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SATELLITE APPLICATIONS TO MARINE GEODESY

by A. G. Mourad, N. A. Frazier, J. H. Holdahl,
F. W. Someroski, and A. T. Hopper

Prepared by
BATTELLE MEMORIAL INSTITUTE
Columbus, Ohio
for

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EXECUTIVE SUMMARY

The results of the Battelle study of the potential for application of satellites to precise positioning in the oceans and to marine geodesy indicate that many attractive possibilities are unexploited. Information contained in this summary report was compiled from personal interviews with individuals representing about 45 private and Government organizations, from the open literature, and from available reports.

Marine geodesy is that part of geodesy which deals with geodetic methods, objectives, and applications at sea. Marine geodesy, therefore, has the same scientific and practical aims as land geodesy: determination of the size and shape of the earth and its gravity field, establishment of geodetic control which is the basic framework required for accurate and reliable mapping, and development of precise measurement technology and computation needed to satisfy these aims.

Marine geodesy does have some unique problems; work must be performed in the dynamic and complex environment of the ocean. Most marine geodetic work must, therefore, be conducted using a ship or surface platform. Consequently, accurate ship positioning is a requirement for precise measurement technology, which is in turn a requirement for marine geodesy. The oceans occupy over 70 percent of the Earth's surface. Precise ship positioning and marine geodesy will certainly play major roles in effective exploration and exploitation of the ocean and their resources.

Satellite methods were investigated during this study in the light of:

(1) Problems and needs related to precise positioning in the oceans and to marine geodesy

(2) Sources of these problems as they relate to major types of surface-based positioning systems

(3) Role of marine geodesy with respect to problems and needs in various areas.

The potential for satellite use in marine geodesy and precise positioning is almost without limit. Satellites should make possible development of either a relative or an absolute geocentric coordinate system based on accurate underwater geodetic control points.

Satellite-based positioning system could overcome some of the limitations inherent in surface-based systems with respect to range, local shore control, and 24-hour capability. Satellite-based systems would also offer a distinct advantage in that all ocean work could be related to a single reference datum.

Accuracies reported for satellite position fixes have ranged from 100 to 1000 meters, depending upon the corrections applied, with perhaps the range between 200 and 400 meters being representative. Accuracy from 100 to 150 meters appears possible if ship speed is known to about one-quarter of a knot. On the basis of these numbers, it seems that satellite-based systems within the present state of the art could meet many of the requirements stipulated by potential users for 200-meter accuracy in positioning in the open ocean.

In terms of reoccupying a position, present satellite capability appears to be outside of, or just approaching, the least stringent of the requirements stated. Also, existing satellites do not provide continuous positioning capability, the desirability of which was stressed by most of those interviewed.

The establishment of marine control points will require much higher accuracy (10-30 meters) than might be possible at present. It is not known how accurately these control points can be established using satellite-based systems. However, satellites apparently do have the potential for satisfying such accuracy requirements. They also have an obvious advantage in that the control points could be established either progressively or simultaneously in different areas of the world oceans using the same satellite system. Several supercontrol points could be established at sea to complement the points being established under the National Geodetic Satellite Program (NGSP), thus helping to meet the geometric and gravimetric geodesy goals of the NGSP and also contributing to the establishment of geodetic standards at sea.

Response to Revealed Needs

Effective response to the needs revealed by the study would necessitate that geodetic standards be established at sea; that there be optimum combination of satellites in terms of areal coverage and frequency of position fixes; and that positioning operations be expanded to include the use of multisystems involving satellite, inertial, acoustic, geodetic-control and surface-based-electronic systems.

Future accomplishments will depend, to a great extent, upon clearer definition of problems that have been revealed by experience so far: unmet requirements for accuracy and precision, lack of standards, and shortcomings of specific types of equipment and systems. Three major areas of interest should be considered: economic, research and development, and geodetic.

