schedule, and obtain further information on transceiver availability.

Navstar GPS

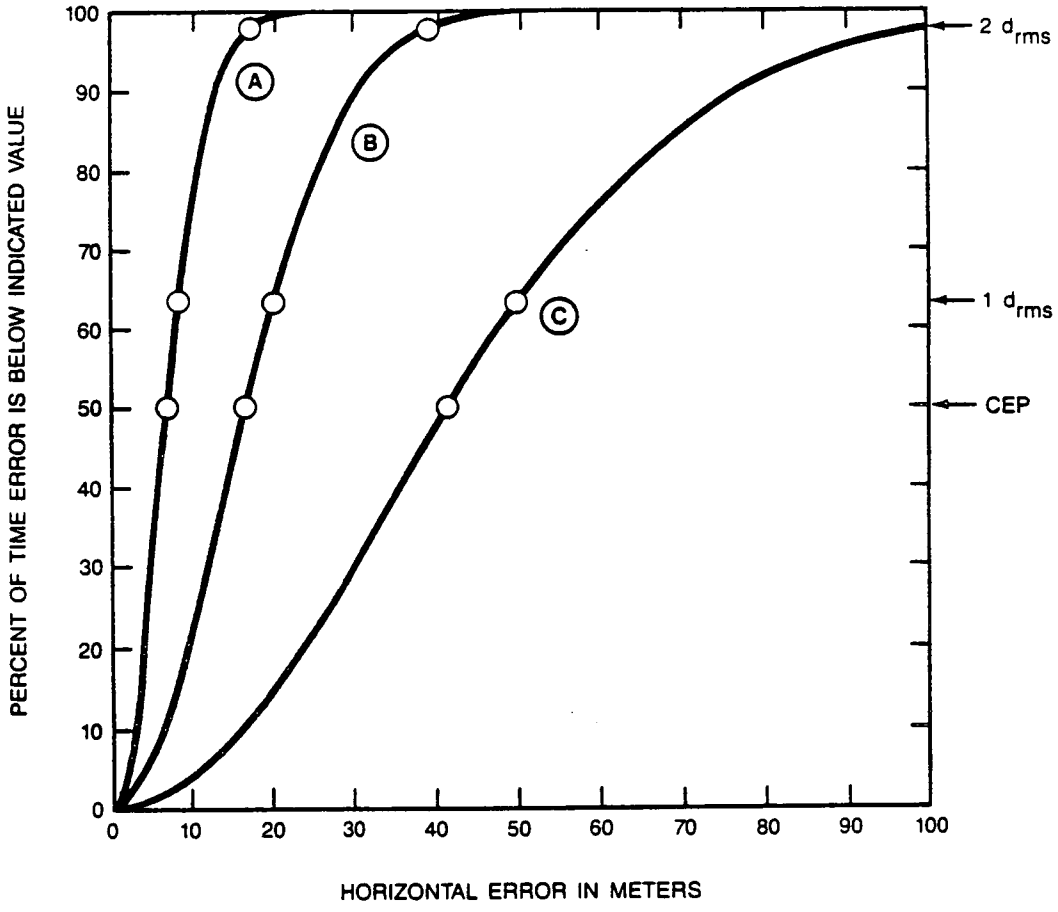
The Navstar Global Positioning System (GPS) is a second-generation satellite navigation system currently under development by the U.S. Department of Defense. Its purpose is to provide precise, continuous, worldwide, all-weather, three-dimensional navigation for land, sea, and air applications. Under current plans, 18 satellites will be launched into three co-planar orbits 120° apart to provide continuous transmission of time, three-dimensional position, and velocity messages to system users. The GPS satellites transmit at 1,227.6 MHz and 1,575.4 MHz to permit the measurement and correction of ionospheric refraction error. Currently, five developmental satellites are in orbit, providing approximately 4 h of coverage twice daily, separated by a 12-h period. Continuous two-dimensional positioning information should be available with 12 satellites by February, 1988, and three-dimensional coverage is projected for late 1988 or early 1989 (DeGroot, L., 15 January 1985, personal communication; Stansell 1984). The system consists of the satellites in 12-h, 20,200-km (12,552-mi) orbits, a U.S. master control station, several monitoring stations, and user equipment in the form of small, lightweight, relatively inexpensive receivers. Signals received from any four Navstar satellites are demodulated, time-correlated, and processed to obtain precise position information.

