Chapter 7
Positioning Techniques for Offshore Engineering Surveys

7-1. General Scope and Applications

This chapter covers general procedural guidance and quality control criteria for visual, mechanical, electronic, and satellite positioning methods used to control surveys of river and harbor projects. Both terrestrial and satellite positioning systems are covered in this chapter. Terrestrial positioning methods include traditional land-based techniques such as sextant resection, triangulation, tag lines, microwave electronic distance measurement (EDM) systems, and electronic total stations. Since the early 1990's most of these terrestrial positioning methods have been largely replaced by satellite-based positioning methods, namely GPS and more accurate code phase Differential GPS (DGPS) and Real Time Kinematic (RTK) carrier phase DGPS. Since there are still isolated project areas where satellite GPS methods may be inaccessible or impractical, one of the traditional terrestrial survey methods covered in this chapter may be needed to provide survey control. Examples of such cases may include: (1) small dredging or marine construction projects where only a limited amount of depth coverage is required, (2) areas under bridges, in deep-draft harbor berths, or near dams where GPS satellite view is blocked, (3) intermittent, low-budget projects where traditional positioning methods may prove more economical than equipping a fully automated DGPS-based hydrographic survey system, or (4) rough reconnaissance surveys where meeting a specific positional accuracy standard is not required. Procedural methods and quality control (QC) criteria for some of these older survey techniques are retained in this manual primarily for reference purposes. The following topics are covered under this chapter:

Section I:	Sextant Resection Positioning
Section II:	Triangulation/Intersection Positioning
Section III:	Visual Positioning Methods
Section IV:	Tag Line Positioning Methods
Section V:	Range-Azimuth Positioning Methods
Section VI:	Land-Based Electronic Positioning Systems
Section VII:	Global Positioning System Techniques
Section VIII:	Summary of Positioning System Quality Control Standards

7-2. Positional Accuracy

All the positioning methods described in this chapter will meet USACE positional accuracy standards in Table 3-1 provided that distances from the shore-based reference point and the vessel are kept within tolerable limits. The "tolerable limit" will vary with the type of positioning method, procedures employed, and accuracy of the instrumentation used. In general, the positional accuracy of all systems will degrade as a function of distance from the baseline reference points--some faster than others. For example, a poorly conducted tag line survey may exceed Corps accuracy standards 300 feet from the baseline whereas an electronic total station could be extended 1000 ft or 2000 ft from the reference point. Sextant, triangulation, and range-range EDM are extremely geometry dependent; thus the accuracy of such methods will vary widely over a project area. DGPS-based positioning is not as significantly effected by such distance and geometrical accuracy degradations. Therefore, terrestrial-based positioning methods should only be employed where DGPS positioning is not available. Users must also fully assess and evaluate the resultant accuracy of any positioning method, including DGPS. Some visual or mechanical positioning methods can, under some conditions, exceed DGPS accuracies.

Section I
Sextant Resection Positioning

7-3. General Applications

Sextant positioning involves the simultaneous observation of two horizontal angles between three known objects from which the position of an offshore platform is resected--see Figure 7-1. Although sextant resection positioning was once one of the most widely used methods of positioning hydrographic survey vessels, channel sweep rafts, and dredges, it is now rarely, if ever, used. Sextant positioning was also widely used to calibrate medium frequency hyperbolic, range-range, and microwave positioning systems. Until the mid 1990s, sextant positioning was the primary method used by the US Coast Guard to locate and place buoys. Sextant positioning is totally performed aboard the survey vessel. It is not dependent on electronics, communications, or shore-based support. Under restricted conditions (i.e., close in on targets and near static position fixes), it can be relatively accurate when properly executed. In general, however, sextant positioning under dynamic vessel conditions is no longer considered accurate for most navigation or dredging applications. Currently, inexpensive hand-held GPS (Standard Positioning Service--SPS) receivers will typically provide accuracies that equal or exceed sextant positioning accuracies.

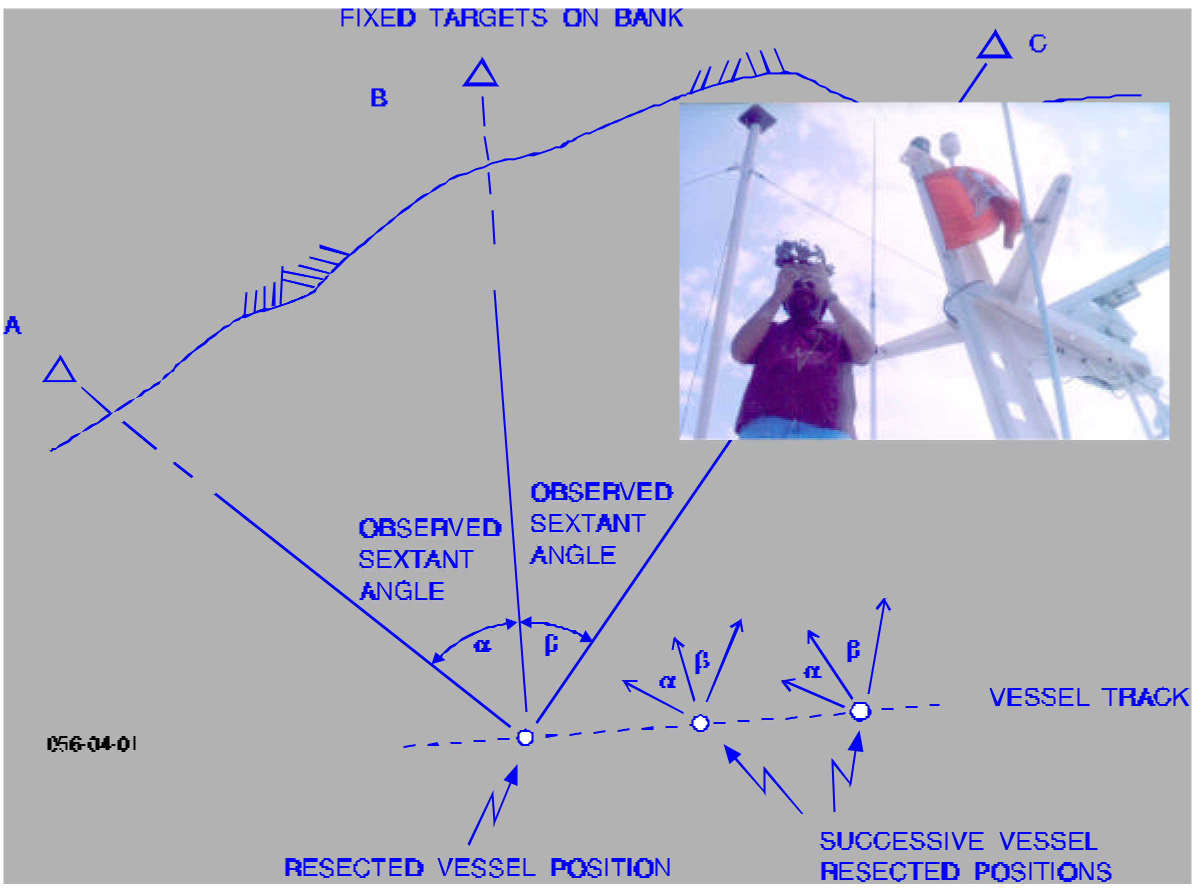

Figure 7-1. Sextant resectioning

7-4. Sextant Resectioning Procedures

Two sextant observers aboard the vessel are required. Sextant "fix" angles are usually taken at some even time interval or as called for by the depth observer (lead line or echo sounder). These angles are called or radioed to the recorder/plotter, along with depth information from that observer. Observed sextant angles are recorded with their times and, if applicable, depth data. These data can be recorded on a worksheet form or in a standard field survey book, or they can be directly input into a data logging device. The vessel's position is determined at the time of the fix by manual plotting with a three-arm protractor. Preconstructed constant sextant angle curves can also be drawn on a plotting sheet for on-line manual plotting. Alternatively, the two observed angles can be input into a computer containing standard survey resection software. Formulas for performing such computations are found in any standard surveying or geodesy textbook. The density of position fix updates varies with the timing and speed of the sextant observers and plotter/computer input. Overall, the process is extremely labor-intensive, requiring a boat operator, two sextant observers, a depth recorder operator, and a data logger/plotter. In extreme cases, these functions can be doubled or even tripled up (i.e., one of the sextant observers could also perform the recording and plotting function).

a. Hopper dredge positioning. A single sextant angle may be used in conjunction with a fixed range line of position, as shown in Figure 7-2. In years past this was a common technique for locating hopper dredges. Preplotted sheets showing the intersecting sextant angles and ranges were drawn up for each channel. A single sextant angle would quickly locate the dredge running along a constant channel range.

b. Redundant sextant resectioning. On stable offshore vessels and other platforms, multiple sextant angles can be observed to several targets. The resultant fix can be adjusted by onboard software using least squares adjustment techniques. This adjustment will provide an assessment of the positional accuracy. The results of a multiple resection can be quite accurate, and can be less than ± 1 m in some isolated cases. The US Coast Guard used this technique on buoy tenders.

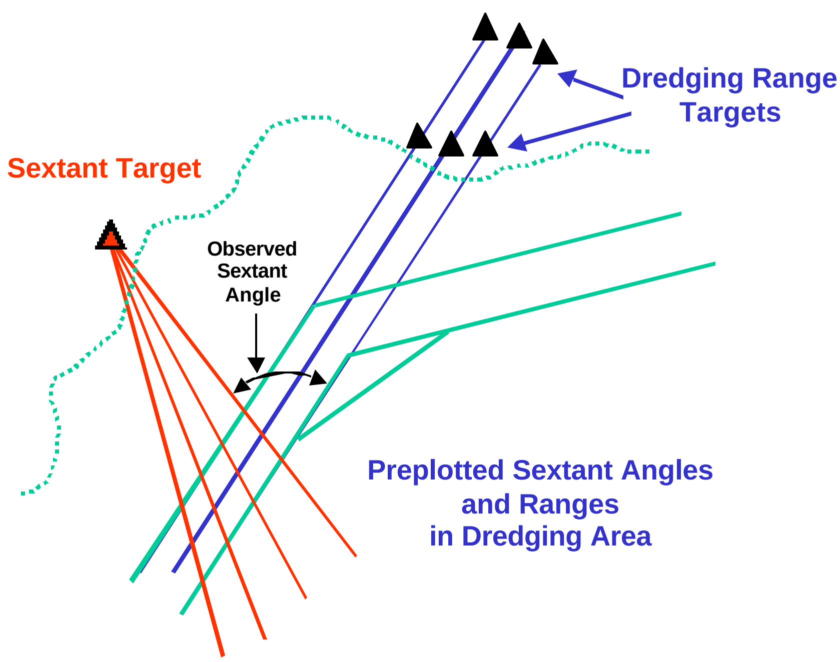

Figure 7-2. Hopper dredge control using combined visual ranges and sextant angles

7-5. Accuracy and Quality Control of Sextant Resection Positioning

The two observed sextant angles form the loci of circles, the intersection of which is the vessel's position. Each angle forms a circle defined by three points: the two shore control points/targets and the vessel. The geometry of these two intersecting circles is a primary factor in determining the strength of a sextant resection. As the two intersecting circles converge on each other, the resultant position weakens drastically. This is often termed the "swinger" since a three-arm protractor will swing along this arc to any position. As a result, the accuracy of a sextant position varies significantly with the geometrical location relative to the targets. In the best conditions, dynamic positional accuracies rarely exceeded 5 meters (95% RMS). Average accuracies were generally in the 10 to 20 meter range.

a. Determining the accuracy of a resected position. Historically, various numerical formulas were developed to depict the relative accuracy of a resected position. Constant error contours could also be drawn for any given target configuration. The simplest method for estimating resection accuracy at any point is to move each angle by its estimated accuracy and assess the resultant change in position. This is readily done when automated resection computing software is available, or by noting the position shift in a three-arm protractor. Positional accuracy needs to be accessed at various points in the work area.

b. Quality control factors. In performing sextant resection positioning the following QC factors must be considered. All impact the overall accuracy of a resected position.

(1) Precision of sextant angles. This is a function of the instrument's resolution, sharpness of the shore-based targets, relative rate of angular change, and, most importantly, the skills of the observers. Estimating the standard error of a sextant angle observed on a moving vessel is difficult--a range of ±1 to ±5 minutes of arc is typical. Sextant angles are usually recorded to the nearest minute of arc and, in some cases, to the nearest 0.1 minute of arc.

(2) Observer synchronization. Both angles must be observed simultaneously and from the same point. This is usually not feasible in practice, and observer eccentricities are accepted errors.

(3) Plotting errors. Plotting sextant fixes with a three-arm protractor aboard a moving vessel is not an exact process, and significant inaccuracies can result.

(4) Velocity and motion of the vessel. Vessel motion affects the ability of the observers to maintain angles on both targets. Slow vessel velocities are essential in performing accurate sextant surveys.

(5) Observer fatigue. Continuous sextant surveying is extremely fatiguing for the observers and plotter. Data quality usually degrades during the course of a survey due to fatigue.

(6) Targets. Sextant angle targets may include water tanks, lights, daymarks, beacons, etc. When natural targets with coordinated points are not available, temporary targets must be constructed and surveyed. The type of target (and its distance away when fog or haze is present) affects the sextant pointing accuracy.

c. Sextant calibration. Due to design and handling, internal sextant instrument calibration is not particularly stable. Observers must continuously check the calibration of their sextants. This is usually done periodically during the survey--typically at the end of each survey line.

d. Quality assurance. Few opportunities existed to perform QA checks on sextant positioning. When more than three targets were visible, different resection positions could be compared at an anchored position.

Section II
Triangulation/Intersection Positioning

7-6. General Applications

An offshore vessel or platform can be positioned (triangulated) by transit or theodolite angles observed from base line points on shore. This method was also commonly used to calibrate microwave positioning systems when fixed points were inaccessible to the vessel (e.g., dredges, drill barges). Intersection techniques are no longer employed in dynamic hydrographic surveying practice; however, the technique may have application in areas where electronic positioning systems cannot be deployed or where increased positional accuracy is required. As with sextant surveying methods, angular intersection positioning techniques are labor-intensive. As indicated in Figure 7-3, two (or more) shore-based transit or theodolite observers are required, along with either visual or radio communication equipment with which to transmit the observed angles (or direction azimuths) to the offshore vessel for on-line recording, plotting, and/or calibration analysis. Due to the higher precision and stability of the instruments, the resultant positional accuracy can be quite good, provided observing procedures are properly executed. Theodolite angular observations to align static platforms are extremely accurate, and triangulation techniques are often used to supplement electronic distance measurement (EDM) or DGPS positioning of fixed offshore structures (piers, bridges, rigs, etc.)--both during construction and subsequent deformation monitoring.

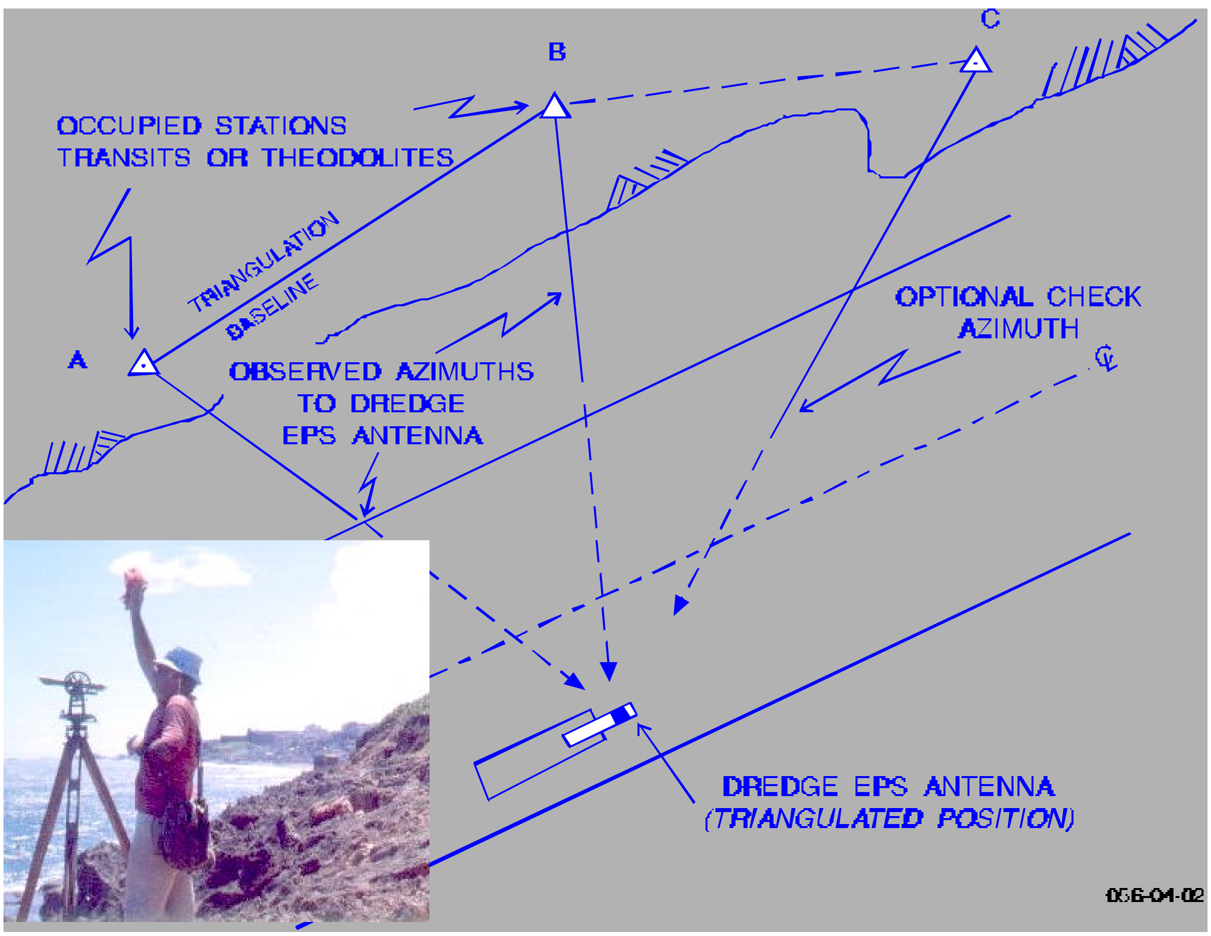

Figure 7-3. Vessel location using triangulation/intersection positioning methods

7-7. Intersection Positioning Procedures

A wide variety of angle or azimuth direction measuring instruments may be used. These include standard surveying transits, geodetic theodolites, and total stations. Instruments have been designed with hand cranks to facilitate continuous tracking of a moving vessel. The shore-based direction measuring instruments are set over known control monuments and aligned/referenced to one another or other positioned targets or landmarks. Two backsight check points are recommended, and frequent rechecks of the backsight orientations should be made during the course of the survey (normally every half-hour). Backsight orientations may be set to zero (resultant direction observations to the boat are then angles) or aligned to the grid azimuth between the occupied point and reference backsight (resultant directions to the boat are direct grid azimuths). The selected orientation depends on the onboard position computation/plotting method employed. Simultaneously observed positional "fixes" are usually called for from the boat by radio (or by visual flags where radio communication is unavailable). Fixes may be at equal time intervals or as called for on a random or as-needed basis. Advance warning is made of upcoming fix events so that observers can initiate precise tracking of the boat. A defined point aboard the vessel is tracked. This well-marked point should be centered over the echo sounder transducer or may be the positioning system antenna in the case of calibration work. In some instances, a preset alignment of an offshore platform is required. In this case, the precomputed alignment is set into each of the instruments and the platform is "walked" into position by the observers.