Economic Interests

Economic interests of the organizations surveyed generally dictate a requirement for recovery of position within 30 to 100 meters in continental shelf areas throughout the world. These organizations, although they have at their disposal the most sophisticated surface-positioning systems available, are nevertheless unsatisfied. Despite the fact that these systems are rated as having capabilities well within the range of 30 to 100 meters as generally specified, their performance is seldom adequate in actual field operations. This inadequacy is causing increasing concern because drilling and mining technology now permits extending operations to greater depths and to greater distances from shore. Some potentially productive continental-shelf areas extend 200 to 400 miles from land. Economic exploitation of these areas depends on development of reliable positioning capability beyond the rated capability of the best present surface systems by a factor of about 2 to 4.

Economic interests also dictate exact locating of geographic positions when lease boundaries, drainage areas, geologic structures, drill sites, and mineral deposits are involved. In some cases errors should be no greater than about 100 meters; in others they should be much less.

Research and Development Interests

Each of the multitude of current and planned research-and-development programs and test-and-evaluation activities presents its own positioning requirements. In general, such operations require capability for recovery of position with about the same accuracy as operations reflecting economic interests. However, requirements can range down to the minimum error feasible. Some programs also require location of actual positions in a geocentric, geodetic, or local system or with respect to shore control stations.

Many persons interviewed expressed dissatisfaction with results being achieved. They want better positioning capability and will use it if it becomes available. The vertical coordinate in major portions of oceanographic work is very significant; reference surfaces are needed with accuracy from 1 meter down to the least number of decimeters possible.

Geodetic Interests

Basically, there are two possibilities for the geodetic application of satellites: (1) to provide geodetic standards at sea in the form of a marine geodetic range for testing, evaluating, and comparing positioning systems and various types of equipment and methods when the errors in distance or position variables must be known, and (2) to provide one or more geodetic control points in an area of operation. If control points were to be established, the hardware could be either of the recoverable type or of the permanent type intended to be left in place.

The expense of increasing positioning capability to an appropriate degree would be difficult, if not impossible, to justify for the construction of a single map or chart or for any single and relatively small ocean operation. However, collectively considered, present ocean operations involving data gathering and related activities represent expenditures of many millions of dollars annually, and justification for any measure to reduce all-over expense is readily apparent. For example, many interests would benefit if the need for repeating surveys were eliminated or if all positioning data were based on the same reference system.

Mapping and charting requirements vary according to the scale involved. Requirements for map accuracy range from 20 to 300 meters, with a definite trend toward requirements for the lower numbers. In general, satisfying needs means making observations at accuracies of about one-half of these numbers. It is also necessary to begin planning for systematic mapping of the ocean floor.

Although the use of satellites in the establishment of marine geodetic control apparently has great potential, with the exception of some work involving photographic methods, there has been no experimental evaluation of possibilities. The results of the limited work that has been done on the photographic method indicate an accuracy of 10 to 20 meters relative to North American Datum (NAD) is possible.

The Doppler satellite method offers most immediate promise because Doppler satellites are already operating; they have all-weather capability; they offer relative ease of operation; appropriate methods and techniques have been worked out to some degree; and the amount of positioning experience at sea is considerable. Theoretically, it appears that the use of Doppler satellite for establishment of geodetic control at sea could also provide nearly the accuracy achieved on land (10 to 30 meters in a geocentric coordinate system).

Specific Recommendations

The following specific recommendations are based on the results of the Battelle study:

(1) Precise geodetic measurement capability at sea should be established on the basis of a marine geodetic range

(2) The feasibility of using the GEOS-II satellite to establish a marine control point should be evaluated experimentally

(3) Various systems (e.g., satellite-based, intertial, acoustic) should be used in combination to achieve maximum positioning capability

(4) The possible advantages of launching additional satellites for greater areal coverage and greater frequency of fixes should be explored

(5) All ocean maps and surveys should be referenced to a single datum

(6) Some standard method should be devised for expressing accuracy ratings, requirements, and achievements.