Two levels of positioning accuracy are achievable with the Navstar GPS system. The lower level is obtained from the Standard Position Service (SPS) using the coarse acquisition or "C/A code." When the system becomes fully operational, navigational accuracy from these signals should be approxi-

mately 100 m (328 ft) 2 d_{rms}, or a circular probable error (CEP) of 40 m (131 ft) (Montgomery, B., 15 January 1985, personal communication). More accuracy can be achieved using the Precise Positioning Service (PPS) or "P-code" (i.e., 8-9 m two-dimensional CEP). Accuracy obtained during testing with a multichannel, two-frequency, P-code receiver and with a single-channel, one-frequency C/A code receiver is shown in Figure B-1. Accuracy available to civilian users is indicated by curve C. Additional positioning accuracy can be achieved by operating in a differential mode, in which receivers on a vessel and at a known onshore location simultaneously receive the satellite signals. The onshore receiver is calibrated. Bias corrections based on signals received at the fixed station are then transmitted to the mobile receiver. These area-specific corrections yield more accurate positional determinations. With differential GPS, a two-dimensional position should be definable within a range of 2 to 5 m (6.6 to 16.4 ft) (Montgomery 1984; Stansell 1984).

Due to lack of full-time coverage at the present time, both SPS and PPS are available to military and civilian users. However, the government intends to encrypt the P-codes, allowing use only by the military and other authorized users [e.g., National Ocean Industries Association (NOIA) members]. NOIA has proposed that all P-code receivers be owned and operated by a single service company that would provide both the equipment and personnel when national security conditions are met and no other reasonable navigational alternatives are available (Stansell 1984). Under U.S. Department of Defense policy, access to PPS is available to civilian users operating in the "national interest" (Anonymous 1985). Equipment, cryptography, and support services will be provided under contract to the user. However, it would appear that general users in coastal areas will be limited to C/A code equipment. It will therefore be necessary to operate in the differential mode in order to achieve the positional accuracies needed for coastal monitoring.

Because the GPS system is in a developmental stage, cost estimates for the equipment are difficult to make. Several major equipment manufacturers are in the process of designing receivers with varying capabilities, and a limited number of models are now available. Some manufacturers envision that receivers with 100-m (328-ft) accuracy will cost less than $500 when



SOURCE: Stansell 1984

Figure B-1. NAVSTAR/GPS test network accuracy.

mass produced (e.g., for automobiles). At the other extreme, Texas Instruments sells the TI4100 Navstar Navigator for $140,000. It is said to be capable of slow dynamic positioning within a few meters, speed within tenths of a knot, and time to the microsecond (Montgomery 1984; St. Pierre, R., 15 January 1985, personal communication). Motorola anticipates that the initial cost of two stations needed to operate in the differential mode will be in the $100,000 range (Sheard, S., 15 January 1985, personal communication). Magnavox has a five-channel T-Set GPS Navigator, with real time differential GPS operation as a planned option. A two-unit system, excluding communications link, costs approximately $100,000 (Driscoll, C., 15 January 1985, personal communication). Rockwell International sells a prototype C/A code receiver for $17,500 and anticipates that GPS receivers will cost under $10,000 by 1988 (DeGroot, L., 15 January 1985, personal communication). Tracor expects initial models to sell for under $10,000, falling to around $1,000 in 3-5 years (Murphy, W., 15 January 1985, personal communication).

Using the C/A code in a differential mode, the Navstar GPS positioning system should provide the ± 3 m (± 9.8 ft) accuracies recommend for coastal monitoring near ZIDs. Errors as low as 1 m (3 ft) at a range of 200 km (12.4 mi) from the reference station are predicted for daytime operation. Smaller errors are expected at night (Kalafus 1985). However, testing with the actual satellite signals modified to reduce achievable accuracy will be required to confirm this capability. The two required stations may be expensive at first, but competition and the large potential market are expected to drop the price much lower.