7-8. Data Recording and Plotting

Angles/direction azimuths are observed to units commensurate with the instruments and relative distance and velocity of the offshore vessel. Normally the nearest minute (or 0.01 deg) is adequate for dynamic hydrographic applications. Static observations will use repeated directions to increase accuracy to the ±1 second of arc level if needed. Angular data are relayed to and recorded aboard the boat and, in cases in which communications are erratic, at the instrument point also. Data may be recorded on worksheet forms or standard field survey books or input into a data logging device. Intersection data may be plotted aboard a dredge or survey vessel using standard drafting machines or preplotted azimuth array sheets. Neither of these methods is considered highly accurate, but each is adequate for visual navigation purposes

7-9. Accuracy of Triangulation/Intersection Positioning

As in conventional land surveying triangulation work, the accuracy of a point intersected by two azimuth directions depends on the precision of the instruments (their tracking accuracy) and the geometrical strength of the intersection. The positional accuracy, therefore, varies throughout the project area. An overall error analysis is complex since the angular standard errors for each instrument vary as a function of distance between the instrument and the vessel. Thus, determining the dimensions of the resultant error ellipse is more difficult.

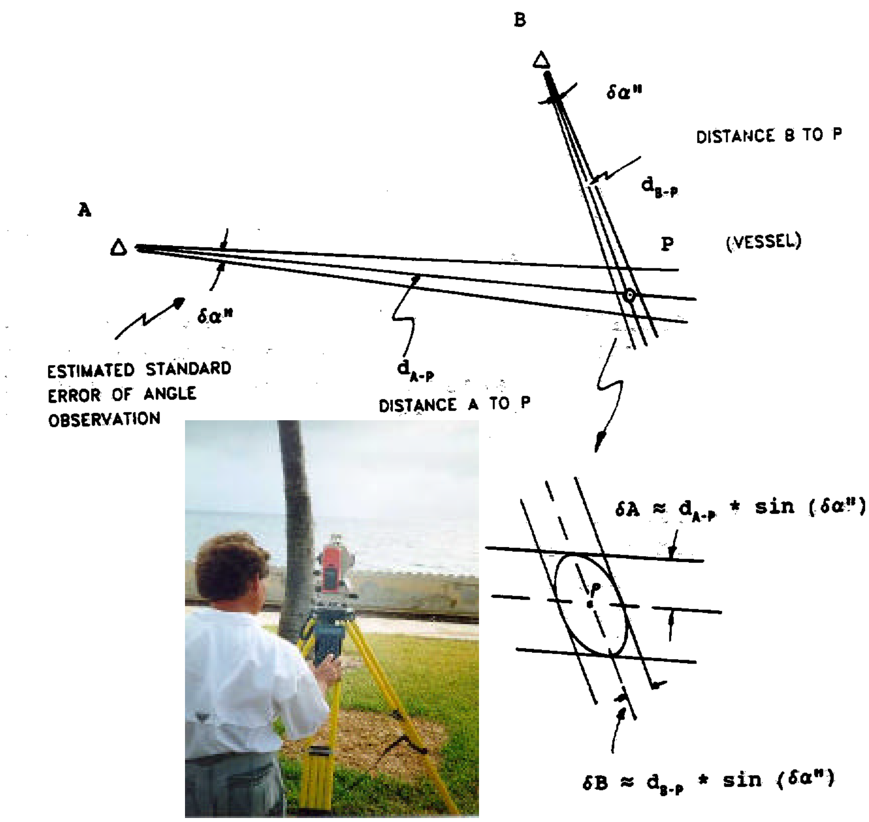

Figure 7-4. Estimating accuracy of intersected angles

a. A practical (but only *approximate*) estimate of the accuracy of an intersected position may be made by averaging the standard errors of each azimuth displacement at the offshore location, using the computed distances from each observing point. Given the theodolite/transit observing points *A* and *B*, and distances $d_{A\text{-}P}$ and $d_{B\text{-}P}$ to the offshore platform (Figure 7-4):

$$\delta_A = d_{A\text{-}P} \cdot \sin(\delta \alpha'')$$

$$\delta_B = d_{B\text{-}P} \cdot \sin(\delta \alpha'')$$

$$\text{then,} \quad s_{Avg} = (\delta_A + \delta_B) / 2 \qquad \text{(Eq 7-1)}$$

where

s_{Avg} = estimated standard error of an azimuth displacement at the offshore point

$d\ a''$ = estimated angular tracking accuracy of the particular instrument used (assumed the same for both instruments) *b.* The RMS error (at either 1-σ or 95%) can be estimated using Equation 7-2:

$$RMS_{(1\text{-}\sigma)} = 1.414 \cdot \sigma_{AVG} \cdot \text{cosec } A$$

or at 95% confidence level; (Eq 7-2)

$$RMS_{95\%} = 2.447 \cdot \sigma_{AVG} \cdot \text{cosec } A$$

where *A* is the angle of intersection between the two transit/theodolite azimuths at the offshore point.

c. The above computation may also be performed graphically. The left page in Figure 7-5 depicts a sample field computation of the accuracy of a static intersected point (i.e., spudded dredge) using the above approximate formulas. The right page shows an alternate method of computing the RMS accuracy when the distances are simply averaged.

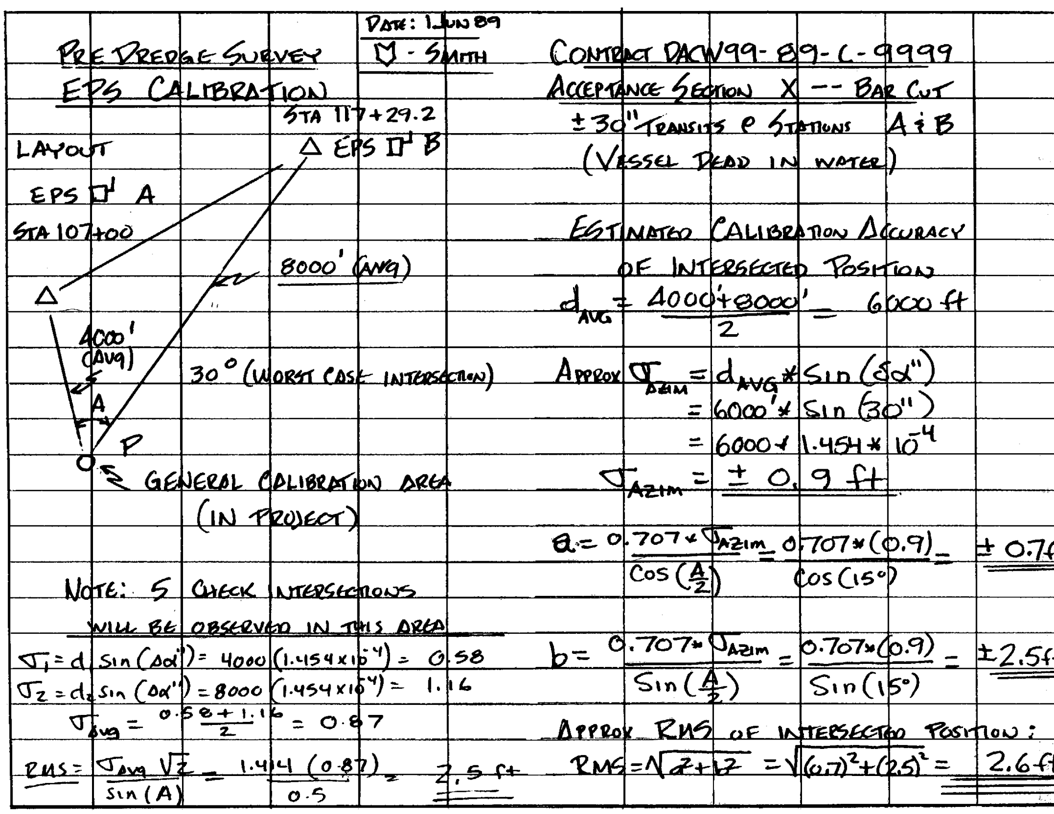

Figure 7-5. Field computation of intersected position accuracy

d. Multiple azimuth intersection techniques. To increase the accuracy of a triangulated point, additional shore stations are occupied in such a manner that each vessel position has three or more azimuth observations. This procedure provides redundancy and allows for an on-line assessment of the accuracy of the resultant position. Normally, a least-squares adjustment technique is performed on computers aboard the vessel. In aligning offshore structures during construction, or monitoring subsequent deformations, redundant theodolite azimuths are normally required. Theodolite (or total station) directions are repeatedly observed to increase accuracy. These azimuth alignments are combined with concurrent EDM or GPS distance observations in a properly weighted least-squares adjustment.

7-10. Quality Control and Quality Assurance

Periodic backsight checks should be made during the course of the survey. Like sextant survey methods, observer and plotter fatigue can impact quality. A third instrument provides the only semblance of an independent QA check on intersected point; however, this was rarely practical in practice.

Section III
Visual Positioning Methods

7-11. General Applications

Visual location relative to known shore features or flags was once a common hopper dredge positioning method. Few applications remain today, other than for construction--e.g., horizontal and vertical alignment of construction equipment, rigs, barges, etc. Dynamic hydrographic survey positioning by intersecting visible ranges and other identifiable objects is now rarely performed, given the wide availability of GPS control. Relative visual positioning is generally suitable only for non-navigation reconnaissance work where identifiable features on the furnished drawing, navigation chart, or map will be assumed to be accurate for this type of survey. These include navigational aids, beacons, day markers, bridges and other structures or map features. For some dredging and other investigative work, additional range poles, flags, and/or lasers are set ashore, as shown in Figure 7-6. Fixes are typically taken when the boat is abeam or lateral of an identifiable object and a constant speed is maintained to the next identifiable object or range intersection. Intermediate soundings are interpolated between the two fixes. The plotted features are presumed to be error-free, and a constant vessel speed is assumed to have occurred between the control features. Ranges established by sighting across such features or additional shore points may be intersected for position determination. Accuracies of such surveys are considered marginal, at best. All drawings depicting these surveys should caution users concerning the approximate nature of the data and warn against their use in design or construction.

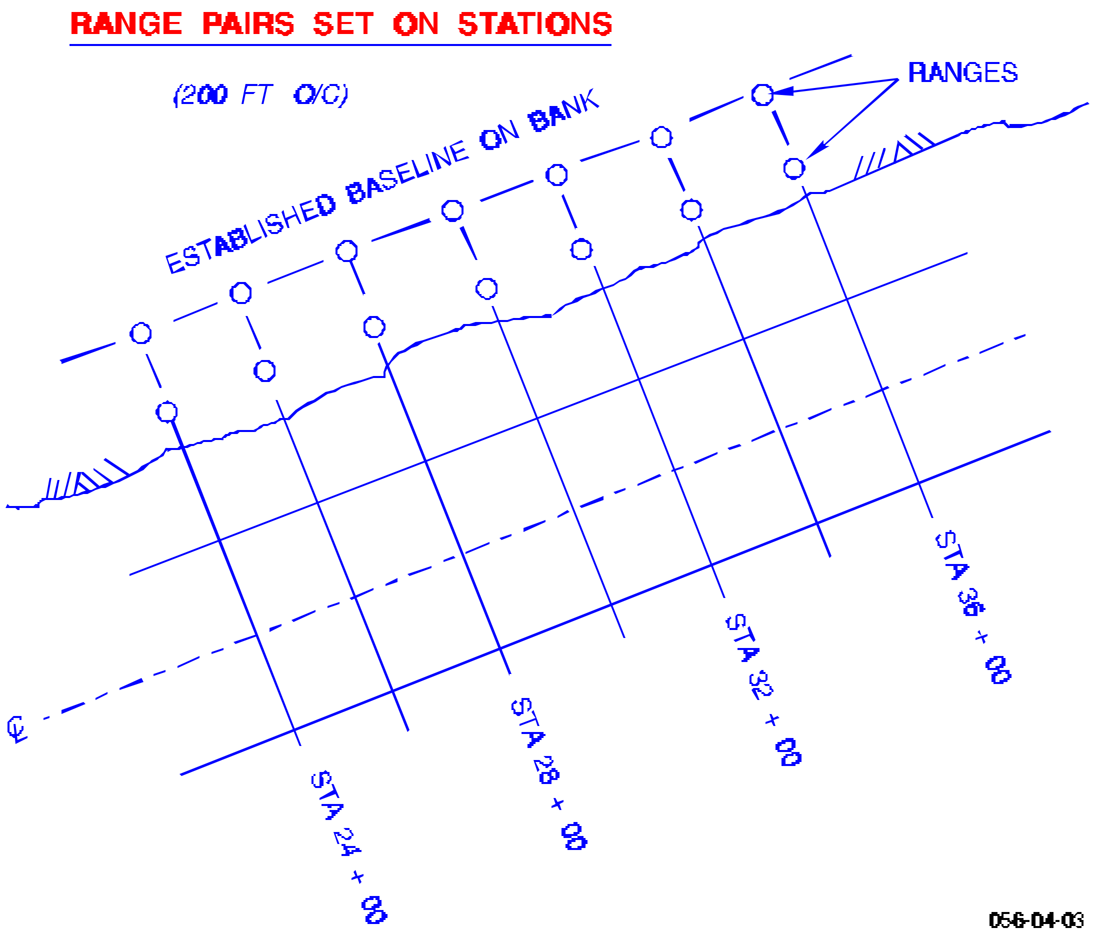

Figure 7-6. Typical visual dredging range configuration

7-12. Construction/Dredging Control Using Ranges

Offshore construction platforms, including dredges, can be effectively (and often accurately) controlled from visual ranges. Directional lasers are often used in place of range targets, and can provide both horizontal and vertical alignment to construction vehicles. In some hopper dredge work, alignment control is required only lateral to the project axis--see Figure 7-6. Sets of range pairs are typically set along a canal bank or bulkhead or at the projected end of the channel. Existing sailing ranges may also be used. Normally, range pairs are established at fairly dense intervals (e.g., 100 ft O/C). The limiting factor is the distance offshore relative to the range spread. A common rule-of-thumb is that the ratio should not exceed 10 to 1. For canal or other limited area construction projects, visual alignment accuracies can be quite accurate.

7-13. Uncontrolled Project Centerline Surveys

Approximate visual positioning was once commonly used in running centerline check surveys over uncontrolled recreational projects of relatively shallow project depth. The vessel is maintained relative to the approximate center of the project using local visual navigation aids, taken from a map or other source. The lateral error is a function of the ability of the boat operator to estimate the project's center. The accuracy of the resultant profile depends on the distance between identifiable features, chart scale, constant vessel velocity, and numerous other factors. Errors could approach 100 m. However, since these relative surveys are intended for reconnaissance purposes only, such inaccuracies may be tolerable. Any shoals encountered during these reconnaissance surveys that warrant a more detailed investigation would be developed using electronic or satellite positioning techniques. Survey data from visually controlled surveys are normally plotted in either plan or profile format, and not at a larger scale than that used to control the survey.

7-14. Accuracy and Quality Control

The accuracy of visual positioning techniques is difficult to access. Laser guided horizontal and vertical alignment can be highly accurate at reasonable distances from the target. Visual range pair alignment accuracy is a function of the distance from the targets and the range pair spread. Positioning relative to existing map features varies with the map scale, interpolations, and feature accuracy. For these reasons, visual techniques are no longer used for navigation and dredging drawings. QA checks are rarely performed on visual positioning.

Section IV
Tag Line Positioning Methods

7-15. General Applications

Tag line positioning employs a calibrated wire rope stretched perpendicular from hubs on a baseline to the survey boat (Figure 7-7). Up until the 1970s dozens of Corps survey crews used tag line survey methods to monitor dredging progress of navigation projects. In addition to traditional channel cross-section surveys, tag lines were employed to position floating platforms (barges) used in subsurface investigation for channel obstructions, core borings, jet probings, and channel clearance sweep surveys. In the 1970s, tag line methods were largely replaced by microwave EDM and range-azimuth techniques, which in turn were replaced by GPS positioning in the mid-1990s. A few USACE districts have maintained a tag line survey capability for critical site investigation work; typically in areas where GPS signals are blocked, such as around berthing areas. Usually, however, an electronic total station is preferred for such surveys. A tag line survey requires no electronics or communication devices. Within limited distances off the baseline, and with proper execution, a tag line controlled survey is an accurate and stable method of performing hydrographic surveys and other investigative work for marine design and construction.