SATELLITE APPLICATIONS TO MARINE GEODESY

INTRODUCTION

The NASA Office of space Science and Applications (OSSA) has within the overall objectives of its National Geodetic Satellite Program three specific goals:

(1) Geometric Geodesy Goal - determination of geodetic station locations in a worldwide datum accurate to ±10 meters and referenced to the Earth's center of mass and mean rotational axis.

(2) Gravimetric Geodesy Goal - determination of the coefficients of the Earth's gravity potential up to the 15th degree.

(3) Earth-Science and Application Support - application of geodetic satellite knowledge to solid Earth geophysics and geology, meterorology and aeronomy, space dynamics and astronomy, and oceanography.

The great potential for utilization of space science and technology for the benefit of other sciences and engineering and to promote economic development has been realized for some time. However, evaluation of the transferability of specific facets of the information obtained and actual transfer are tasks of large proportions. Effective performance of these tasks will result in betterment for major segments of the world population. For example, benefits are now being realized from the application of satellites to navigation at sea and to weather forecasting. Applications of spacecraft technology to other endeavors, such as commercial fishing, agriculture, forestry, oceanography, and oil and mineral exploration are at various stages of evaluation.

The investigations reported here represent another important step taken by NASA toward new and practical use of satellites. This study has revealed how satellites might be used for establishment of geodetic control at sea. This work, in conjunction with other NASA work on satellite altimetry, could be of far-reaching significance to oceanography, to the infant science of marine geodesy, and to precise positioning capabilities at sea. Most important, studies of the type reported here represent another facet of the many investigations directed toward developing capability for realization of the benefits that will ultimately evolve from the ordered understanding and development of the over 70 percent of the Earth's surface which the oceans represent.

REPORT ORGANIZATION

Results of the study are presented in this report in five major sections. Section I, immediately following, describes the research program and its background and gives over-all project objectives. The approach used during the program is also outlined and the new science of marine geodesy is described. The specific reasons for considering the possibility of utilizing satellites to advance this infant science are also discussed.

Section II contains the major findings of the study and the recommendations based on them. Section III concerns the requirements and needs of those involved in problems of precise positioning and geodetic control at sea. Section IV deals with major positioning systems used in marine operations. Section V examines in some detail possible applications of satellites to meet the requirements and needs described in Section III.

Appendix A contains commentaries on the most representative of the interviews conducted as part of this study. Appendix B provides a detailed review of the technology of applicable satellite methods; it is a compilation of background information used in preparing Section V. References to the literature are listed in Appendix C.

SECTION I

PROJECT DESCRIPTION AND BACKGROUND

Projected growth in world population, will bring about a trend to depend more and more on the sea for both life-sustaining elements and employment. This trend will include a transition period to orderly development and utilization of marine resources. Orderly development will depend on the capability to explore and map the oceans. The usefulness of ocean survey data must be maximized in time and in the number of user needs which data from specific surveys can fulfill.

There is no ingredient of exploration and mapping that is more basic than the ability to display properly positioned thematic data on maps. The degree of order which can be achieved in the development of marine resources, then, is directly proportional to precise positioning capability and the availability of geodetic control upon which mapping and surveying is ultimately based.

The purpose of this study was to explore the potential inherent in satellites for enhancing positioning capability and for providing a means for establishing marine geodetic control. Results of the study indicate that the potential is considerable and it is recommended that this potential be effectively exploited with as much urgency as is feasible.

OBJECTIVES

The overall objective of this study was to provide NASA with information for use in planning related to satellite applications. The specific objectives were to ascertain the following:

(1) Capabilities of major marine positioning systems

(2) Requirements for precise positioning and geodesy at sea

(3) Role of marine geodetic control points in the light of these requirements

(4) Possible role of satellites in establishing marine geodetic control points and in precise positioning.