SERIES

The SERIES positioning and navigation system (Satellite Emission Range Inferred Earth Surveying) evolved from a technique originally developed to measure movements in the earth's crust for tectonic studies and earthquake predictions. The system enables use of signals from existing Navstar GPS satellites with no knowledge of either the P or C/A codes by simultaneous pseudoranging to multiple satellites in a differential mode. Accuracies on the order of 2 m (6.6 ft) CEP or 5 m (16 ft) 2 d_{rms} are said to be achievable for vessels in a slow dynamic mode (0-10 kn) (ISTAC 1984). This is accomplished

by comparing Navstar signal arrivals at one receiver to the same signals received at another shore-based geodetic reference mark. By explicit differencing of the frequency and phase measurements observed from each satellite, it is apparently possible to eliminate the effects of Navstar signal variations that secure the satellites from an unauthorized user in an autonomous, single-receiver, real time mode. SERIES receivers are codeless spectral compressors that simultaneously receive and incorporate spread-spectra modulations of several Navstar satellites and then extract the frequency and phase of each satellite in view. Data are processed by a combination of Doppler positioning and phase ranging.

System components include an unattended, fixed reference station, a marine vessel station, and a reference link (via satellite or terrestrial radio) to transfer the reference station signal to the marine vessel for real time positioning. The reference station includes an SERIES GPS receiver (MPS-1), a rubidium frequency reference, and a customer-supplied radio transmitter (200 Hz analog signal). The marine station consists of the GPS receiver with an integrated Navstar C/A-code-correlating subsystem for broadcast satellite ephemerides, a rubidium frequency reference, a microprocessor for real time position computations, and a customer-supplied receiver for fixed reference station signal reception. A standardized RS-432 interface is provided for communication of the position information to the vessel's navigation system.

The initial MPS-1 units are estimated to cost $205,000 for a ship system and $82,000 for the fixed base system required for differential mode operation (Whitcomb, J., 14 January 1985, personal communication). The system will probably be available on a lease or service-contract basis, as well.

When operational, the SERIES system may offer a high-accuracy alternative to the Precise Positioning Service of Navstar GPS or to differential mode operation with the C/A code. Although the projected cost for an initial unit is high to recover research and development expenditures, cost should decrease with further production. Potential users should confirm price,

verify accuracies achievable from a mobile marine vessel, and identify specific data-link components that need to be supplied by the user.

Aero Service GPS

The Aero Service Division of Western Geophysical Company of America is developing a codeless satellite navigation system for marine positioning. The system will enable real time navigation in the slow dynamic mode to less than 5 m (16.4 ft). For vessels in the semi-static mode (on station) for 30 min, the system will reportedly yield a position fix accuracy of less than 1 m (3.3 ft) (Mateker, E., 17 January 1985, personal communication). The system will require one unit onshore at a fixed position, and one unit on the survey vessel. Continuous real time communication between the two systems may or may not be necessary, depending on steps by the U.S. Department of Defense to degrade certain elements of the GPS satellite signals. Prototype testing was scheduled for September, 1985, with production systems planned for early 1986.

This system is noteworthy, as it will probably be based on methods now used for land surveying in the MACROMETER Interferometric Survey System. The MACROMETER is designed for very precise positioning in a fixed-point (static) mode, using GPS signals but no codes. Company tracking stations (Phoenix, Arizona, and Woburn, Massachusetts) will follow up to six satellites simultaneously. The MACROMETER is capable of providing position in terms of latitude, longitude, and ellipsoidal height to within a few parts per million of the distance from a reference point. In the continental U.S., 1-3 h of observation will yield first-order (1:100,000) accuracy in all three coordinates using the GPS satellites. Data for a third-order (1:10,000) survey point may be collected in less than 1 h (e.g., as little as 15 min of observation).

The MACROMETER surveying system includes two or more field units and an office data processer. Each V-1000 field unit includes an antenna, receiver, tape drive, 30 m of cable, time receiver, power package, battery chargers, generator, and DC/AC inverter. The P-1000 Office Data Processer computer subsystem includes hard and floppy disk drives, video terminal,

tape drive, printer, modem, and all necessary software. A 1,000 series two-unit surveying package is currently priced at $235,000. The system can be rented for $5,000 per V-1000 unit per month, with a 2 month minimum on each unit.