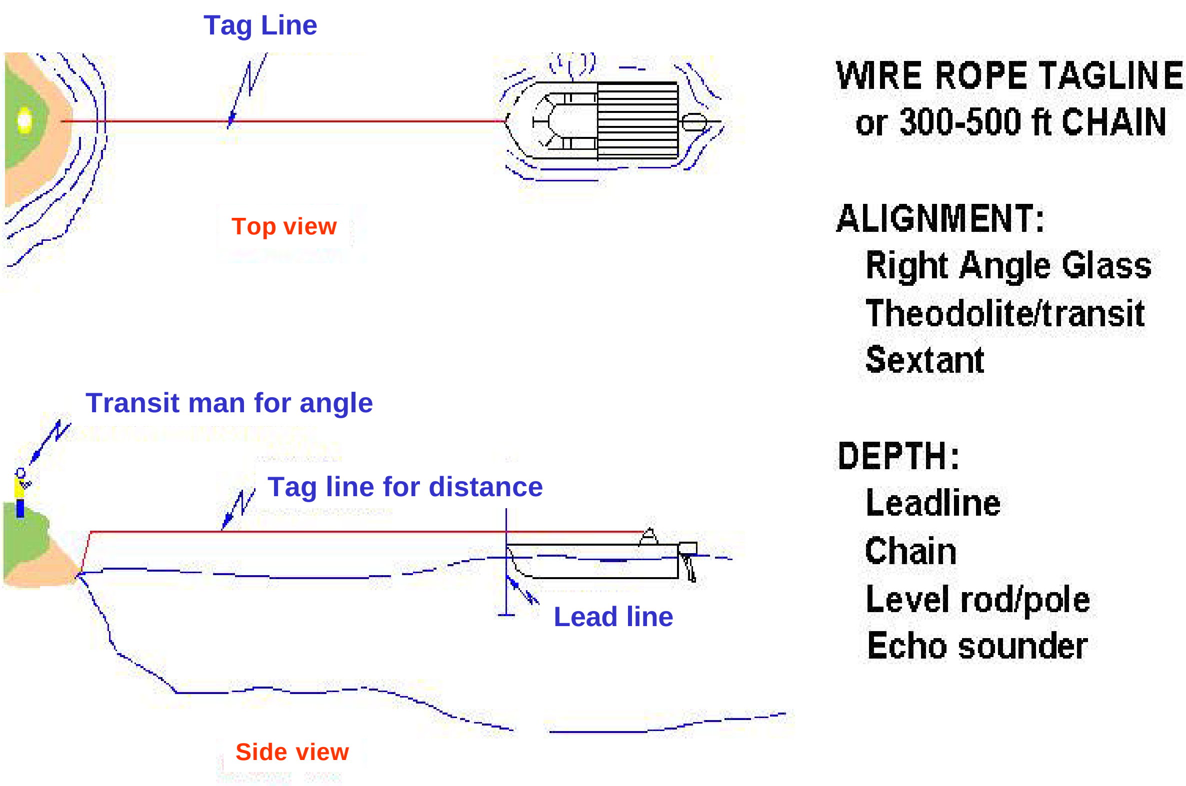

Figure 7-7. Tag line surveys

7-16. Tag Line Measurement Procedures

A tag line survey is simply a hydrographic method of running cross sections from a fixed baseline. Except for the boat and use of wire rope instead of chain, the same survey procedures are used as in highway cross-sectioning. The most accurate tag line distance measurements are conducted while the survey boat is stationary and holding constant tag line tension and alignment. Tag line surveys run dynamically (using echo sounders) are not as accurate as those conducted statically. Depths are observed with lead lines, sounding poles, level rods, or acoustically.

a. Static observations. Tag line length observations are made when the boat is properly aligned on the section and the wire is pulled taut to minimize sag. The zero end of the tag line must be firmly anchored on the baseline and held with a pole of sufficient leverage to withstand the pull from the boat. The tag line is payed out over the bow with the boat in reverse, and the winch clutch braked for each reading. The line is stopped when the interval mark is precisely at the depth measuring point on the boat (bow or transducer). The boat operator must maneuver the boat onto the proper cross-section alignment. This may be directed from ashore by hand signals or radio. Once on line, and with the tag line winch fully braked, the boat motor speed is regulated to hold the line taut out of the water and with only minimal apparent sag, at which time the depth is observed. Depending on the vessel power available and the weight of the line, the distance a tag line can be pulled fully taut will vary--pulls up to and exceeding 2,000 ft are possible. The accuracy of a tag line measurement will degrade drastically once the vessel is no longer able to provide sufficient power to suspend the line out of the water.

b. Dynamic or continuous tag line surveys. Some tag line surveys are conducted in a continuous (dynamic) mode using analog echo sounders. The boat is not stopped at tag line intervals, but the echo sounder is "fixed" at observed intervals as the reel pays out. Controlling alignment and tag line tension is not assured when this survey method is used.

c. Baseline boat tag line extension methods. Tag lines may be anchored to a floating vessel (baseline boat) that has previously been positioned by tag line or other means. Due to the compounding accumulation of error, such techniques are highly inaccurate. Since right angle prisms are typically used to hold the alignment of both the baseline boat and extended tag line boat, resultant positional errors of ±50 m or more are not uncommon.

d. Other tag line survey methods. A tag line may be used to maintain a constant range from the baseline hub. The line is held taut and the boat traverses along the constant tag line arc. Position fixes along the arc may be taken with a sextant or transit. Radial tag line surveys may be conducted from a single point on the baseline, with the survey vessel progressing outward along constant radials. Substituting an electronic ranging device for a tag line provides a better distance accuracy at extended ranges. In addition to normal cross-sectioning of harbors and canals, this survey method is commonly used in running-river cross sections and offshore sections for beach renourishment studies. The electronic positioning device and orientation instrument are moved to each incremental hub along the baseline. In some cases, a radial pattern may be run from one station. The survey vessel is guided along a constant azimuth in the same manner used in tag line work. Along-track (section) distance fixes are taken visually from an automated positioning system display. The accuracy of these distance readings is a function of the positioning system's stability, its update cycle, and the velocity of the boat. Higher accuracy surveys are obtained at slower velocities.

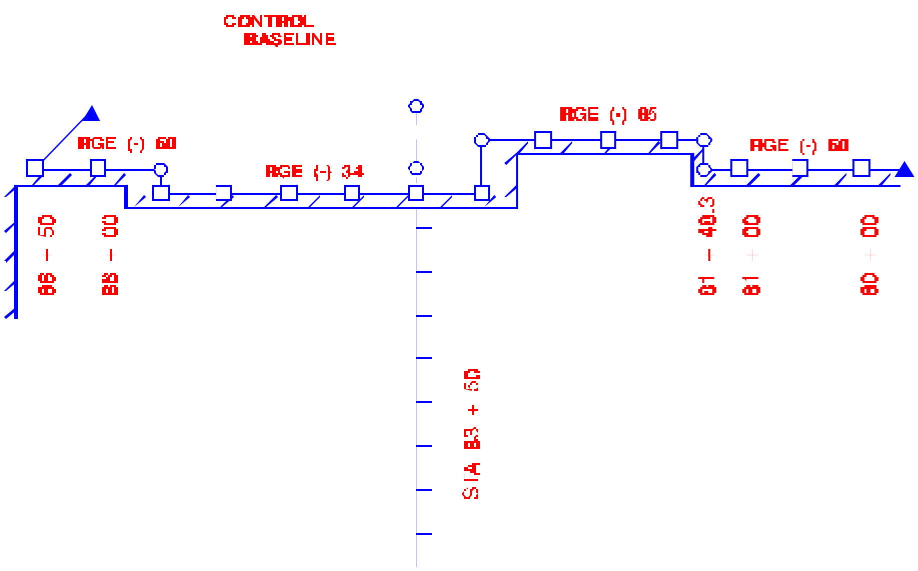

Figure 7-8. Typical baseline layout along bulkhead

e. Baseline layout for tag line surveys. Baselines for controlling tag line work are set using standard construction survey techniques and standards. Intermediate points (i.e., hubs) are surveyed at the line spacing required, usually 25, 50, or 100 ft O/C. These baselines should ideally be tied to USACE 3rd Order, Class II project control. However, 4th Order procedures may be used in setting intermediate control points along the baseline. Standard chaining or total station methods are used to lay out baselines. Baselines are normally aligned to the project's local coordinate system (station-range/offset) rather than a state plane system. See Figure 7-8.

(1) Intermediate points, or hubs, may be set for permanent or temporary use. Intermediate hubs can be marked by stakes, PK nails, flagging, or any other method. Back range hubs are established behind the baseline if needed. Project stationing and range offsets should be marked on the stakes and/or painted on bulkheads facing seaward for offshore identification. Baseline hubs must be located at points that are unobstructed to seaward and where the tag line end can be firmly secured.

(2) Baselines can be established in shallow water by staking with 2- by 2-in. wooden stakes, iron pipe, rebar, etc., for tagging locations. Baselines staked in shallow water can be used by small shallow-draft workboats (outboard motor or inboard/outboard motor propulsion). The chain/weight used on the end of the tag line forming a loop will hold the tag line at the base of the stake/pipe/rebar when tension is applied to the line by the motor and braking assembly on the power/manual reel or winch. In far offshore projects, piles have been driven adjacent to the channel in order to establish a baseline.

f. Tag line alignment methods. Lateral alignment control of the survey boat can be the weakest link in the performance of tag line surveys, especially if strong currents are present. The method used to project the desired cross-section alignment (usually 90 degrees) off the baseline is also critical. Poor alignment techniques will limit the distance that a tag line cross section can be reliably projected from the baseline.

Methods for holding alignment include visual range flags, right angle prisms, transits, theodolites, sextants, and total stations. The use of visual range poles or flags presumes an adequate range base is established. Right angle prisms shall generally not be used beyond 200 or 300 ft unless only rough reconnaissance surveys are being performed.

g. Data recording procedures. Tag line survey and related depth measurements may be recorded on worksheets or in a standard field survey book (Figure 7-9). Survey data are plotted in either site plan or section formats.

	STA.	16+00	CUT	S -	19
RGE.	SDG.	TIDE	RED.	TIME	
-75	7.2	+0.9	6.3	1:50	
-50	7.4		6.5		
-25	7.5		6.6		
0	7.6		6.7		
25	7.5		6.6		
50	11.7		10.8		
75	11.7		10.8		
100	11.7		10.8		
150	11.8		10.9		
175	11.9		11.0		
200	11.3		10.4		
225	8.0		7.1		
250	7.8		6.9		
275	7.8		6.9		
300	7.7		6.8		

	STA.	37+	65.94	CUT	S-19
RGE.	SDG.	TIDE	RED.	TIME	
-75	7.0	+0.9	6.1	10:24	
-50	7.2		6.3		
-25	7.1		6.2		
0	8.6		7.7		W. LIMIT
25	9.3		8.4		
50	10.4		9.5		
75	11.2		10.3		
100	11.7		10.8		
150	10.8		9.9		
162	6.3		5.4		Rock
175	10.9		10.0		
200	7.7		6.8		
225	7.5		6.6		
236	7.4		6.5		E. LIMIT
250	7.4		6.5		
275	7.3		6.4		

Figure 7-9. Field book recording of depths at 25-ft tag line marks

h. Survey boats. Any size and type of boat may be used for performing tag line surveys. The most common types used in USACE are open workboats of rugged hull construction. Open boats provide ease and flexibility of tag line measurement and allow maintenance to the tag line power winches. Typical boat lengths range from 16 to 25 ft. Drafts of less than 1 ft are essential in order to work in shallow areas and to provide ease of beaching. Reinforced hulls are necessary since many tag line surveys are conducted adjacent to revetments, stone jetties, and other structures. An experienced boat operator is essential to the accurate and safe execution of a tag line survey. The operator must simultaneously maintain lateral alignment in currents, control the tag line tension, and, in some cases, operate the power winch mechanism. Lead line, sounding pole, or echo sounding depth observations are taken and recorded at the boat operator's signal. In cases in which tag line surveys are performed in navigable waters with heavy shipping traffic, the boat operator may have to release tag line tension to allow the wire to lower and rest on the channel bottom while a vessel passes.

7-17. Tag Line Equipment

Tag line surveys can be conducted using any type of continuous measuring device. Over short distances, tag line surveys may be performed using 50-ft cloth tapes or 100- to 300-ft surveyor's chains. Revolution-counting payout gages/meters are also employed. For greater distances, however, a lightweight, stainless steel (corrosion-resistant), braided cable, or wire rope (7 strand ($\pm$), 7/32-in. diam or larger, depending on use of the tag line) is normally used. Wire rope tag line lengths vary from 500 to over 5,000 ft., and baseline boat tag lines from 5,000 to 15,000 ft long. A 2-ft loop of galvanized chain (5/8- to 3/4-in.) with a galvanized clevis and swivel should be used to connect the tag line wire to the chain.

a. Marking. The tag line cable is marked at any desired interval, usually every 25 ft. A variety of methods are used to mark and code the intervals along the tag line. Leather or plastic flagging or galvanized sleeves may be firmly crimped to the line using wire splicing/crimping tools--see Figure 7-11. Strands of polypropylene rope may also be inserted through the sleeves prior to crimping. Marks are coded by color and/or size. These marks and the coding system must be readily identified to prevent reading blunders, a common problem on tag line work.

b. Swivels. Corrosion-resistant swivels are inserted along the tag line at intermediate points, usually at the 100-ft mark, the 500-ft mark, and at subsequent 500-ft intervals thereafter. The swivels help in eliminating loops (pig tails) in the wire when continuous tension is not maintained. When the line becomes slack, wire rolls and loops appear, causing crimps and breaks in the wire. The swivels also serve as checks for incremental, even, 500-ft distances.

c. Power winches. Power winches are used to reel and control tag line pay-out. The winches are permanently mounted amidships and may be manually, electrically, or gasoline powered. Clutching and braking assemblies in the power winches regulate tag line payout. Line payout can be alternated over the bow or stern. A guide or fair lead is used for maintaining control during payout and reeling in of the line. Hand reels or manual winches are normally used on sounding boat tag lines because of the shorter or limited wire lengths deployed. Power reels/winches are commonly used on baseline boats due to the longer amounts of line involved. Power reels should have manual hand crank backup capability in case of power failure. Figure 7-10 depicts a typical installation of a power winch aboard an open workboat.

Figure 7-10. Tag line equipment aboard small 19-ft workboat (Jacksonville District)

7-18. Accuracy, Calibration, and Quality Control Requirements

a. Accuracy. Tag line surveys are highly accurate only within finite limits. Critical limitations include the length of extended line off the fixed baseline hub, the ability to measure and hold vessel alignment in strong currents, and the ability (power) of the boat to maintain a taut (sag-free) line over a given distance. The positional accuracy of a point positioned by tag line may be computed using the estimated accuracy of the alignment and distance measurements; similarly to that done with range-azimuth survey methods. Up to about 1,000 ft from the baseline, a tag line will maintain acceptable accuracy for dredging and navigation surveys; provided that it is pulled taut and accurate azimuth alignment is held.

b. Calibration. Flagged tag line intervals must be periodically calibrated every 3 to 6 months against a chained or EDM distance. The tag line should also be recalibrated after breaks have been respliced. Wire rope splicing must be performed so the original length is maintained as closely as possible. Calibration is done by comparing distances of the marked intervals with corresponding distances measured with a tape or instrument of higher accuracy (Figure 7-11). This is most easily performed along a pier or wharf where the tag line can be fully extended and compared with taped or EDM distances. At each marked interval on the tagline, a difference shall be observed and recorded in a field book.

c. Quality assurance. Independent checks on tag line surveys were rarely performed in practice. Occasionally, when baselines could be set on opposite canal banks, duplicate (overlapping) cross-sections could be run from opposing baselines as a check.

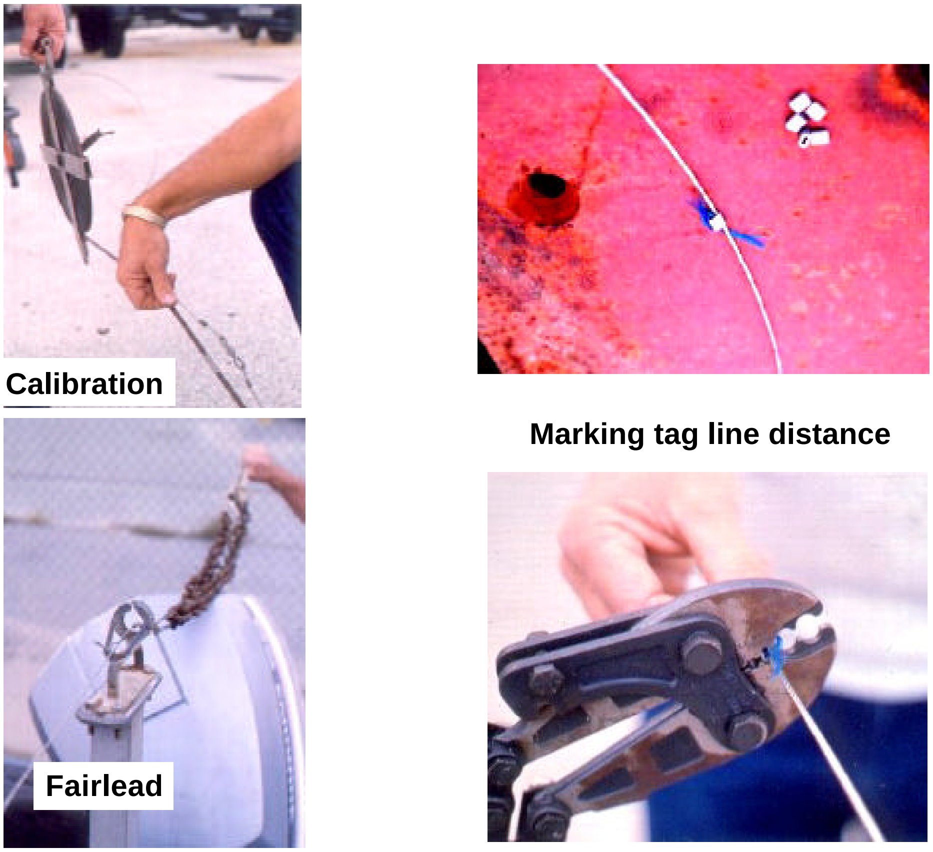

Figure 7-11. Tag line marking and calibration

Section V
Range-Azimuth Positioning Methods

7-19. General Applications

Range-azimuth positioning is most simply a forward traverse computation, based on the intersection of an angular and a distance observation, normally generated from the same shore-based reference station--Figure 7-12. Angular azimuth to the offshore vessel is observed by transits, theodolites, or manually or automated tracking total stations. The angular data can be manually observed and voice-relayed to the boat by radio or digitally recorded and transmitted to the boat. The distance measurement can be made by any number of EDM devices, such as microwave, laser EDM, and infrared light EDM. Although once a widely used positioning method, range-azimuth techniques are now employed only where GPS positioning cannot be obtained—usually due to satellite blockage. Today range-azimuth surveys are mostly performed using electronic digital theodolites--i.e., total stations. Range-azimuth positioning is typically used on projects located within four miles of a shoreline or river bank. Depending on the type of equipment used, range-azimuth surveys have high relative accuracies. Because range-azimuth positioning is nonredundant, periodic calibration is essential. This survey method is relatively efficient. Only a two- or three-man crew is required to perform the survey. Any type of boat may be used, but open or enclosed work boats 17 to 26 ft long are common. This section covers hydrographic range-azimuth positioning methods where angles and distances are obtained visually or electronically, using alidades, transits, theodolites, EDM and full electronic total stations.