APPROACH

The approach was basically one of identifying requirements and matching them against capabilities (see Figure 1). Requirements were identified from two sources of information (left branch of Figure 1): (1) interviews with individuals of industrial, governmental, university, and private organizations, the scope of the sample representing a wide variety of ocean-related pursuits, and (2) review of literature and reports. Capabilities of positioning systems and satellite methods were determined by the same

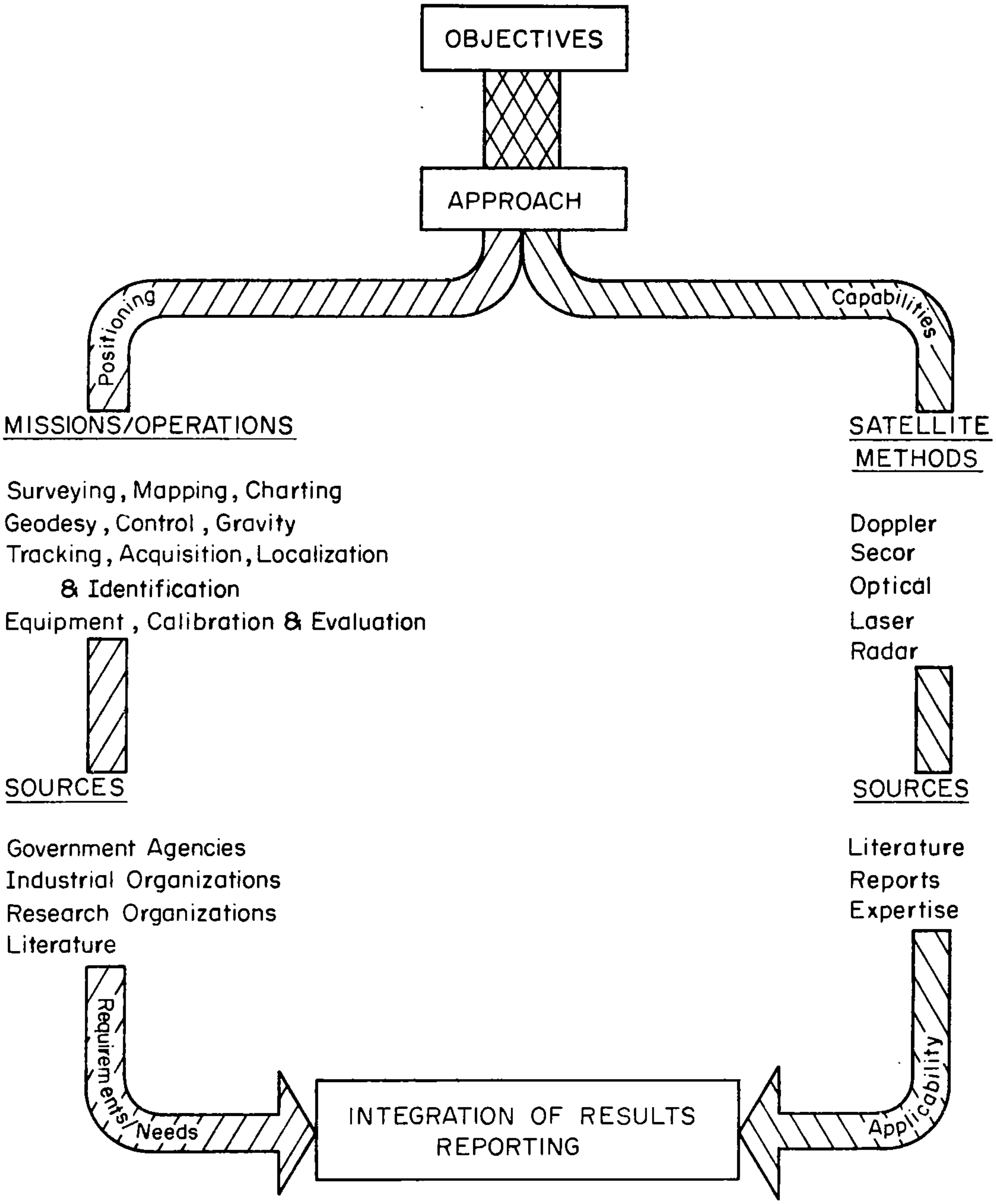

FIGURE 1. PROJECT APPROACH

procedure – discussions with persons expert in the subjects and review of literature and reports (right branch of Figure 1).