HYBRID POSITIONING TECHNIQUES

Characteristics of three systems which measure both range and azimuth (therefore requiring a single onshore station rather than two or more) are given in Table B-10. Modular units for use with an already-owned system can be obtained for approximately $20,000. Semi- to fully-automatic complete systems are available for $70,000-$100,000. Angular and range accuracies are adequate for the recommended coastal position requirements.

AZTRAC

The ODOM Offshore Survey AZTRAC is a semiautomated optical angle-measuring and transmitting system which can be used in conjunction with an independent distance-measuring system to position a vessel. The AZTRAC system consists of a modified Wild Heerbrugg T16 theodolite, an onshore transmitter, and a vessel receiver. The theodolite has an infinite tangent drive and provides information in a digital format. Typically, the separate distance-measuring system consists of a microwave master receiver on the vessel and a remote unit transmitter located at the theodolite.

For a survey, the AZTRAC theodolite and transmitter are setup at a point of known position and the theodolite is zeroed on a known azimuth line of backsight. The theodolite operator then sights and tracks the survey vessel's ranging antenna or transponder. As the vessel moves, the microwave ranging system continuously measures distance between the shore station and the vessel. The tracking motion produces pulses that are decoded by the AZTRAC transmitter and displayed to the theodolite operator as the angle to the vessel from the reference azimuth line. The angle is also converted to binary code serial format and used to activate the transmitter, which sends the information to the survey vessel. The AZTRAC receiver converts the angle information to parallel format and displays it for manual

TABLE B-10. RANGE-AZIMUTH POSITIONING SYSTEM CHARACTERISTICS

SYSTEMS	FREQUENCY	RANGE	NOMINAL ACCURACY AZIMUTH	RANGE	POSITION	COST
AZTRAC Odom Offshore Surveys Baton Rouge, Louisiana (504)769-3051	Optical and microwave (typical)	Visible	0.01^{o}	Both depend on accuracy of ranging system used		$22,500 plus ranging system cost cost
POLARFIX Krupp Atlas-Elektronik Webster, Texas (713)338-6631	Laser (904 nm) UHF Telemetry (406-470 MHz)	5000 m	0.01^{o}	±0.1m±0.1m/km	±0.1m±0.2m/km	$100,000
ARTEMIS Andrews Hydrographics Houston, Texas (713)558-2236	9.2-9.3 GHz	10-1400 m or 200-30,000 m	0.03^{o}	0.5 m short 1.5 m long	Not stated	$70,000 to $75,000

recording. It simultaneously outputs the angle as serial data for automated recording or processing by any available onboard computer or plotting system.

AZTRAC is designed to operate with most microwave ranging systems. Two AZTRAC units working in an azimuth-azimuth mode can provide positioning in survey areas where reflections from metal structures or electrical noise from radar and other transmitters limit use of microwave ranging. The Wild T16 theodolite has a 30X magnification, 27-m (89-ft) field of view at 1,000 m (3,280 ft), and an angular resolution of 0.01° (36 arc sec). At a distance of 5 km (3.1 mi), this corresponds to an absolute arc length error of 0.9 m (3.0 ft).

The National Ocean Survey recently examined range-azimuth positioning of a vessel moving at a nominal speed of 6 kn (11.1 km/h) at ranges of up to 3,000 m (9,842 ft). Instruments used included a Wild T2 theodolite, from which angles were manually recorded onshore, and the AZTRAC, whose angles were recorded on the vessel. Pointing errors (68 percent probability) of these two instruments were found to be approximately 1.3 m (4.3 ft), independent of range when standard deviations of right and left movement data were pooled (Waltz 1984).

The theodolite was sited on a white Del Norte Trisponder transponder on the moving vessel. Visibility was good during the 2-day survey (off Monterey, CA), with calm mornings giving way to afternoon winds of 15 kn and 0.6-0.9 m (2-3 ft) seas. Apparently, range could have been extended much farther under such conditions, particularly if color had been added to the vessel target (Waltz, D.A., 18 January 1985, personal communication). U.S. Army Corps of Engineer users have confirmed the effectiveness and reliability of the AZTRAC system in conjunction with several different microwave ranging systems (Ard, R., 18 January 1985, personal communication). The system has also proven effective in port and harbor surveys when it was impossible to achieve optimal shore station geometry for range-range or hyperbolic operation.