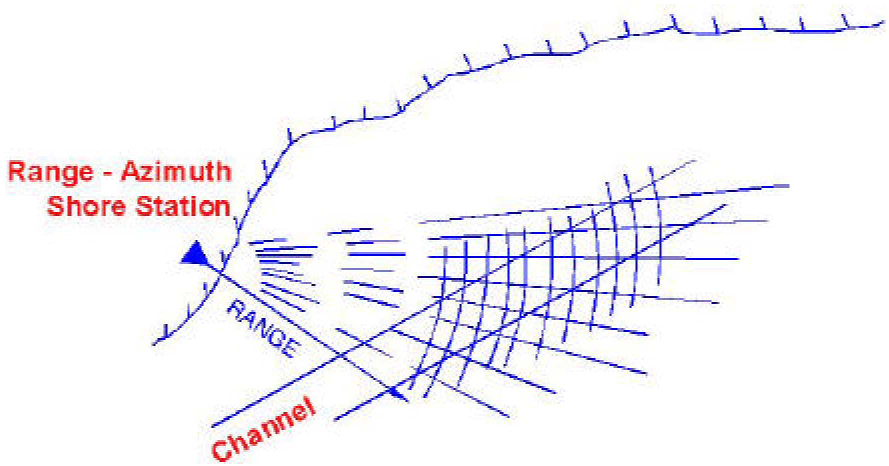

Figure 7-12. Range-Azimuth positioning

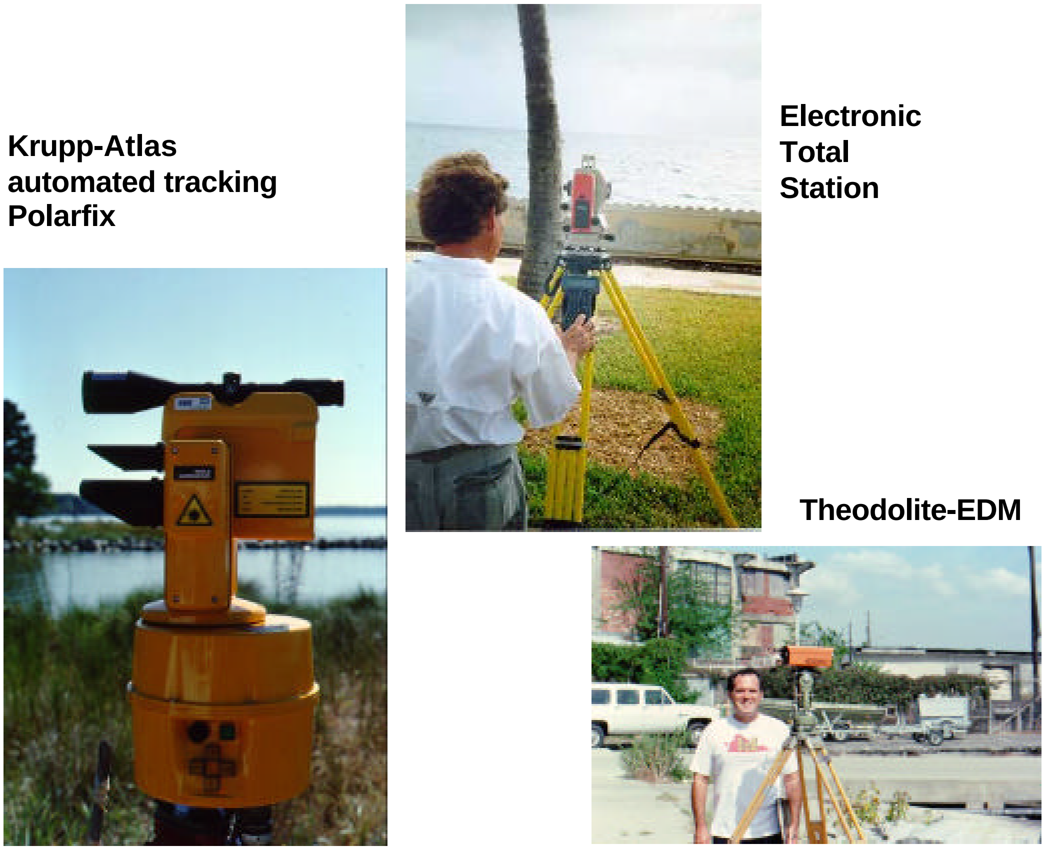

Figure 7-13. Various Range-Azimuth positioning instruments used in Corps (Norfolk District)

7-20. Range-Azimuth Survey Procedures

Total stations, theodolites, transits, or plane tables (i.e., alidades) are aligned on the local project datum in a manner similar to that described for triangulation intersection positioning (Section II). Thus, observed directions to the survey vessel are oriented in true grid azimuth reference for ease in plotting. Distances from the same point to the vessel are likewise observed, either visually (i.e., stadia) or electronically. Figure 7-13 depicts some of the systems used in the Corps.

a. Manual range-azimuth tracking procedures. It is usually easiest for the tracking instrument operator to call the shot or fix events to the survey boat. The analog echo sounder record is fixed at each shot and the azimuth recorded. Constant azimuth increments may be computed based on the distance offshore. The angular spacing should conform (roughly) to the desired position fixing interval, i.e., 50, 100, or 200 ft depending on the type/class of survey. These increments are usually rounded to a convenient even value (1 min of arc or 0.01 deg) for ease of setting in the instrument. The azimuth is set in the instrument, and the vessel is tracked only for the period it is within the scope. The fix is called to the survey boat when the boat's antenna crosses the vertical crosshair. Alternatively, the survey vessel may call the fix/shot; however, this procedure requires constant tracking by the instrument man.

b. Constant range tracking. Constant circular range arcs may be tracked with fixes taken at prescribed angular (azimuth) intercepts. The boat operator follows a constant range using the microwave system display. Ranges are incremented based on the line spacing coverage desired. Azimuth intercepts to the boat are either observed at regular angle intercepts or called for by the survey boat. The observer manually tracks the boat throughout the survey and calls the observed azimuths to the boat by radio. Digital theodolites or total stations may be configured to telemeter the angular data directly to the boat. Angular intercept increments are designed to provide positions at roughly constant distances (e.g., every 100 ft) along the circular track. Thus, the angular increment will decrease as the distance offshore increases. Because the resultant data plot is along circular sections, which may not be aligned to the project, the data may not be suitable for quantity takeoffs unless DTM quantity-estimating techniques are available. This is, however, an excellent and efficient method of obtaining coverage over a given project area.

c. Separated range-azimuth reference points. The angular and distance measuring instruments need not be situated at the same point. For instance, a microwave system remote unit may be located on a sailing range structure and the tracking theodolite located at a more stable place ashore. The angle of intersection is no longer 90 deg in this case. To avoid degradation in geometry of intersection, the intersection angle should be kept larger than 45 deg within the project area. Manual tracking and positioning are accomplished in the same manner as described above.

d. Stadia distance measurement. Most traditional survey instruments are capable of determining slope/horizontal distances by tachymetric methods, i.e., using fixed cross-hair stadia intercepts. In many transits and levels with constant stadia intercept ratios, distances can be directly observed and rapidly computed by the instrumentman. Alidades typically reduce slope distances to horizontal--not required for most hydrographic applications. Visually observed stadia distances are relatively accurate over short distances--typically ± 5 to ±10 ft out to 300 foot distances on a dynamic platform. Beyond 300 ft to 500 ft, accuracy rapidly degrades. Ranges beyond 500 feet can be observed using "half-stadia" interval readings, and doubling the intercept value. Either level rods or painted "stadia boards" may be used for observing stadia distances. Level rod divisions are usually too difficult to read , so normally 8 to 12 foot long stadia boards are used. Boards are painted in with large black & white divisions, usually at 0.1 foot intervals, although larger intervals could be used if longer stadia distances are needed. The accuracy of observed stadia readings also degrades as vessel motion increases and visibility of the stadia board intercepts becomes obscured at longer ranges.

e. Data recording and plotting. Distances and azimuths are simultaneously observed by the instrumentman and recorded in a standard survey field book or electronic log by fix or time event. Radio contact with the vessel is maintained with the vessel normally calling for fix observations at prescribed intervals. The depth sounder is event-marked at the same time. Position data may be plotted either ashore or on the survey boat; or post plotted if real time navigation or coverage information is not required. Plane table observations are directly plotted ashore as observed. Transit-stadia observations may be plotted at either location, using drafting machines or preplotted range-azimuth sheets. If navigation guidance is needed aboard the survey vessel, then position data must be relayed to the vessel for on board plotting. The position update interval is limited by the instrument observer's and plotter's expertise in observing, transferring, and plotting. Typically, 45 to 60 second fix intervals are the best that can be performed in real time; thus, these methods are best for shot point depth observations under more static conditions. Total stations will typically compute and log vessel positions at a rapid update rate; however, in order to obtain real-time navigation aboard the vessel, the position data must be relayed to the vessel. Manual plotting of range-azimuth surveys can be performed using a drafting machine and beam compass to lay out the azimuth and circular range arrays provided that the project area and reference station fall on the plotting sheet. If the project area is beyond the reach of these mechanical devices, the azimuth/circular array must be computed and drawn with spline curves. Angular position fixes are plotted along the constant range arc, and depth data are plotted relative to these points. Intermediate depth data points between fixes are interpolated between the fix events on the analog record. Range-azimuth position and depth data may also be encoded/digitized and plotted using automated techniques.

7-21. Total Station Range-Azimuth Surveys

Electronic total stations can be configured to provide highly accurate hydrographic positioning. The latest generation total stations can provide direct, real-time X-Y-Z coordinates on the vessel. If reflector-transducer offsets are applied, the X-Y-Z coordinate of the bottom can be computed/reduced in real-time. Robotic total stations can automatically track the vessel. A fully automated systems like the Krupp-Atlas Polarfix, contains a communications link that transmits the measured azimuth and distance to the boat. This communications data link is often the weak point in the system; care should be taken to ensure that there is no interference from other sources. These data are transformed to a local project coordinate system (station-offset, beach/river profiles, etc.) which is used for vessel operator steering guidance on a digital or analog left-right indicator. Topographic or construction total stations must be modified for hydrographic tracking applications if the beam width is not large enough to track the vessel. Philadelphia District has modified conventional topographic total stations for hydrographic survey purposes. Topographic total stations must also be configured to relay navigation data (via radio communication link) to the survey vessel processor for navigation and data logging purposes. Without on board navigation links, total stations are usually set up over established ranges--a common procedure for beach sections.

7-22. Range-Azimuth Accuracy

The accuracy of a range-azimuth position can be estimated from the following equation:

$$RMS_{95\%} = 1.73 \cdot sqrt [a^2 + (d \cdot \tan b)^2] \qquad \text{(Eq 7-3)}$$

where

a = estimated standard error (1-sigma) of the distance measuring system (e.g., tag line, EDM, stadia)

d = distance offshore

b = estimated standard error (in arc-sec) of azimuth measuring system (e.g., total station, right angle glass, transit, sextant)

Within a few hundred feet from the instrument, theodolite/EDM/total station range-azimuth systems are highly accurate for dredging and navigation surveys. Microwave based EDM will rarely meet current 2 m or 5 m positional accuracy standards. Dynamic alidade or transit stadia distances are accurate to 5 meters within ranges of only 100-200 ft, depending on conditions.

7-23. Quality Control Requirements

a. Angular orientation. The tracking instrument should be referenced to the grid azimuth for the project. This is accomplished by setting the lower plate to the grid azimuth of the reference backsight. The farthest or most reliable point should be selected as the reference orientation. Additional reference points should be pointed on to verify orientation. All available visible control should be sighted on, and any error or discrepancy resolved onsite. All orientation checks (including grid azimuth computations) must be recorded on a worksheet or field book.

b. Periodic orientation checks. During the course of the survey, the initially set orientation should be periodically checked to ensure that no movement in the instrument has occurred. Periodic orientation checks should be noted in instrument operator's field book. These checks are normally done at the end of each survey line. The instrument should be readjusted and releveled as required during these checks. If significant movement has occurred, all work done since the last orientation check was made should be rejected and rerun.

c. Quality assurance checks. Like most visual survey positioning methods, independent positional checks on range-azimuth positions are rarely available. When the vessel can be maneuvered to another project control monument, a check on the position can be made. This should always be done for critical navigation surveys.

Section VI
Land-Based Electronic Positioning Systems

7-24. General Scope

Use of electronic distance measurement (EDM) techniques to position hydrographic survey vessels derived from hyperbolic aircraft navigation systems first developed during World War II. The Corps first began using hyperbolic and range-range electronic positioning during the mid 1950's--in Detroit and Norfolk Districts. A variety of systems have been used since that time; most of which became quickly obsolete when GPS became fully operational. However, the basic operating concepts behind land-based EDM and related trilateration positioning (including GPS) have not significantly changed. This section describes these electronic distance measurement and positioning principles of these older land-based electronic positioning systems; including procedural criteria for using such systems. Land-based (or terrestrial) positioning systems are distinguished from satellite (extra-terrestrial) positioning systems. All these systems use time difference and trilateration techniques to determine a position. The main focus of this section is on land-based microwave positioning systems as opposed to now nearly obsolete low- or medium-frequency hyperbolic systems such as LORAN-C.

7-25. Types of Electronic Positioning Systems

One method of classifying electronic positioning systems is by their operating frequencies. The frequency generally determines operating range and accuracy and, in turn, a system's applicability for a particular type of work. Figure 7-14 lists some types of electronic positioning systems by their bandwidths. In general, the higher the frequency of the electronic positioning system, the more accurate the resultant position determination. Systems in the medium frequency range and below are typically hyperbolic phase/pulse differencing, and can reach far beyond the visible or microwave horizons. These systems were more suited for long-range navigation purposes or far offshore geophysical exploration work. Only those systems operating above the medium frequency bandwidth range had any practical application to USACE construction work. Microwave systems in the Super High Frequency (SHF) range were most commonly used to precisely control offshore survey vessels and dredges. Operating distances for these systems are generally limited to line of sight, which is adequate to cover most river, harbor, and coastal construction applications. Modulated lightwave and infrared spectrum electronic distance measurement instruments (e.g., electronic total stations) can be used over relatively limited distances, usually less than 3 to 5 miles offshore. These systems provide the highest distance accuracy measurements.

Bandwidth	Symbol	Frequency	System
Very Low Frequency	VLF	10-30 KHz	Omega
Low Frequency	LF	30-300 KHz	LORAN-C
Medium Frequency	MF	300-3000 KHz	Raydist, Decca
High Frequency	HF	3-30 MHz	Fundamental Earth Frequency 10.23 MHz
Very High Frequency	VHF	30-300 MHz	VOR Aircraft Navigation
Ultra High Frequency	UHF	300-3000 MHz	Del Norte
L-Band			NAVSTAR GPS
Super High Frequency	SHF	3-30 GHz	(Microwave EPS)
C-Band			Motorola
S-Band			Cubic
X-Band			Del Norte
Visible Light			EDM*
Laser Light			EDM
Infrared Light			EDM, Polarfix

* Electronic distance measuring instrument.

Figure 7-14. Frequencies of various positioning systems used for hydrographic surveying (1950 to date)

a. Medium-frequency positioning systems (RAYDIST/DECCA). Raydist and Decca positioning systems were first deployed by Corps districts in the mid 1950's and were used up to the early 1970's. They are no longer used. Systems in this frequency range operated by time/phase differencing methods--resulting in either circular or hyperbolic lattices (time differences). These systems required repeated calibration to resolve whole-wavelength (lane) ambiguities and continual monitoring during the course of the survey to resolve lane, or cycle, slips--no different than integer ambiguity determination requirements for modern day DGPS. Onsite calibration was essential to maintain accuracy. However, given the far offshore uses of these systems, calibration was often impossible. Many of the visual positioning techniques described in previous sections were used to calibrate these systems.

b. Low-frequency positioning systems (LORAN-C). LORAN-C is a low-frequency time-differencing hyperbolic system and has been the primary marine and airborne navigation system for over 40 years. It is suitable only for general navigation or reconnaissance surveys; and perhaps for general dredge/dump scow monitoring. Daily near-site or onsite calibration is critical if any semblance of absolute accuracy is to be maintained. (This is not the same as relative accuracy.) Without onsite calibration, absolute positional accuracy of LORAN-C is ± 0.25 mile at best. Recently developed differential Loran-C has a much higher accuracy. LORAN-C is expected to be decommissioned by the US Coast Guard in the early 2000's.