Interviews were held with one or more persons representing a total of 45 organizations prominent in marine activities. In addition, discussions were held with numerous persons during attendance at technical meetings. Appendix A contains excerpts from the trip reports covering the most representative of the visits.

DESCRIPTION OF MARINE GEODESY

Marine geodesy is that part of geodesy which deals with geodetic methods, objectives, and applications at sea. The science, therefore, has the same scientific and practical aims as land geodesy – determination of the shape and size of the earth and its gravity field, and precise measurement and computation for establishment of geodetic control which is the basic framework required for accurate and reliable mapping. Marine geodesy does have some unique problems; work must be performed in the dynamic and complex environment of the ocean.

An artist's concept of marine geodesy in action is shown in Figure 2. Portrayed at the left is an aircraft measuring the distance (airborne DME) between two ships positioned over and with respect to bottom points to become marine control points by trilateration methods. In the center, a satellite is shown used in geodetic mode to extend geodetic control to sea. At the right a photomapping aircraft is portrayed tying fixed surface features, such as offshore platforms, into geodetic points on land using photogrammetric methods.

A marine geodetic control point is a point to be located on or referenced to the sea floor in terms of geographic coordinates (latitude, longitude, and depth) or in an absolute three-dimensional coordinate system. Gravity measurements, deflection of the vertical components, and geoidal reference determinations are also desirable quantities to be associated with the control point. In one configuration, a control point could consist of one or several underwater acoustic transponders placed on or slightly above the ocean floor and powered with a long-life power source. To be of use, a control point must have capabilities to acquire, identify, and/or return signals transmitted from a ship. This can be accomplished in several ways, as described in literature(68, 69)* and in Section III.

REASONS FOR CONSIDERING POSSIBLE SATELLITE APPLICATIONS TO MARINE GEODESY

Earth satellites offer great promise for overcoming the limitations of other methods in that they have the range capability and singularity of the reference datum needed for precise geodetic measurement and large-area surveys, for intercontinental datum connection, etc. Distances of the order of thousands of miles can be determined using satellite geodetic techniques. If the accuracy of satellite measurements over the oceans,

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*References are in Appendix C.

not yet comparable to the accuracy of satellite measurements achieved on land, can be improved, satellites will offer the solution to many problems involved in operating on the oceans.

One outstanding potential advantage of satellites is that of reducing cost. The establishment of the marine control or datum could be made progressively or simultaneously in different areas using the same technique (satellite), with each separate chart datum referenced to the same geocentric coordinate system. The resulting economic benefit is obvious: the charts of today would be compatible with those which will be made in the future, thus eliminating the traditional and current problem of continual conversion of land maps from one reference system to another.