For use in a coastal monitoring program, the theodolite could be set at a predetermined angle, with the operator indicating when the vessel

was in the sight path. Vessel range could then be adjusted until a predetermined distance was achieved, allowing a marker buoy to be released. Anchors could then be set upwind and downwind, with line-out adjusted until a properly buoyed position was achieved. Alternately, the vessel's bow could be held into the sea and on the buoy, provided an offset correction to the sampling point was allowed.

The current cost of the AZTRAC alone is $22,500 (Apsey, B., 10 January 1985, personal communication). A system consisting of the AZTRAC, a Motorola Falcon 484 with one reference station (approximately $32,000) and an interface unit ($10,000) would cost $64,500. Thus, provided the required range is achievable under anticipated visibility conditions, the additional versatility of the AZTRAC can be realized for $25,000 above the $39,300 cost of a two-station Falcon 484 range-range microwave system.

POLARFIX

POLARFIX is a dynamic range-azimuth positioning system by Krupp Atlas-Elektronik. The system uses a scanning (30° horizontal) pulsed laser beam from a single, fixed, onshore tracking station to follow the survey vessel (up to 10°/sec) and to transmit range and angle information via telemetry link. The system incorporates a fully automated onshore tracking station, which requires no attendance beyond initial station setup and azimuth referencing. The shore station can locate the mast-mounted prism reflectors, follow the vessel, and, if necessary, relocate the vessel by performing a routine search pattern based on a record of tracking history. The shore tracking station consists of a laser-sensing head mounted on a conventional survey tripod, linked by cable to an integrated control unit that houses data control, transmission, and telemetry transceiver equipment. An integral control unit (including a display and a second telemetry receiver), keyboard terminal, printer, telemetry antenna, and prism reflector assembly are onboard the vessel.

Under clear operating conditions, a 3-km (1.9-mi) range using a Class I laser or a 5-km (3.1-mi) range using a Class IIIa laser may be selected. Maximum range achievable varies with the prism assembly used to reflect

the tracking station's laser beam. In foggy weather, range is said to be 1.5 times visible range, due to use of the pulsed infrared laser. Single-, dual-, and triple-ring omnidirectional prism assemblies can be stacked on the vessel antenna. For average weather conditions, a two-prism assembly (each with five reflectors) gives approximately 3.5 km (2.2 mi) of range. This can be extended to approximately 5.0 km (3.1 mi) with the addition of more assemblies.

Range accuracy is reported as 0.1 m $\pm$0.1 m/km (0.3 ft $\pm$0.5 ft/mi) of measured range. Azimuth accuracy is said to be 0.01° or better. The resulting positional accuracy at 1, 3, and 5 km (0.6, 1.9, and 3.1 mi) is approximately 0.3, 0.6, and 1.0 m (1, 2, 3.2 ft), respectively. The positional algorithm given is $\pm$0.1 m $\pm$0.2 m/km ($\pm$0.3 ft $\pm$1.1 ft/mi). Current cost of the system is $100,000 (Guillory, J., 28 January 1985, personal communication).

ARTEMIS

The ARTEMIS by the Christiaan Huygenslabortorium (Holland) is a distance-bearing type of microwave positioning system capable of measurements at ranges of 10 m (32.8 ft) to 30 km (18.6 mi), and angles from 0° to 360° from a single fixed shore station. Accuracies at the two-sigma or 95 percent level are given as $\pm$1.5 m (4.9 ft) distance, and $\pm$0.03° azimuth, equivalent to $\pm$0.5 m/km (2.6 ft/mi).

Angle measurements are based on automatic tracking antennas on the vessel and at the shore station. Once locked, the two antennae move, always pointing towards each other. A maximum combined tracking speed of 3°/sec is allowable to achieve the angle error specified. The direction of the fixed station antenna is measured very accurately with a precision shaft coder, which is mechanically coupled to the main shaft of the antenna. Measured angle data are transferred to the mobile station via the established continuous microwave channel. The same microwave link is used to measure distance by controlled interruption of the microwave signal. Both angle and distance are normally displayed on the Mobile Control Data Unit, although readout at the shore station is also feasible. The microwave link is also