7-26. EDM Measurement Process

Most EDM systems operate either by resolving two-way travel phase delays of a modulated electromagnetic carrier pulse/wave between the offshore vessel and shore-based reference transmitter or by measuring the two-way travel time of a coded electromagnetic pulse between these points. GPS operates in a similar manner to the conventional systems except the travel distances from the satellites are one-way. Code-phase

GPS is similar to microwave coded pulse systems, and carrier phase GPS operates on the carrier wave (phase differencing) used to transmit coded information. Phase differencing techniques are also used on land surveying EDM instruments, with the carrier being a visible laser or infrared light. Microwave pulsing type systems (Motorola, Del Norte, Micro-Fix, etc.) measure the round-trip travel time of a pulse generated at the offshore vessel, to the shore repeater station, and back to the vessel. The remote shore stations are variously referred to as transponders (XPDR), trisponders (TPDR), or responders (RPDR), depending on the manufacturer. They receive, process, and retransmit the signal. Some microwave systems use passive radar reflectors. For a pulsing system, the round-trip distance is computed by multiplying the measured elapsed time (less internal system time delays) by the assumed velocity of propagation of electromagnetic energy. The distance, or range, is computed by the following equation:

$$d \text{ (meters)} = c \cdot (t_m - t_d) / 2 \tag{Eq 7-4}$$

where

c = assumed velocity of propagation (m/sec)
t_m = measured round-trip travel time (sec)
t_d = internal system delays (sec)

a. Distance determination. Under ideal conditions, and with repeated measurements, the travel time (t_m) can be measured fairly accurately (to better than the 1-nsec (1-ft) level) and far more accurately (sub-centimeter) when modulated phase comparison techniques are employed, such as on infrared and some microwave systems. However, all three factors on the right side of Equation7-4 are subject to both random and systematic errors. The only way to minimize these errors is by external and internal calibration of the equipment. Internal system delays (t_d) can be controlled relatively effectively on some modern pulsing systems. Such control is often termed "self-calibrating." The assumed velocity of propagation (c = speed of light) and other local anomalies or inherent system measurement instabilities cannot be controlled or corrected by the measurement system. Thus, an independent, on-site calibration must be performed if errors due to these sources become significant, which is normally the case (i.e., ambient project conditions different from nominal conditions). As a result, a calibrated microwave positioning system operating in a dynamic hydrographic survey environment can measure a range to an accuracy ranging between ± 3 m and ± 10 m (95% RMS).

b. Velocity of propagation variations. Variations in the velocity of propagation in air are caused by changes in air density due to temperature, humidity, and air pressure. The effect on land-based microwave positioning systems is more pronounced than on light waves. A factory-calibrated microwave system may be operated in atmospheric conditions differing significantly from the nominal calibration conditions. A change of 50 to 75 ppm could result, or 0.5 to 0.75 m in 10,000 m. Although such a variance may not be significant in operations 6 miles offshore, it is a systematic error, which could be compensated for by proper calibration. Assumed stability in the pulsing system time (t_m - t_d) or phase measurement process cannot be guaranteed. Periodic independent calibration is essential to check this stability. No independent calibration of positioning systems is totally effective unless it closely duplicates the actual operating ranges and conditions.

c. Microwave antenna considerations. Microwave propagation/refraction problems may exist in some areas during hydrographic surveys. Moving antennas a small distance (vertically or horizontally) sometimes eliminates the problem. Weather, especially humidity and temperature, affects microwave propagation through the air. Large ships, metal buildings, and even the water surface can create unwanted reflections of the microwave signals received at the antenna. Experience with microwave equipment problems and knowledge of the survey area will minimize the recurrence of these types of problems. Different antennas may be used to either boast a signal into a sector (sector antenna) or allow transmission over a full circle (omnidirectional) from the station. Circular polarization is another technique used to reduce multipath effects. Another technique used is antenna separation, which switches from one antenna to another to reduce multipath phenomena. GPS manufacturers use concentric metallic raised rings surrounding the antenna to reduce multipath effects.

d. Multipath effects. Signal multipath reflection is a major systematic error component for equipment operating in the microwave band. Errors due to this effect are difficult to detect. Most critically, they can gradually accumulate with vessel location and orientation relative to a particular remote reference station. An abrupt change due to multipath is usually readily apparent, as is total signal cancellation, termed "range holes." This gradual range increase of 1 m or more can cause what appears to be a course anomaly on a plot of the vessel's position, as if some erratic current displaced the vessel for a period of time. In addition, multipath may be present when the system is calibrated at a particular point. Consideration of multipath during antenna placement, enhanced antenna design (circular polarization, space diversity, etc.), and other internal electronic techniques and filters are required to identify and/or minimize multipath effects. None are totally effective in all cases. Antenna spacing or systems with circular polarization are recommended to minimize the possibility of these effects.

7-27. Microwave Range-Range Positioning Systems

These systems were first used by Corps districts in the early 1970's. The first systems were manufactured by Cubic Corporation, Motorola, and Del Norte Technology. They effectively replaced tag line and medium frequency (Radist and Decca) positioning methods that had been used by districts since the 1950s. Up until the mid 1990's, microwave positioning systems were the primary positioning system in nearly every district. After 1992 when full coverage differential GPS became available, use of microwave systems rapidly declined. In 1998 only one or two districts were still utilizing microwave positioning--all the others have gone exclusively to GPS positioning. It is unlikely such systems will be in use much after 2000. Range-range positioning by microwave systems is accomplished by determining the coordinates of the intersection of two (or more) measured ranges from known shore control points--a process termed trilateration. When two circular ranges are measured, two intersection points result, one on each side of the fixed baseline connecting the reference stations. The ambiguity is usually obvious and is controlled by either initializing the computing system with a coordinate on the desired side of the baseline or referencing the point relative to the baseline azimuth. Prior to automated data acquisition systems, microwave ranges were visually observed and steered, with data logging and plotting performed manually. As automated data acquisition systems began to be used in the early 1970s, ranges and computed positions were electronically recorded and the resultant position sent to a track plotter and helmsman guidance display unit. These microwave range-range positioning methods used by the Corps during the period from about 1970 until 1999 are described below.

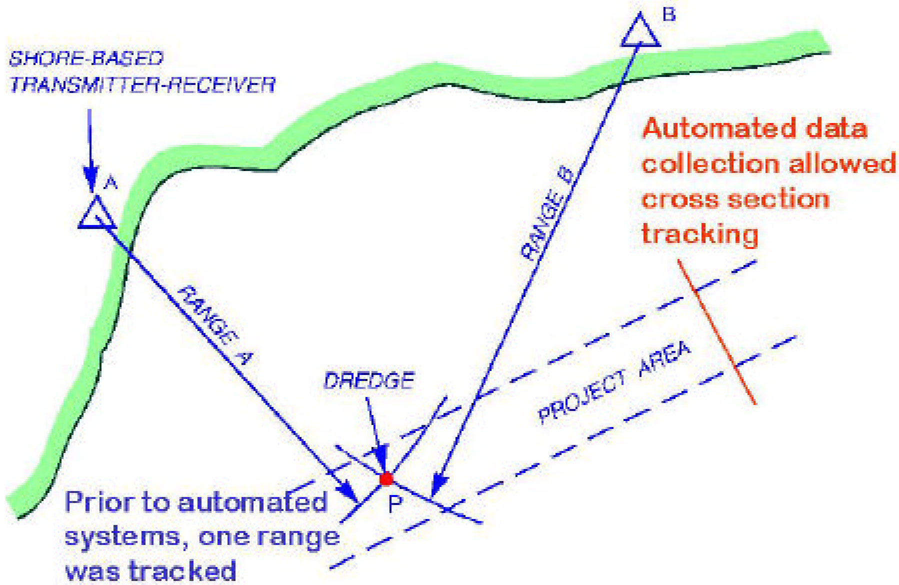

Figure 7-15. Range Range intersection

a. Constant range tracking. Before automated data logging and processing systems were available, the survey boat was positioned by steering a constant range from one reference station and fixing at range intercepts from the other reference station (Figure 7-15). At higher vessel velocities, this is not an accurate positioning method, due to the need to estimate the intercept between range updates. In addition, the resultant survey lines are circular and are not aligned to the project coordinate system. This survey method provided a good backup capability when failures occurred in automated positioning and guidance systems. It was rarely employed, however.

b. Automated range-range tracking. When automated positioning and guidance systems were employed, the range intersection coordinates were automatically computed and transformed relative to the project alignment coordinate system (station-offset). This data was then fed to an analog or digital course indicator (or left-right track indicator), allowing any particular station/cross section or offset range to be tracked. Along-track position fixes were then taken by manually observing an along-track indicator or track plotter. The analog depth recording device is marked at each position. Normally, however, digitized depth data are correlated with positional data in an automated system at regular preset intervals by time or distance. Figure 7-16 shows typical electronic ranging and positioning equipment used by the Corps during the past 30 years.

c. Range-Range accuracy. The positional accuracy of a range-range intersection position is a function of the range accuracy and the angle of intersection of the ranges. The angle of intersection varies relative to the baseline so the positional accuracy varies as the survey vessel changes location. Assuming both ranges have equal value, the positional accuracy at any offshore point can be estimated from:

$$RMS_{95\%} = 2.447 \cdot s \cdot cosecant\ (A) \qquad \text{(Eq 7-5)}$$

where

s = estimated standard error of measured range distance (1-sigma)
A = angle of intersection of ranges at vessel (or angle from vessel to baseline stations)

Since the angle of intersection (*A*) has a major effect on positional accuracy, quality control criteria will restrict surveys within intersection tolerances--e.g., *A* must be between 45 deg and 135 deg. The accuracy of microwave ranges is difficult to estimate since it is not constant with distance from a shore station. Manufacturers typically claimed accuracies of ± 1 m (1-sigma), or ± 2 m (95% RMS). These estimates were for ideal (calibrated) conditions. More likely microwave range accuracies were on the order of ± 3 m. This would yield an average positional accuracy of about 8 m (95% RMS) at 60 deg range angle of intersection. Although an 8 to 10 m RMS error may seem excessive by today's DGPS standards, this represented a major improvement in the 20 to 50 m accuracies achieved by earlier positioning methods--especially on a project site 10 miles offshore.

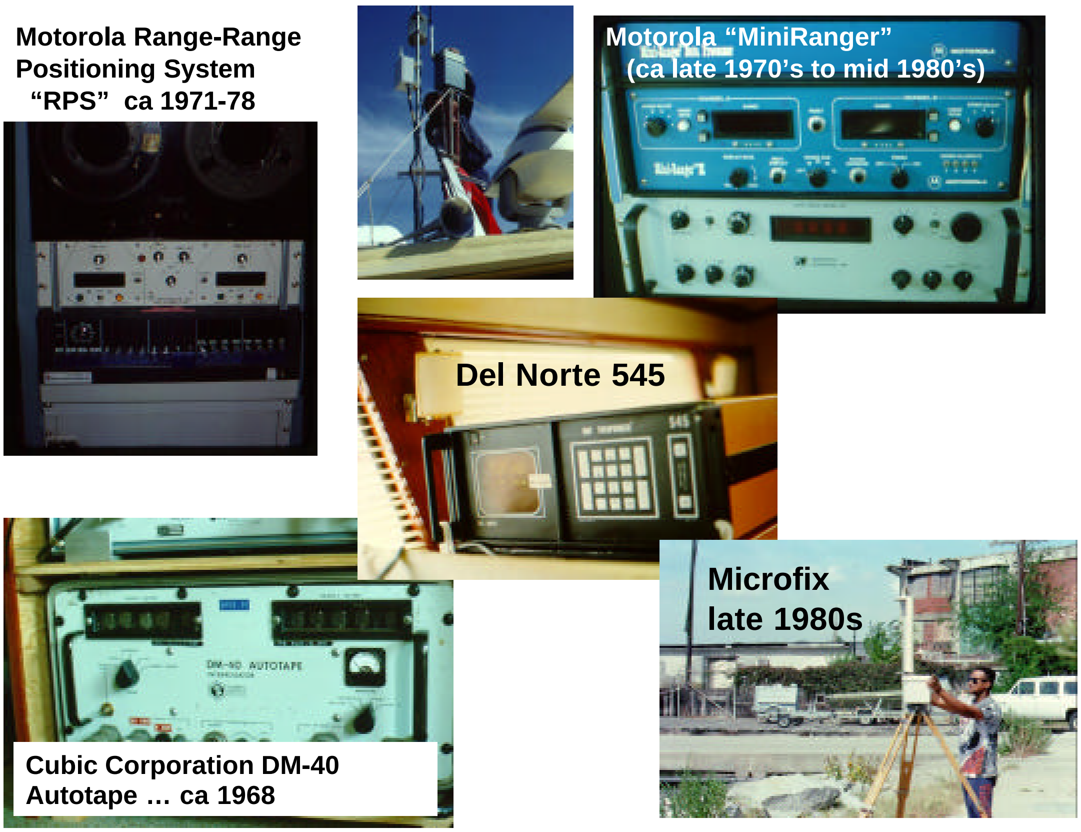

Figure 7-16. Range-Range positioning systems used in Corps (1970-1995)

d. Multiple range positioning techniques. This method is simply an expansion of the range-range method described above. Jacksonville District first developed this technique in 1979. In this case, three or more ranges are simultaneously observed, and a positional redundancy results. (The Racal Micro-Fix system allowed selection of up to 8 ranges from a total of 32 interrogated.) The position is determined from the computed coordinates of the intersections of the three or more range circles. Since each range contains observational errors, all the circles will not intersect at the same point. In the case of three observed ranges, three different coordinates result. Four ranges result in six separate coordinates. The final position is derived by an adjustment of these redundant coordinates, usually by a least-squares minimization technique. Some automated microwave positioning systems simply used the strongest angle of intersection as the "adjusted" position, and others take the unweighted average of all the intersecting coordinates. All adjustment methods were typically performed on-line at each range update cycle, normally every second. The positional data are then transformed to a project-specific coordinate system in a manner similar to that described for a two-range system.

(1) Using multiple ranging can minimize positional uncertainties. The coordinated position contains redundancy and can be adjusted. Such a process reduces the geometrical constraints and provides an opportunity to evaluate the resultant positional accuracy as the survey progresses. An on-line accuracy assessment is thus provided. This is accomplished by evaluating the positional misclosure which occurs when three or more position lines containing errors intersect, a so-called triangle of error for the simple case of three intersecting ranges, as shown in Figure 7-17. The position of the vessel is obtained by adjusting the three ranges to a best fit.

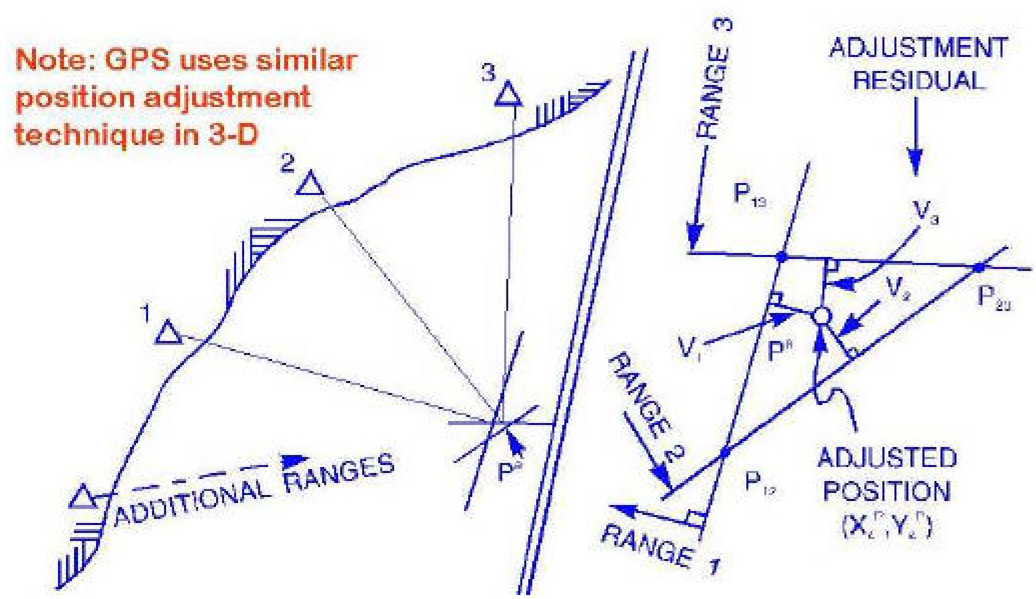

Figure 7-17. Multiple range positioning

(2) An assessment of the range measurement accuracy may be obtained by computing the residual range errors (v) for each position. These are the corrections added to each range so that all ranges intersect at the same point. When a least-squares type of adjustment is performed, the sum of the squares of the residual errors (v) is made a minimum. The magnitudes of these residual range corrections provide the statistics for an accuracy estimate of the observed distances or, more practically, an approximate quality control indicator. When a least-squares adjustment is performed, it is possible to obtain an accuracy estimate of the positional RMS error. Automated software can provide such data at each position update. If known, different weights may be assigned to individual range observations. This proved useful when different types of positioning systems were mixed during a survey (i.e., microwave and medium wave ranges).

(3) An on-line quality control indicator (e.g., 95% RMS error) can be computed. This can be directly obtained from the least squares adjustment matrix and computed from:

$$RMS\ Error_{95\%} = 1.73 \cdot sqrt\ (s_x^2 + s_y^2)$$

(Eq 7-6)

where

s_x and s_y = estimated positional standard errors in x and y coordinates (from variance-covariance matrix)

Automated systems were designed to alarm when positional RMS accuracies fell outside the prescribed limits, indicating calibration problems. The initial standard error of the microwave ranges was usually assumed constant throughout the survey.

(4) Alternatively, the residual range errors (*v*), which result from comparing the observed distances with the inversed distances between the adjusted position and the remote shore transmitters, could be used to evaluate the accuracy of the range measurements. A variety of methods were used (on-line and/or off-line) to compute these residual errors. An approximate (unbiased) estimate of the range accuracy is obtained from the following:

$$Estimated\ Range\ Accuracy\ (1\text{-}s\ ) = sqrt\ [\ S\ (\ v^2\ ) / (n\text{-}1)\ ]$$

(Eq 7-7)

where

n = number of observed ranges
$S\ (v^2)$ = sum of the squared residuals

Adding redundant ranges will not necessarily make a significant improvement in the positional accuracy because the inherent random and systematic errors are still present. It will, however, help detect the existence of large systematic errors (and most critically, observational blunders) that might have otherwise gone undetected using a nonredundant range-range system.