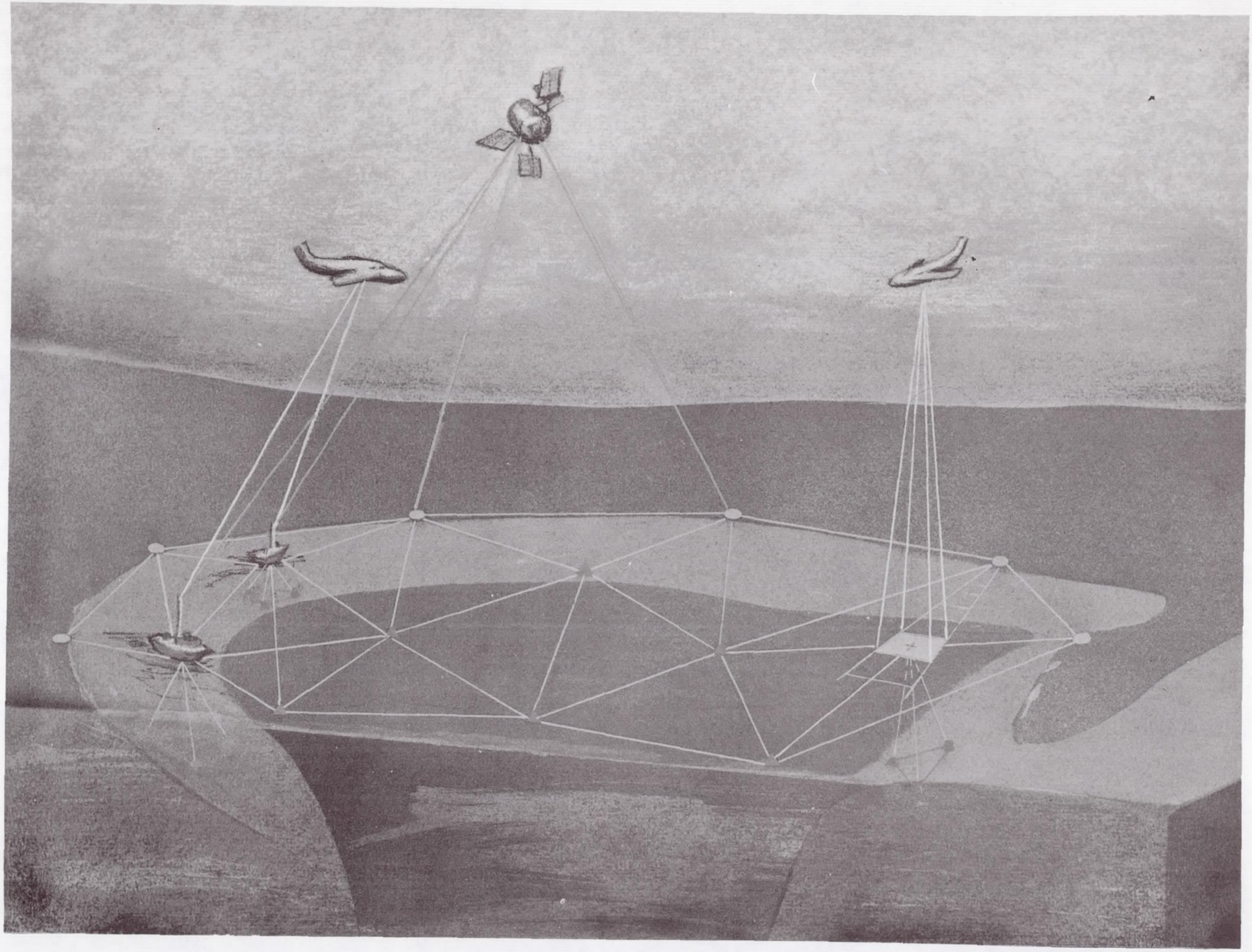

FIGURE 2. MARINE GEODESY

SECTION II

SUMMARY OF RESULTS AND RECOMMENDATIONS

On the basis of this study it appears that satellite-based systems offer capabilities that can play a significant role in meeting the requirements identified for precise positioning, establishment of geodetic control in the deep ocean, and overcoming some of the limitations inherent in other systems. Although no single system can meet all requirements, the potential for use of satellites, in varying combinations with inertial electronic or acoustic systems, or with geodetic control, appears to be limitless.

Table 1 shows the range of accuracy requirements identified in four specific areas. However, because of the various personal standards, evaluations, terms, and interpretations associated with accuracies, and because of the many types of ocean activities represented, these numbers pertain to a necessarily generalized and broad view of requirements. Moreover, it proved next to impossible to interpret expressed needs in some areas so that they could be presented uniformly. Nevertheless, despite the fact that Table 1 is general and far from complete, a valid picture of the situation is presented.