(5) Figure 7-18 demonstrates the use of multiple ranging in an offshore location where no independent method of calibration at the job site was available. Figure 7-19 shows another project with six intersecting points, resulting from the four observed ranges. Error ellipses for each of the two-range intersections are shown. The on-line least-squares adjusted position is shown along with its (smaller) error ellipse.

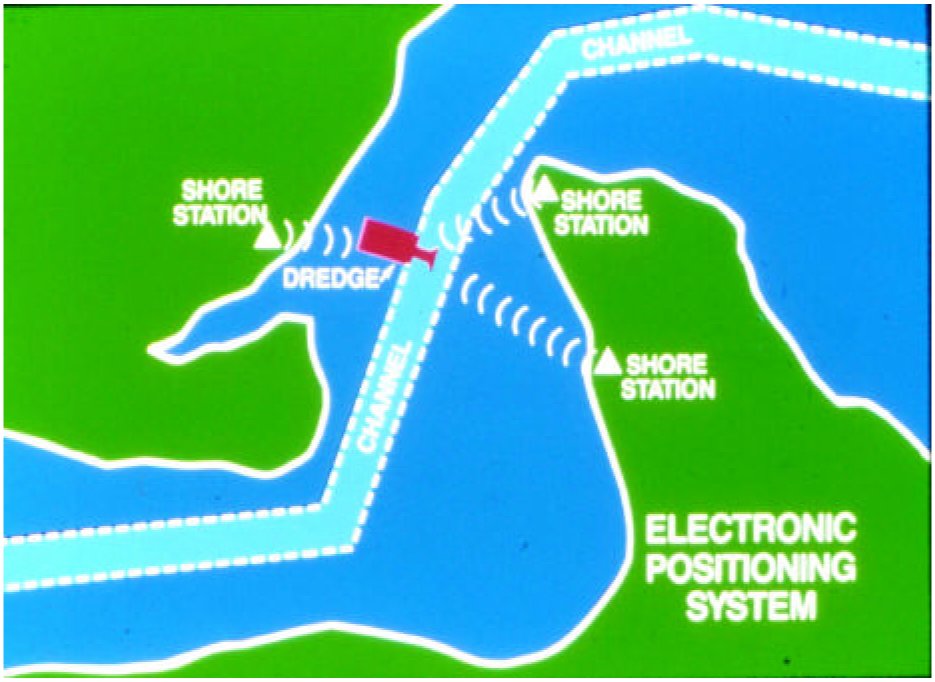

Figure 7-18. Three range microwave positioning scheme

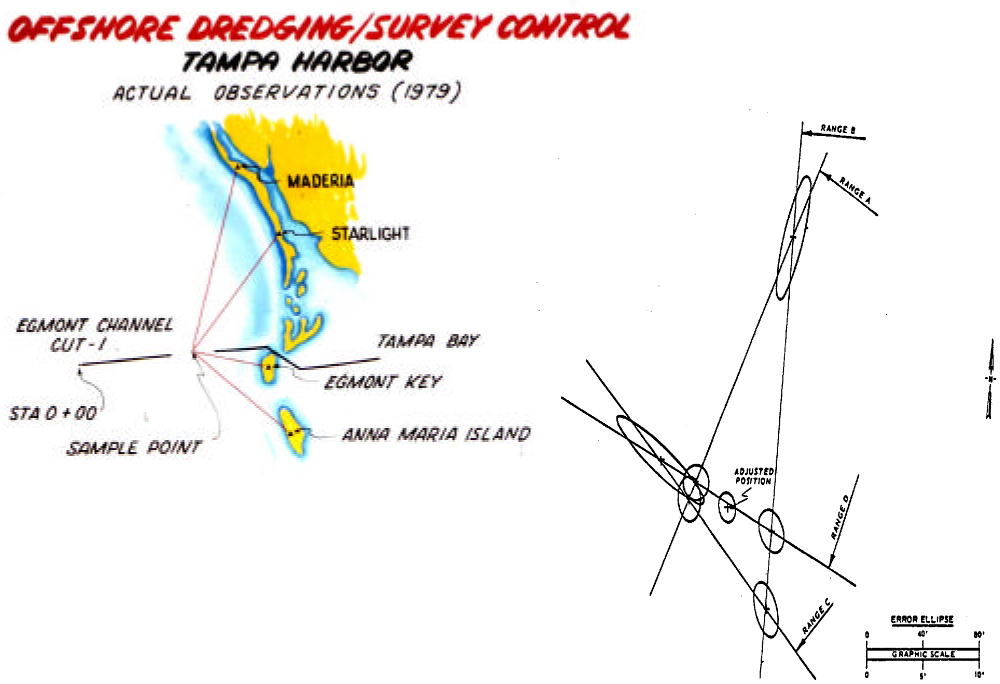

Figure 7-19. Four range intersection position solution (Tampa Harbor, Jacksonville District)

7-28. Microwave System Calibrations and Quality Control

A microwave system calibration processes basically involve an independent determination of the vessel's antenna location, followed by comparison of differences between the observed microwave ranges and the distances computed from the independent calibration. An independent calibration should be at least one order of magnitude more accurate than the microwave system being calibrated. Such systems would include: theodolite triangulation, total station observations, or EDM trilateration methods. If automated coordinates are observed rather than direct ranges, inverse coordinate computations will have to be made to determine the observed ranges. If a series of independent calibrations is made, the mean range difference over this series represents a correction to be applied to the system. This range correction is dialed in the microwave system range console or is stored for software application during the position computation. Given the instability of many microwave ranging systems, coupled with inaccuracies in the calibration process itself, determining whether a range correction is statistically valid is difficult. This problem frequently occurs when baseline comparisons are made at two (or more) different calibration points offshore.

a. Repeated calibrations. An advantage of EDM, total station, sextant, or triangulation intersection calibrations is that a series of 5, 10, or more independent calibrations may be obtained at various locations in the work area. If the calibration technique is performed accurately, the mean range difference correction may be statistically valid. Its validity is best estimated by computing the standard deviation from the mean of the series of range differences. Applying a calibrated range difference may often be debatable from a statistical standpoint. For example, assume that a microwave range is calibrated by five independent distance measurements. The accuracy of the calibration process is estimated at ±0.5 m and the range is presumed stable to ±0.5 m. The series of calibrations yields a (-) 0.3-m correction ±1.0 m. The ±1.0-m deviation contains the error budget of the microwave range, the calibration process, and other unknown factors (control, eccentricities, etc.). A (-) 0.3-m correction in this case would seem marginal. However, for consistency, it should be applied since no simple rule-of-thumb exists for deciding when such a correction is statistically valid.

b. EDM calibration. Direct ranges to the shore-based receiver stations may be observed using precise phase differencing laser/infrared electronic distance measurement instruments. Typically, the EDM is moved to the two or more receiver monuments, and the reflector prism is placed above or below the vessel's antenna. Depending on the type of EDM used, vessel stability is critical for maintaining lock on the reflector. A series of EDM distance readings is directly compared with the simultaneously observed microwave ranges, and corrections are assessed as described above. EDM observations are taken and corrected for slope and atmospheric refraction in accordance with standard survey methods. If control monuments other than the microwave remote receiver's are occupied, a trilaterated position of the vessel must be determined and inversed along the microwave ranges for comparison. This method is especially suitable for periodic calibration of dredges.

c. Baseline calibrations. Baseline calibrations are performed by locating the survey vessel alongside a known reference point and comparing the computed (inversed) distances with the ranges observed by the microwave system. This is the simplest and most common microwave calibration method. Any eccentricities between the vessel's antenna and the known monument must be corrected. This is usually done by observing an angle and taped distance from the reference point to the antenna and computing the grid coordinates of the actual antenna. A sextant bearing is adequate over short distances. In some instances, the vessel antenna may be removed from its mounting and placed directly over the known monument. Such a procedure may change antenna receiving characteristics and induce multipath error. Some automated systems allow input of the antenna coordinate and directly compute the distance comparisons or, alternatively, directly correct the observed ranges to agree with the fixed coordinate. (This latter method assumes only one calibration check will be employed--or the differences from different points are insignificant.) Such a process is useful on multiple ranging systems. Regardless of the method employed, a few minutes of observations should be recorded. Lengthy calibration observations at the same point serve no purpose other than measuring the system's precision (not accuracy) at that particular point. Range corrections are computed and assessed. For critical surveys, the same process should be performed at a second calibration point. Significant differences in the range corrections for each point may indicate problems with the control network, multipath errors, or both. The magnitude of the recorded range differences from each calibration point is another rough indicator of the quality of the survey. If the magnitude of these differences (or standard errors from the mean values) is significant, the source of the problem must be determined. This may require calibration at a third fixed point.

d. Total station instrument calibration. Since a typical total station EDM yields direct and accurate X-Y-Z coordinates of the remote point, it may be used to compare the coordinates of an automated positioning system. A total station may be set up at any known point with visibility to the offshore point (and within the operation ranges of both systems). With the vessel held as motionless as possible, the retro-prism is held adjacent to the microwave system antenna, and simultaneous total station and microwave system coordinates are observed at different locations. Inversed distances and microwave ranges are compared as shown in previous examples.

e. Triangulation intersection. Triangulation methods are suitable for areas where no onsite calibration points are available. This method is also particularly ideal for calibrating dredges and other large plants that cannot perform static or direct baseline calibrations. Triangulation methods are potentially the most accurate form of microwave calibration in that the process is performed in a dynamic (true working) environment. To attain this, however, excellent intersection geometry and visibility are necessary, and highly skilled theodolite tracking observers are essential. Vessel velocity must be kept at a minimum during the tracking process. For high-accuracy triangulation calibration, a third theodolite is added for redundancy. A series of 5 to 10 or more intersection fixes is made on a stable or slowly moving survey vessel or dredge at or near the work area. Microwave ranges are read at the time of each intersection fix. Triangulated positions are computed for each position, inversed, and compared with the observed range. Care should be taken to ensure that all computations and comparisons are based on grid distances. As described previously, based on the deviations in the range differences, a judgment must be made as to whether the mean range correction is statistically valid.

f. Sextant resection. Sextant resection calibrations are valid only when resection geometry is ideal, for nearshore projects where distinct sextant targets are clearly visible and vessel velocity is near dead slow or stopped. A series of 5 to 10 simultaneous sextant resection angles and microwave range observations should be made. The sextant observers must be centered about the microwave antenna to minimize eccentricities. On a stable or spudded platform, redundant angles should be observed. Resection computations should be performed manually or with standard software. Graphical resection (three-armed protractor plots) shall not be used. Resection software should provide an estimator or indicator of the quality of the resection based on the geometry and estimated standard error of the observed angles. Without such a quality estimate, the resection solution may be less accurate than the microwave solution. Resected grid coordinates are inversed and compared with the observed microwave ranges. Range differences for each position are computed and meaned. A standard error of each mean should be computed to judge whether applying a mean correction to the range is statistically appropriate. Large variances between the resected ranges and the microwave range indicate poor resectioning, unstable microwave ranges, or both.

g. General QC criteria for electronic positioning systems. Some basic criteria for performing positioning system calibrations are described below. Some of these factors are also applicable to GPS positioning techniques.

- The independent calibration procedure used must have an accuracy at least equal to or better than the system being calibrated. This is not always easily accomplished when dynamic calibrations are performed.

- Multipath effects may not be eliminated by calibration since they can depend on the antenna location (ashore and afloat) and the orientation of the offshore vessel.

- A static calibration does not simulate the dynamic survey condition. Thus, any errors due to vessel motion will not be picked up (e.g., electromechanical lags or lack of system synchronization--latency errors).

- Calibrations must simulate, to the maximum extent possible, the actual conditions existing in the project area. This requires calibration as close to the work site as possible.

- Measurement systems known to be relatively stable, such as infrared electronic distance measurement devices, “self-calibrating” or phase comparison microwave systems, total stations, and GPS, must also be independently checked, or verified, to prevent blunders. The frequency of such verification checks is more relaxed for these systems.

- Calibrations of pulsing microwave positioning systems are valid only for the particular range measurement system used. When antennas, receiver units, connecting cables, and the like are modified, moved, or swapped out, a full recalibration of the system must be performed. Calibration must be performed while the shore-based receivers are located at their actual sites and referenced to the permanently located vessel antenna. If not, some large systematic effects may not be properly compensated for.

- Calibration procedures must be consistent during the course of a project (i.e., both pre-dredge and after-dredge payment surveys). The same baselines and/or procedures should be employed.

- Remote points used to calibrate an established network must be adequately connected by surveys relative to the positioning network. This is especially important when calibrating from large offshore range structures which may not have been accurately positioned, or where the center point is not easily defined. This is especially applicable to long-range DGPS observations.

Section VII
Global Positioning System Techniques

7-29. General

The Global Positioning System (GPS) has rapidly become the standard surveying and navigation mode in USACE replacing microwave ranging and R/A systems. Visual R/A systems will be used only in isolated instances where GPS satellite coverage is obscured. Real-time GPS positional accuracies now exceed those of any other hydrographic survey positioning system. Most significantly, GPS does not require the time-consuming calibrations described for microwave equipment. Numerous public and private differential GPS systems now exist which allows for nationwide coverage. This section details USACE applications of current GPS technology.

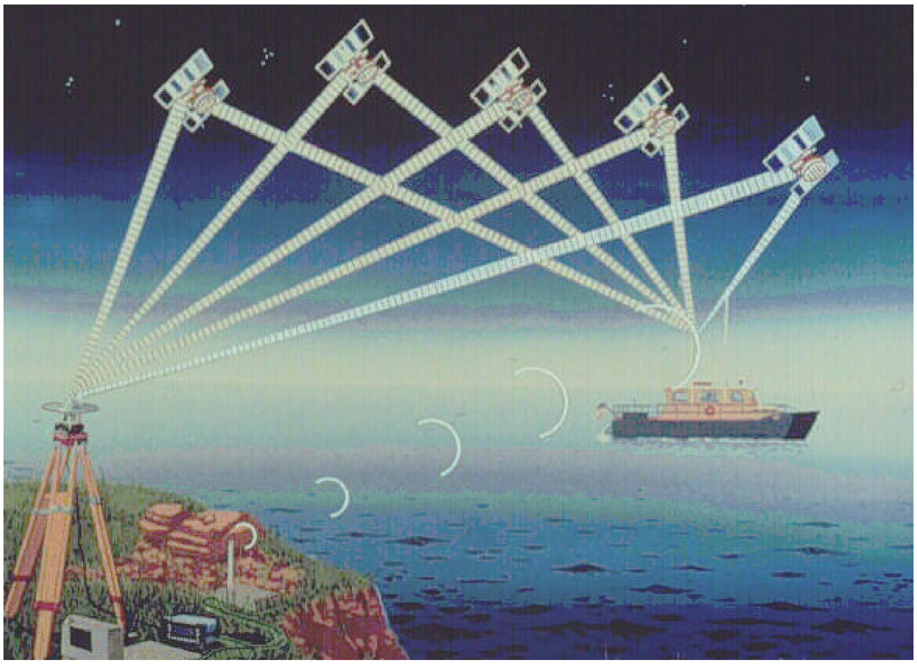

Figure 7-20. Differential GPS positioning of a hydrographic survey vessel

a. GPS is a real-time, all-weather, 24-hour, worldwide, 3-dimensional absolute satellite-based positioning system developed by the U.S. Department of Defense. This system consists of two positioning services: the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). PPS was developed for the U.S. military and other authorized users, uses the P(Y)-code on the L1 and L2 carriers, and provides an accuracy of 5-10 meters in absolute positioning mode. SPS is available to civilian users, uses the C/A-code on the L1 carrier, and provides accuracy of 10-20 meters in absolute positioning mode.

b. For many applications, absolute positioning does not provide sufficient accuracy. Differential GPS (DGPS) is a technique which can provide relative positioning with an accuracy of a few meters to a few millimeters depending on the DGPS method used. DGPS utilizing code phase measurements can provide a relative accuracy of a few meters. DGPS utilizing carrier phase measurements can provide a relative accuracy of a few centimeters. DGPS requires two or more GPS receivers to be recording measurements simultaneously. With two stations recording observations at the same time, GPS processing software can reduce or eliminate "common errors". If one of the stations is a survey control point, DGPS will determine a baseline between the stations and effectively establish the position of the other receiver in the same reference system as the survey control point. Both code and carrier phase DGPS can be performed in real-time thereby positioning moving platforms and survey vessels--see Figure 7-20.

c. The differential GPS technique has application to positioning USACE survey vessels, dredges, and other mobile platforms. When operating in a differential mode it is capable of providing real-time positional and navigational information at accuracies required for present-day hydrographic surveying and/or dredge positioning. Use of GPS has provided more accurate payment surveys and thus reduces disputes and claims arising from errors in survey measurements. Differential GPS is applicable for all USACE hydrographic survey and dredge positioning needs.

7-30. GPS Tracking Modes

a. There are basically two general modes, which are used to determine the distance, or range, between a NAVSTAR GPS satellite and a ground-based receiver antenna. These measurements are made by signal phase comparison techniques. Either the satellite's carrier frequency phase or the phase of a digital code modulated on the carrier phase may be used, or tracked, to resolve the distance between the satellite and the receiver. The resultant positional accuracy is dependent on the tracking method used. These two-phase tracking techniques are:

- Carrier phase tracking
- Code phase tracking

b. The GPS satellites actually broadcast on two carrier frequencies: L1 at 1575.42 MHz (19-cm wavelength) and L2 at 1227.60 MHz (24-cm wavelength). Modulated on these frequencies are the Coarse Acquisition (C/A) (300-m wavelength) and the Precise (P) codes (30-m wavelength). In addition, a 50-bps satellite navigation message containing the satellite ephemeris and health status of each satellite is transmitted. The C/A and P codes are both present on the L1 frequency. Only the P code is present on the L2 frequency. The higher frequency of the carrier signal (L-Band) has a wavelength of 19 and 24 cm from which a distance can be resolved through post-processing software to approximately 2 mm. The modulating code has a wavelength of 300 m and will only yield distances accurate to about 1 m. Both of these tracking methods have application in hydrographic and conventional surveying.