By and large, the numbers represent allowable errors in either determination or recovery of positions. Data obtained during the survey were not amenable to computation of standard accuracies such as circular, spherical, or map accuracy because no standard error components in the coordinates of points were cited. Individually, and collectively, the requirements identified provide strong evidence of the need for improving precise positioning capability at sea.

The results and recommendations presented here are arranged in the same way as the discussion of the related subjects in Sections III, IV, and V.

RESULTS

Requirements and Needs Identified

Three major requirements or needs common to all areas of interest were identified:

(1) Continuous positioning information with world-wide coverage, preferably with reference to a single system and with much less dependence on local shore control

(2) Greater positioning accuracy than obtainable at present

(3) Standards for evaluation of positioning equipment, measurements, and resultant products such as thematic data and maps.

TABLE 1. STATED POSITIONING ACCURACIES

Topic Area	Range of Accuracy Required, m	Range of Accuracy Achieved, m
Geodesy		
Control and Standards	10-30 (as good as land)	Not known
Geoid (direct measurements)	0.1-5 (in vertical coordinates)	Not known
Gravity measurements	50-200	200-600
Gravity base stations	15-50	Not known
Boundary determination	5-100	50-300
Surveying and Mapping		
Hydrographic and Bathymetric	10-100	60-600
Seismic	20-200	150-600
Gravimetric	20-200	100-300
Magnetic	60-400	300
Geologic	30-200	100-600
Oceanographic	20-1,000	300-2,000
Tracking		
Space	10-150	200-
Search and Rescue	10-20	12-200
Deep submersible	0.3-10	20-
Equipment Test and Calibration		
Acoustic	0.3-10	Not known
Electronic	1.0-100	Not known
Inertial	Near perfect	200-2,000 m/hr

Geophysics and Geology

Requirements identified with respect to geophysics and geology are:

(1) The ability to recover positions within the general limits of 30 to 100 meters

(2) The ability to recover positions within errors that are known

(3) The ability to employ a single worldwide system providing 24-hour-a-day continuous positioning capability.

Freedom from dependence on traditional shore-control installations, particularly in foreign areas, is also desired. Accuracy requirements for positions are 30 meters or less in situations involving lease boundaries, lease drainage, drill sites, geologic structure, or mineral recovery. Moreover, the urgency of the requirements is increasing as operations move farther out from shore.

Positioning accuracy actually achieved with present equipment and methods is generally not known because of lack of standards for evaluation, except when seismic tie lines are near. Except for ideal situations and near-shore operations, the accuracy achieved is often several factors less than required.

The use of satellites, singly or in combination with other systems, for solution to positioning problems in geology and geophysics is being viewed with great anticipation and enthusiasm. Satellites at present can meet range requirements and have 24-hour capability. Satellite accuracy has not yet been evaluated for geophysical exploration, but expressed errors of the order of 100 to 500 meters have been reported from other endeavors. Continuous positioning is not available with existing satellites. Marine geodetic control points are of considerable interest, but their capability and utility must first be demonstrated.

Hydrographic and Bathymetric Charts and Maps

Requirements identified for hydrographic and bathymetric surveying relate to the type, scale, and purpose of maps. Generally, these requirements are for improved accuracy in positioning and development of a means for geodetic control, particularly in broad ocean areas. Accuracies desired are 20 to 200 meters for large-scale maps between 1:2,000 and 1:40,000 and 100 to 200 meters for small-scale maps between 1:250,000 and 1:1,000,000. Emphasis was placed on systematic mapping of the oceans on a 1:1,000,000 scale and on the development of an operational marine geodetic control, preferably one using a single positioning or surveying system with one reference datum.