7-31. GPS Accuracies

The absolute range measurement accuracies obtainable from GPS are largely dependent on which code (C/A or P) is used. These estimated user range accuracies or deviations, when coupled with the geometrical relationships of the satellites during the position determination (i.e., dilution of position or geometrical dilution of precision), result in a three-dimensional (3-D) confidence ellipsoid that depicts uncertainties in all three geocentric coordinates. Given the changing satellite geometry and other factors, GPS accuracy is time/location dependent. Error propagation techniques are used to define nominal accuracy statistics for a GPS user. The user range errors/deviations will yield geocentric coordinates (*X*-*Y*-*Z*) and a covariance matrix. These can be transformed to a local datum (N-E-U or u-v-h). The 3-D covariance matrix defines the dimensions of the error ellipsoid, which can be assessed in any direction or coordinate system. The more common error measures used are described below.

a. Root mean square error measures. 2-D (horizontal) GPS positional accuracies are normally estimated using a RMS radial error statistic. A 1 RMS error equates to the radius of a circle in which the position will lie with an approximate probability of 63%. A circle of twice this radius (2 RMS or 2DRMS) represents a 98% positional probability circle. This 98% probability circle, or 2DRMS, is a common 2-D positional accuracy statistic used in GPS surveying literature. Occasionally, a 3DRMS, or 99+% probability circle, is used. USACE hydrographic survey accuracy requirements stated in this manual are given in terms of a 2 RMS error statistic.

b. Probable error measures. 3-D GPS accuracy measurements are most commonly expressed by Spherical Error Probable, or SEP. This measure represents the radius of a sphere with a 50% confidence or probability level. This spheroid radial measure only approximates (or averages) the actual 3-D ellipsoid representing the uncertainties in the geocentric coordinate system. In 2-D horizontal positioning, a Circular Error Probable (CEP) statistic is commonly used, particularly in military targeting. CEP represents the radius of a circle containing a 50% probability of position confidence. Another 2-D measure occasionally used is the radius of a 95% confidence circle.

c. Accuracy comparisons. It is important that GPS accuracy measures clearly identify the statistic from which they are derived. A “100 meter” or “3 meter” accuracy statistic is meaningless unless it is identified as being 1-D, 2-D, or 3-D, along with an applicable probability level. For example, a PPS 16-m 3-D accuracy is, by definition, SEP (i.e., 50%). This 16-m SEP equates to a 28-m 3-D 95% confidence spheroid, or when transformed to 2-D accuracy, roughly 10 m CEP, 12 m RMS, 24 m 2DRMS, and 36 m 3DRMS. In addition, absolute GPS point positioning accuracies are defined relative to an earth-centered coordinate system/datum. This coordinate system will differ significantly from local project or construction datums. Nominal GPS accuracies may also be published as design or tolerance limits, and actual accuracies achieved can differ significantly from these values.

d. Relative accuracy measures. Engineering, construction, and dredging surveys are not so concerned with absolute positions (φ-λ-h) as with local project coordinates (X-Y-h), and with insuring high accuracy within a local construction project. Thus, relative project accuracy is far more important than absolute (world-wide) positional accuracy. Standard surveying and differential GPS (DGPS) linear baseline accuracy is therefore normally expressed by a relative accuracy measure--typically in parts per million (ppm) as a function of the distance between two points or receivers. This measure is usually given at the one-sigma standard error (or standard deviation) level--a 68% probability measure. DGPS system accuracy definitions of 3 m and 0.1 m are, in effect, maximum 1-σ 3-D baseline vector errors relative to the fixed reference point.

e. Dilution of precision. The final positional accuracy of a point determined using absolute GPS survey techniques is directly related to the geometric strength of the configuration of satellites observed during the survey session. GPS errors resulting from satellite configuration geometry can be expressed in terms of Dilution of Precision (DOP). In mathematical terms, DOP is a scaler quantity used in an expression of a ratio of the positioning accuracy. It is the ratio of the standard deviation of one coordinate to the measurement accuracy. DOP represents the geometrical contribution of a certain scaler factor to the uncertainty (i.e., standard deviation) of a GPS measurement. In a statistical sense, DOP is equivalent to the square root of the sum of the squares of the confidence region axes corresponding to the parameters being assessed in an error ellipse.

f. Reference datum. Since differential survey methods are concerned only with relative coordinate differences, disparities with a global reference system used by the NAVSTAR GPS are not significant for

USACE purposes. Therefore, GPS coordinate differences can be applied to any type of local project reference datum (i.e., NAD 27, NAD 83, or local project grid and/or dredging reference system). However, it is recommended that the NAD 83 datum be used to avoid mistakes, since most maps and charts produced today use this datum. In order to obtain accurate NAD 83 coordinates for the reference stations, static GPS surveys can be performed. If this is not feasible, then CORPSCON can be used to convert NAD 27 coordinates to NAD 83.

7-32. GPS Error Sources

Table 7-1 lists the GPS modes and QC standards for hydrographic surveying positioning. The accuracy of GPS is a function of errors and interferences on the GPS signal and the processing technique used to reduce and remove these errors. The same types of phenomena as range-range microwave systems affect GPS signals. Both types of systems are highly affected by humidity and multipath. In addition, the GPS signals travel from 20,000 km out in space through ionosphere and troposphere layers of the earth that delay the satellite signals. Satellite signals can be altered for national security reasons by S/A and AS. Surveying in differential mode close to the reference station can eliminate most of these errors. The further the remote operates from the reference station, the less similar will be the errors received by both receivers. Consequently, less error is being eliminated by the pseudo-range corrections sent over the data link.

a. Tropospheric error. Humidity is included in this error. Humidity can delay a time signal up to approximately 3 m. Satellites low on the horizon will be sending signals across the face of the earth through the troposphere. Satellites directly overhead will transmit through much less troposphere. Masking the horizon angle to 15 deg can minimize the tropospheric error. If this blocks too many satellites, a trade-off down to 10 deg may be necessary. Manufacturers model the tropospheric delay through software. Tests have determined that the tropospheric models used by software manufacturers work reasonably well.

b. Ionospheric error. Sun-spots and other electromagnetic phenomenon cause errors in GPS range measurements of up to 30 m during the day and as high as 6 m at night. The errors are not predictable but can be estimated. The ionospheric error is assumed to be the same at the reference receiver as at the vessel receiver. This assumption is sound for GPS formulations where the stations are separated by a few nautical miles. Ionospheric models have been implemented for dual frequency receivers.

c. Multipath. Multipath is a reception of a reflected signal in lieu of a direct signal. The reflection can occur below or above the antenna. Multipath magnitude is less over water than over land, but it is still present and always changing. The placement of the GPS receiver antenna should avoid areas where multipath is more likely to occur (e.g., rock outcrops, metal roofs, commercial roof-mounted heating/air conditioning, buildings, cars, ships, etc.). Increasing the height of the antenna is one method of reducing multipath at a reference station. The multipath occurrence on a satellite range can last several minutes. Masking out satellite signals from the horizon up to 15 deg will also reduce multipath.

d. Selective availability (S/A). S/A purposely degrades the satellite signal to create position errors. The error can be in excess of 100 m; typically, S/A will be below 100 m 95% of the time according to the Federal Radionavigation Plan. Differential operation can eliminate S/A (under current GPS operations). As of May 1, 2000 S/A has been turned to zero and therefore eliminated its affects on the GPS signal. Even with S/A set to zero DGPS is still needed for most hydrographic surveying applications.

e. Other errors. Other GPS errors are discussed in detail in EM 1110-1-1003.

f. Calibration requirements (checklist). Unlike microwave or R/A systems, DGPS operation has no prescribed calibration requirements. The major items to check for are blunders such as:

(1) Incorrect project datums or geodetic reference datums.

(2) Incorrect master station coordinate values.

(3) Incorrect antenna measure-up values (master and remote heights).

(4) DGPS mode not selected in the unit.

(5) RTCM-104 input/output format not selected in both units for USACE activities.

7-33. GPS Positioning Methods

There are two general operating methods by which GPS derived positions can be obtained:

- Absolute point positioning
- Relative (Differential) positioning (DGPS)

Each of these positioning methods has a variety of survey and navigation applications. In general, absolute point positioning involves only a single passive receiver and is not sufficiently accurate for precise surveying or hydrographic positioning uses. It is, however, the most widely used military and commercial GPS positioning method. Relative (Differential) positioning requires at least two receivers and can provide the accuracies required for basic land surveying and offshore positioning.

a. Absolute Point Positioning (Pseudo-Ranging). When a GPS receiver user performs a navigation solution, only an approximate range, or "pseudo-range," to selected satellites is measured. By pseudo-ranging, the GPS user measures an approximate distance between the antenna and the satellite by correlation of a satellite-transmitted code and a reference code created by the receiver, without any corrections for errors in synchronization between the clock of the transmitter and that of the receiver. The distance the signal has traveled is equal to the velocity of the transmission of the satellite multiplied by the elapsed time of transmission. Tropospheric and ionospheric conditions cause additional delays (errors), which can affect positional accuracy. Four pseudo-range observations are needed to resolve a GPS 3-D position. (Only three pseudo-range observations are needed for a 2-D location.) This is due to the need to resolve the constant clock biases (Δt) contained in both the satellite and the ground-based receiver. Thus, in solving for the X-Y-Z coordinates of a point, a fourth unknown (i.e., clock biases) must also be included in the solution. The solution of the 3-D position of a point is simply the solution of four pseudo-range observation equations containing four unknowns: X, Y, Z, and Δt.

(1) The above solution is highly dependent on the accuracy of the known coordinates of each satellite (i.e., X^s, Y^s, and Z^s), the accuracy of the modeled atmospheric delays (d), and the accuracy of the resolution of the actual time measurement process performed in a GPS receiver (clock synchronization, signal processing, signal noise, etc.). As with any measurement process, repeated and long-term observations from a single point will enhance the overall positional reliability. The accuracy of an absolute point position is a function of the range measurement accuracy and the geometry of the satellites. A description of the geometrical contribution to uncertainty in a GPS-determined point position is termed Dilution Of Precision, or DOP. DOP is roughly related to the physical orientation of the satellites relative to the ground receiver along with the range measurement accuracy. Repeated and redundant range observations to the satellites at varying orientations will improve the positional accuracy. In a static mode (meaning the GPS antenna stays stationary), range measurements to each satellite may be continuously remeasured over varying orbital

locations of the satellite(s). The varying satellite orbits cause varying positional intersection geometry. In addition, simultaneous range observations to numerous satellites can be adjusted using weighting techniques based on the strength of intersection and pseudo-range measurement reliability.

(2) Two levels of absolute positioning accuracy may be obtained from the NAVSTAR GPS satellite system. These are called the (a) Standard Positioning Service and (b) Precise Positioning Service.

(a) Standard Positioning Service (SPS). The SPS user is capable of achieving real-time 3-D absolute positional information on the order of 10-20 m. DOD has implemented Anti-Spoofing (AS), which interchanges the P code with a classified Y code, therefore denying the SPS user the higher P code accuracy. This DOD security action does not significantly affect a hydrographic user operating in a differential positioning mode.

(b) Precise Positioning Service (PPS). The non-military PPS user must be authorized by DOD to have a decryption device capable of deciphering the encrypted GPS signals. This authorization must be obtained from the National Security Agency (NSA). USACE is an authorized user; however, actual use of the equipment has security implications. The PPS user can attain real-time absolute 3-D positional accuracy on the order of 16 m SEP. Again, access to the PPS is not essential to differential positioning.

(3) Since absolute positioning will only provide real-time absolute positional accuracies of, at best, 5-10 m, this method will not satisfy the majority of USACE hydrographic surveying requirements. Exceptions may involve rough reconnaissance surveys that are not used for detailed design or construction. Absolute positioning does have general navigation application and will eventually replace LORAN-C and other satellite navigation systems for ships and aircraft.

b. Relative (Differential) Positioning (DGPS). Relative surveying is the positioning of one point in reference to another. Differential positioning is the technique or method used to position one point relative to another. Differential positioning is not so concerned with the absolute position of the user as with the relative difference in position between two users, who are simultaneously observing the same satellites. Since errors in the satellite position (X^s, Y^s, and Z^s) and atmospheric delay estimates (d) are effectively the same at both receiving stations, they cancel each other to a large extent. Differential positioning can be performed by using code or carrier phase measurements and can provide results in real-time or post processed.

(1) DGPS (Code Phase). Because of the effects of AS on the P-Code, the discussion of code phase DGPS will focus on using the C/A code. Code phase DGPS consists of 2 GPS receivers, one set up over a known point and one moving from point to point or placed on a moving platform, measuring pseudo-ranges to at least 4 common satellites. Since the satellite positions are known and one of the receivers is over a known point, a "known range" can be computed for each satellite observed. This "known range" can then be subtracted from the "measured range" to obtain a range correction or pseudo-range correction (PRC). This PRC is computed for each satellite being tracked at the known point. The PRC can then be applied to the moving or remote receiver to correct its' measured range. Code phase DGPS has primary applications to real-time positioning systems where accuracies at the meter-level are tolerable. Given these limitations, engineering/construction survey applications of code phase DGPS are limited. However, DGPS is applicable to hydrographic survey and dredge positioning, since meter-level positioning suffices for the vast majority of these applications.

(2) DGPS (Carrier Phase). Differential positioning and surveying using the carrier phase is the most accurate GPS survey method. The relative positional accuracies are on the order of two to five parts per million (ppm) between two GPS receivers -- one at a known reference point and the other at the unknown location (aboard a vessel, vehicle, aircraft, etc.).

(a) Differential positioning using carrier phase tracking uses a similar formulation of pseudo-ranges used in code phase tracking systems described above. The process becomes somewhat more complex when the carrier signals are tracked. In carrier phase tracking, the short wavelength, 19 cm, necessitates adding an ambiguity factor to the solution equations to account for the unknown number of whole carrier cycles over the pseudo-range.

(b) Carrier phase tracking provides for a more accurate range resolution due to the short (19 cm) wavelength and the ability of a receiver to resolve the carrier phase down to about 2 mm. This method, therefore, has primary application to engineering, topographic, hydrographic, real estate, and geodetic surveying, and may be employed with either static or kinematic receivers. Methods for resolving the carrier phase ambiguity in a dynamic, real-time mode have been developed and implemented by several GPS receiver manufacturers for real-time positioning and are readily available today. These methods are referred to as real-time kinematic or RTK and provide 3D positions accurate to a few centimeters over a range of approximately 20 kilometers (12 miles).

(3) One advantage of the code phase over the carrier phase is the wavelengths are much longer than the carrier wavelengths, eliminating the ambiguity problem. However, the longer wavelengths decrease the system accuracy and are more affected by signal multipath.

7-34. Real-Time Code Phase DGPS Concept

The code phase tracking differential system is currently a functional GPS survey system for positioning hydrographic survey vessels and dredges. A real-time dynamic DGPS positioning system includes reference station (master), communications link, and user (remote) equipment. If results are not required in real-time, the communications link could be eliminated and the positional information post-processed; however, such an operation is not practical for most construction support activities where immediate results are necessary. Since there are several DGPS services (USCG, Commercial Subscription Services) that provide real-time pseudo-range corrections, it is recommended that these services be used before installing or using a local DGPS system. Only in circumstances where these services do not provide coverage should a local DGPS system be used.

a. Reference Station. The reference station measures timing and ranging information broadcast by the satellites and computes and formats range corrections for broadcast to the user equipment. The reference receiver consists of a GPS receiver, antenna, and processor. Using the technology of differential pseudo-ranging, the position of a survey vessel is found relative to the reference station. The pseudo-ranges are collected by the GPS receiver and transferred to the processor where pseudo-range corrections are computed and formatted for data transmission. Many manufacturers have incorporated the processor within the GPS receiver, eliminating the need for an external processing device.

(1) Reference station placement. The reference station is placed on a known survey monument in an area having an unobstructed view of the sky for at least 10 deg above the horizon. The antenna should not be located near objects that will cause multipath or interference. Areas with antennas, microwave towers, power lines, and reflective surfaces should be avoided.

(2) Reference station processor. The reference station processor computes the pseudo-range corrections (PRCs) and formats the corrections for the communications link to transmit to the offshore vessel. The recommended data format is that proposed by the Radio Technical Commission for Maritime Services (RTCM) Special Committee 104 v 2.0. The reference station processor also performs quality assurance. This routine is required to determine the validity and quality of the computed PRCs. The

reference station processor should be capable of computing and formatting PRCs every 1 to 3 sec. Most GPS receivers have processors built into them for computing pseudo-range corrections.

(3) Algorithm description. For a detailed algorithm description, refer to EM 1110-1-1003.

b. Communications Link. The communications link is used as a transfer media for the differential corrections. The main requirement of the communications link is that transmission be at a minimum rate of 200 bits per second (bps). The type of communications system is dependent on the user's requirements.

(1) Ultra high frequency (UHF) and very high frequency (VHF). Communications links operating at UHF and VHF are viable systems for the broadcast of DGPS corrections. VHF and UHF can extend out some 20 to 50 km, depending on local conditions. The disadvantages of UHF and VHF links are their limited range to line of sight and the effects of signal shadowing (from islands, structures, and buildings), multipath, and licensing issues. USACE is limited to using VHF 164-172 MHz for the transmission of PRCs since USACE has already been authorized to these frequencies.

(2) Frequency authorization. All communications links necessitate a reserved frequency for operation to avoid interference with other activities in the area. Transmitters with power outputs below 100 milliwatts (mW) do not require a frequency allocation and license for operation in the United States. Frequency authorization for the USACE must be obtained through the National Telecommunications and Information Administration (NTIA) of the U.S. Department of Commerce for transmissions that exceed 100 mW. A district's frequency manager responsible for the area of application handles allocation of a frequency. No transmission can occur over a frequency until the frequency has been officially authorized for use. This procedure applies to all government agencies.

(3) Satellite communications. There are several companies that sell satellite communications systems, which can be used for the transmission of the PRCs. These systems are not as limited in range as a UHF/VHF system can be, but are usually higher in price.

c. User Equipment. The user equipment is the most flexible facet of the real-time code phase tracking DGPS. The remote receiver should be a multichannel single frequency (L1) C/A code GPS receiver. The receiver must be able to accept the differential corrections from the communications link in the Radio Technical Commission for Maritime Services Special Committee No. 104 (RTCM SC-104) v.2.0 format and then apply those corrections to the measured pseudo-range. The critical portion of the user equipment is the receiver update rate. The update rate for payment surveys must be 1 to 3 sec. Specific requirements will vary with different manufacturers and with the distance from the reference station. The output from the rover receiver should be in the NMEA-183 sentencing format, because it is the most widely used for input into a hydrographic survey software package. The user equipment also must be capable of maintaining positional tolerances for surveys at speeds of 7 to 10 knots. A DGPS receiver must not bias the position during vessel turns due to excess filtering.

d. Separation Distances. The maximum station separation between reference and remote station, in order to meet hydrographic surveying standards of 2 m, can be maintained up to a distance of 300 km, provided that differential tropospheric and ionospheric corrections are used. These corrections are not presently applied to internal solutions of most GPS receivers. The unaccounted tropospheric and ionospheric errors contribute to horizontal position error on an average of 0.7 m per every 100 km. A limiting factor of the separation distance is the type of data link used. If a DGPS is procured for hydrographic surveying, the reference station should be capable of being moved from one point to another. This will allow the user to move the reference station so that the minimum distance separation requirements are maintained.

e. Satellite Geometry. In code phase DGPS, the Horizontal Dilution of Position (HDOP) is the critical geometrical component. The HDOP should be < 5 for dredging and navigation hydrographic surveys. The final GPS constellation (24 Block II satellites) will maintain a HDOP of approximately 2 to 3 most of the time.

7-35. USCG DGPS Radiobeacon Navigation Service

a. USCG DGPS Radiobeacon System. One function of the U.S. Coast Guard (USCG) is to provide aids to navigation in all navigable waterways. In the past, Loran-C and Omega systems were used as the primary positioning tools for marine navigation. Today, the USCG is making use of the full coverage from GPS for a more accurate positioning tool for marine navigation. Utilizing DGPS and marine radiobeacon technology, the USCG has designed a real-time positioning system for the coastal areas and Great Lakes regions of the U.S. The USCG has also partnered with USACE and other government agencies to expand this coverage to inland waterways and eventually over the entire nation. The system consists of a series of GPS reference stations with know coordinate values based on the North American Datum of 1983 (NAD83) datum. GPS C/A-code pseudo-range corrections are computed based on these known coordinate values and transmitted via a marine radiobeacon. A user with a marine radiobeacon receiver and a GPS receiver with the ability to accept and apply pseudo-range corrections can obtain a relative accuracy of 0.5-3 meters. This accuracy is dependent on many factors including the design and quality of the user's GPS receiver, distance from the reference station, and the satellite geometry. This service can be used for all USACE hydrographic surveys and dredge positioning requiring an accuracy of 0.5 to 3 meters.

b. Site Set-up and Configuration. Each USCG radiobeacon site consists of two GPS L1/L2 geodetic receivers (as reference station receivers) with independent geodetic antennas to provide redundancy and a Marine Radiobeacon transmitter with transmitting antenna. The site is also equipped with two combined L1 GPS / Modulation Shift Key (MSK) receivers which are used as integrity monitors. Each combined receiver utilizes an independent GPS antenna and a MSK near-field passive loop antenna.

(1) Site Location. The location of the reference station GPS antennas are known control points within the North American Datum of 1983 (NAD83) and International Terrestrial Reference Frame (ITRF). The geodetic coordinates for these positions were determined by NGS. DGPS corrections are based on measurements made by the reference receiver and the NAD83 known antenna coordinates. These corrections are then transmitted via a marine radiobeacon to all users having the necessary equipment.

(2) Data Transmission (data types). The corrections are transmitted using the Type 9-3 (three satellite corrections) message of the Radio Technical Commission for Maritime Services Special Committee 104 (RTCM SC-104) version 2.1 data format. Other RTCM SC-104 message types transmitted to the user include Type 3 (contains the NAD83 coordinates for the broadcast site), Type 5 (provides information if a GPS satellite is deemed unhealthy), Type 7 (information on adjacent radiobeacons), and Type 16 (alerts the user of any outages). More detailed descriptions of these message types are explained in the Broadcast Standard for the USCG DGPS Navigation Service, COMDTINST M16577.1, April 1993 that can be downloaded from the USCG Navigation Center (NAVCEN) web site (www.navcen.uscg.mil).

(a) Corrections are generated for a maximum of nine satellites tracked by the reference station GPS receiver at an elevation angle of 7.5 degrees or higher above the horizon. Satellites below a 7.5-degree elevation mask are highly susceptible to multipath and spatial decorrelation. If there are more than nine satellites observed at the reference station above 7.5 degrees, than the corrections broadcast are based on the nine satellites with the highest elevation angle.

(b) The sites transmit these corrections at a 100 or 200 baud rate. Since a type 9-3 message is 210 bits (includes header information and corrections for three satellites), the latency of the data is 2.1 seconds for a site transmitting at 100 baud. For stations transmitting at 200 baud, the latency would be half, 1.05 seconds. The user can expect a latency of 2-5 seconds for all of the corrections for a group of satellites observed at the reference station to reach them. A correction can be considered valid for a period of 10-15 seconds from generation (the USCG limit is 30 seconds). Using corrections beyond this period of time, especially for positioning of a moving platform, may cause spikes in the positional results.

c. Availability and Reliability of the System. The system was designed for and operated to maintain a broadcast availability (i.e., transmitting healthy pseudo-range corrections) that exceeds 99.7 percent (in designed coverage areas) assuming a healthy and complete GPS constellation. The signal availability, in most areas, will be higher due to the overlap of broadcast stations. The USCG monitors each site within the entire system for problems or errors 24 hours a day. Each site is equipped with two integrity monitors (i.e. a GPS receiver with a MSK radiobeacon) that are mounted over known positions. The integrity monitors receive the pseudo-range corrections from that site and compute a position. The computed or corrected position is compared to the known location to determine if the corrections are within the expected tolerance. The corrected positions calculated by the integrity monitors are sent via phone lines to the control monitoring stations. For the stations east of the Mississippi River, this information is sent to USCG's NAVCEN in Alexandria, Virginia. Sites west of the Mississippi River send their corrected positions to the NAVCEN Detachment in Petaluma, California. Users are notified via the type 16 message of any problems with a radiobeacon site within 10 seconds of an out-of-tolerance condition.

d. Coverage. The system was designed to cover all harbors and harbor approach areas and other critical waterways for which USCG provides aids to navigation. Each site has a coverage area between 150 to 300 miles, depending on the transmitter power, terrain, and signal interference. Since the sites utilize an omnidirectional transmitting antenna, some areas have overlapping coverage. Currently the system covers all U.S. coastal harbor areas, the Mississippi and part of the Missouri and Ohio Rivers, and the Great Lakes Region. Additional areas within the Midwest U.S. and other non-coastal areas are being added to provide nationwide coverage. Figures 7-21 and 7-22 depict existing and planned radiobeacon coverage as of 1999. An updated map of the coverage area can be found at the NAVCEN web site under the DGPS section.

Figure 7-21. USCG Radiobeacon DGPS coverage including USACE coverage in inland navigation system (1999)

Nationwide DGPS

Inland Waterway Coverage after Proposed
Decommission/Relocation of Corps Stations

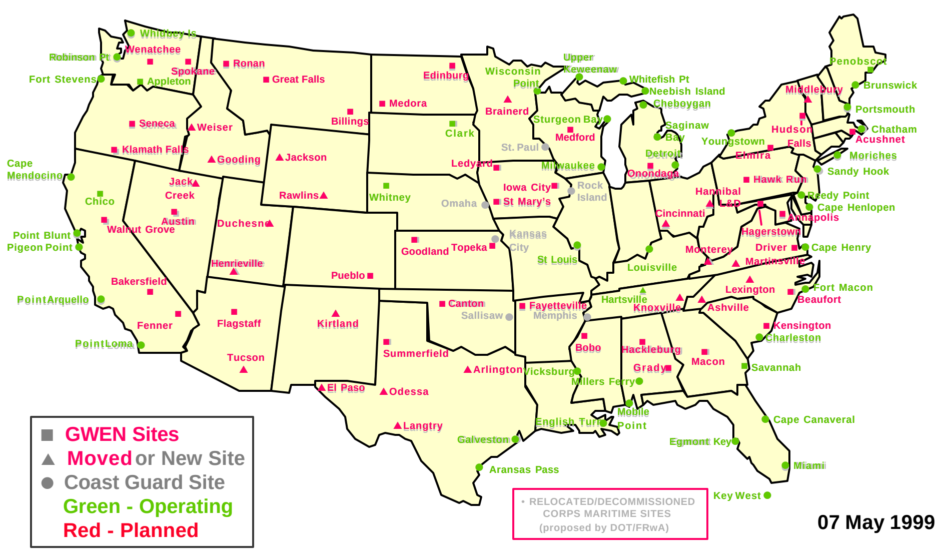

Figure 7-22. Proposed nationwide coverage of USCG radiobeacon network (May 1999)

e. User Requirements and Equipment. To receive and apply the pseudo-range corrections generated by the reference station, the user needs to have a MSK Radiobeacon receiver with antenna and, at a minimum, a L1 C/A code GPS receiver with antenna.

(1) The MSK receiver demodulates the signal from the reference station. Most MSK receivers will automatically select the reference station with the strongest signal strength to observe from or allow the user to select a specific reference station. A MSK receiver can be connected to most GPS receivers. The costs of radiobeacon receivers range from $500 to $2000.

(2) The GPS receiver must be capable of accepting RTCM Type 9 messages and applying these corrections to compute a "meter level" position. Since the reference station generates corrections only for satellites above a 7.5 degree elevation, satellites observed by the user's GPS receiver below a 7.5 degree elevation will not be corrected. Some receiver manufacturers have developed a combined MSK radiobeacon and GPS receiver with a combined MSK and GPS antenna. For a combined radiobeacon/GPS receiver, prices range from $2000 to $5000

7-36. Real-Time Carrier Phase DGPS Concept

a. General. The carrier phase system for hydrographic survey vessels and dredges is capable of centimeter accuracy both horizontally and vertically. This technology will provide real-time elevations of survey vessels and other moving platforms. If adequate motion compensation equipment is used, and project tidal datum modeling has been accomplished, real-time bathymetry (depths) can be directly obtained from the soundings. This positioning system is based on DGPS carrier phase technology similar to the kinematic techniques. In the past, kinematic surveying procedures allow for the movement of a GPS receiver only after the initial integer ambiguity (i.e., whole number of wavelengths) between satellites and receiver had been resolved. Current kinematic techniques allow for the ambiguities to be resolved while the moving receiver(s) is in motion and provides accuracies in the range from 2 to 5 cm. This method of carrier phase positioning is commonly referred to as real-time kinematic or RTK surveying.

b. Reference Station. The carrier phase positioning system is very similar to the current code phase tracking technology previously described. A shore GPS reference station must be located over a known survey monument; however, the reference station must be capable of collecting both pseudo-range and carrier phase data from the NAVSTAR satellites. The reference station will consist of a carrier phase, dual frequency full wavelength L1/L2 GPS receiver with its associated antenna and cables, processor, and communications link. The receiver should be capable of a 1-sec update rate. The location of the reference station will be the same as for a code phase tracking DGPS system. The processor used in the reference station will measure the pseudo-range and carrier phase data and format the data for the communications link. The data will be formatted in the RTCM SC-104 v.2.1 format for transmission to the remote user.

c. Communications Link. The communications link for the carrier phase positioning system differs from the code phase tracking DGPS system in the amount of data that has to be transmitted. The carrier phase positioning system requires a minimum data rate of 4800 baud, as compared to a baud rate of 300 for the code phase tracking DGPS system. This high data rate eliminates many of the low-frequency broadcast systems and limits the coverage area for high-frequency broadcast systems. VHF and UHF frequency communications systems are well suited for this data rate. As satellite communications become more cost-effective, can handle higher baud rates, and employ smaller terminals, this communications option will be used for carrier phase positioning systems.

d. User Equipment. The user equipment on the survey vessel or dredge consists of a carrier phase dual-frequency full-wavelength L1/L2 GPS receiver with a built in processor and associated antenna. The built in processor must be capable of resolving the integer ambiguities while the platform (survey vessel or dredge) is moving. Using a "geodetic quality" GPS antenna will reduce the effects of multipath on the GPS signal. A communications link is needed on the dredge or survey vessel to receive data from the reference station. Frequency approval may be necessary for communication link broadcasts using a power source in excess of 1 watt. The RTK system is not designed to be used for surveys in excess of 20 km from the reference station. The position output for the helmsman is code phase tracking using pseudo-ranges (accurate at the meter level) for vessel navigation in real time. The carrier phase DGPS data will be timed/tagged to allow for recording the true vessel position needed for survey processing. The minimum update rate from the reference station to the vessel(s) is 1 sec.

e. Ambiguity resolution. High-precision kinematic positioning is available from the system once the receiver's processor resolves integer ambiguities. As long as the system remains in the RTK mode, real-time sub-decimeter positioning in three dimensions is available at the (mobile) remote station or platform. To remain in this RTK mode requires both reference station and the remote station receivers to maintain lock (continuous GPS data) on at least four satellites. If that number drops to below four, the ambiguities will again be resolved after the system reacquires lock on a sufficient number of satellites. It will also trigger reinitialization if quality factors based upon residuals fail to meet certain predefined limits.

Section VIII
Summary of Positioning System Quality Control Standards

7-37. Calibration Criteria

All visual, mechanical, and electronic positioning systems must be periodically calibrated (or checked) to minimize systematic errors and/or to eliminate blunders that may be present in the measurements. Failure to perform and record calibrations represents poor quality control performance and, in the case of construction measurement and payment work, can lead to contract disputes and claims over equitable payment. The amount of calibration needed for each type of positioning system varies considerably. Transits and total stations require periodic back sight checks. Microwave distance measurement systems require daily comparisons with independent higher accuracy EDM. GPS has far fewer calibration requirements than other positioning methods. It is mandatory that calibration observations (and related computations and adjustments) must be officially recorded either in a standard field survey book or on a prescribed worksheet and that these records be maintained as part of the project/contract files.

7-38.Quality Control Criteria for Positioning Methods

Table 7-1 resents a summary of minimum QC standards to be followed when using the various positioning systems described in this chapter. These criteria apply only to dynamic hydrographic survey applications, not to observations made to locate or calibrate a stationary platform or structure.

Table 7-1. Summary of QC Standards for Hydrographic Survey Positioning

	PROJECT CLASSIFICATION		
	Navigation & Dredging Support Surveys Bottom Material Classification		Other General Surveys & Studies (Recommended Standards)
	Hard	Soft	
SEXTANT RESECTION			
Allowable procedure	No	No	Yes
Calibrate sextant every	N/A	N/A	30 min
TRIANGULATION/INTERSECTION			
Allowable procedure	No	Yes	Yes
Check backsight	N/A	1/hr	1/hr
VISUAL POSITIONING			
Allowable procedure	No	No	Yes
TAG LINE POSITIONING			
Allowable procedure	Yes	Yes	Yes
Distance from baseline NTE	500 ft	1,500 ft	3,000 ft
Calibrate tag line	project	monthly	annually
Accuracy-nearest	1 ft	1 ft	2 ft
Allowable alignment methods (see Range Azimuth below)			

Table 7-1. Summary of QC Standards for Hydrographic Survey Positioning (Contd)

	PROJECT CLASSIFICATION		
	Navigation & Dredging Support Surveys Bottom Material Classification		Other General Surveys & Studies (Recommended Standards)
	Hard	Soft	
RANGE-AZIMUTH			
Allowable procedure	Yes	Yes	Yes
Distance from observer NTE:			
Stadia	200 ft	500 ft	1,000 ft
Microwave EDM	(0 ft)	5,000 ft	----
Total Sta EDM	(Inst range)	(Inst range)	(Inst range)
Alignment method:			
Right angle glass	100 ft	200 ft	500 ft
Sextant	500 ft	1,000 ft	2,500 ft
Transit/Theod/Tot Sta	(Inst range)	(Inst range)	(Inst range)
Check orientation	2/hr	1/hr	1/hr
Real-time data quality indicator	Recommended	Recommended	Recommended
Alarm at 95% RMS exceeding	2 m	2 m	5 m
MICROWAVE RANGE-RANGE			
Allowable procedure	No	No	Yes
Calibrate	N/A	N/A	monthly
Range calib. accuracy	N/A	N/A	± 3 m
Calib. point at worksite	N/A	N/A	Recommended
Angle of intersection	N/A	N/A	30-150 deg
Real-time data quality indicator	N/A	N/A	Recommended
Alarm at 95% RMS exceeding	N/A	N/A	5 m
GLOBAL POSITIONING SYSTEMS			
Allowable mode			
SPS/PPS	No	No	Yes (marginally)
DGPS (Local Code)	Yes (marginally)	Yes	Yes
DGPS (USCG Code)	No	Yes (marginally)	Yes
DGPS (Carrier/RTK)	Yes	Yes	Yes
Maximum distance from ref sta			
SPS/PPS	N/A	N/A	N/A
DGPS (Local Code)	1 mile	10 miles	50 miles
DGPS (USCG Code)	100 miles	100 miles	200 miles
DGPS (Carrier/RTK)	10 miles	10 miles	20 miles
Position check required	1/day	1/project	1/project
Tolerance check	1 m	2 m	5 m
Real-time data quality indicator	Mandatory	Recommended	Recommended
Alarm at 95% RMS exceeding	2 m	2 m	5 m
RTK vertical check with gage	Mandatory	Mandatory	Recommended

7-39 Mandatory Requirements

The criteria in Table 7-1 for positioning dredging and navigation surveys are considered mandatory.