The largest single source of technical problems confronting surveying and mapping teams was identified as the uncertainty in the accuracy of positioning because of the lack of means for determining definitely the accuracy of positions at sea. Accuracy achieved was not known in most cases. Some interviewees indicated that often a repeatability of 300 meters, which was the maximum allowable error, was not achieved.

Satellite applications for ocean mapping are being viewed favorably, particularly for the deep ocean, to provide a reference datum. Satellite use in conjunction with other systems for continuous positioning is desired. The largest sources of errors in using satellites were attributed to error in determining the velocity of the ship. This will always limit to some degree the resultant position accuracy until the development of marine geodetic control points provides sufficient information that will allow the velocity of the ship to be determined. This will make possible the accuracy obtainable with satellite-based systems for the chart datum which is of such great importance. With such capability, survey patterns and procedures already employed to provide some internal consistency of charts and maps could satisfy most accuracy requirements.

Physical Oceanography

To derive more useful results from oceanographic measurements, a horizontal positioning accuracy of 200 meters in an earth-centered coordinate system anywhere in the world oceans is required. Numerous special types of studies require much higher accuracies on relative or local datums. With regard to vertical positioning, studies of mean sea level and many other oceanographic parameters require reference surface accuracies of 0.1 to 1.0 meter.

Satellite-based systems for horizontal positioning are looked upon with favor by those concerned with physical oceanography. Studies in satellite altimetry hold promise for determining reference surfaces and for comparisons of mean sea levels.

Tracking, Acquisition, Localization, and Identification

Tracking, acquisition, localization, and identification are involved in many ocean activities such as rescue operations. Both deep submersibles and space vehicles are dependent on accurate position information.

Rescue Operations. Requirements for rescue are very stringent and of high priority, particularly where international politics or national prestige and security are at stake. A need for position accuracies between 10 and 20 meters was revealed. This needed accuracy might be achievable with surface-based positioning systems under ideal conditions and near shorelines. However, because of the numerous positioning problems which have arisen recently during the search for lost objects and submarines, such as the Thresher and the nuclear weapon, interviewees expressed the desire for a positioning system independent of shore installations and available at all times on a worldwide basis. Establishment of an underwater grid system based on a bottom-marker system which can be located speedily and geodetically would help meet requirements. It was also indicated that the use of satellites and perhaps inertial systems with this underwater control system could possibly give the capability needed for search and rescue operations.

Deep Submersibles. For deep submersible vehicles a need was expressed for capability to relate the position of a sensor or data generated to a surface ship's position and with respect to the bottom. A need exists first to locate an object intermixed with topographic effects and second to return to that point as required. Simultaneous accurate positioning (0. 1 to 10 meters) in real time for surface, subsurface, and bottom vehicles and compatibility of equipment precision is also needed. An ultimate goal of the Navy Deep Submersible program is a positioning capability of 0. 1 meter.

Space Tracking. Requirements for horizontal positioning of Apollo ships are stated as ±300 meters 99. 95 percent of the time in an Earth-centered coordinate system and 20 arc seconds in ship attitude with respect to the true vertical. The need for establishment of a few marine geodetic control points in the Apollo ships' tracking areas with an absolute accuracy of at least ±150 meters and 5 arc seconds from true vertical has also been pointed out.

These needs can be viewed within the perspective of a few "super control points" to be used as ship-tracking stations. They could also be used with low-orbit satellites. Satellite orbit determination to an accuracy of ±1 meter seems to be becoming a realistic goal. Tracking capabilities, particularly in the southern hemisphere, are quite limited because of a lack of land areas for tracking sites. Marine geodetic control points are considered a possibility for providing such tracking capability.

Equipment Test, Calibration, and Evaluation

Requirements in this area relating to standards for test, calibration, and evaluation of positioning systems are also discussed in the section dealing with geodesy. A need to calibrate an acoustic positioning system of ±1 meter was indicated. The best available surface positioning system near shore is unable to satisfy this requirement. Moreover, the lack of standardization has caused misinterpretation of data reliability estimates and duplication of efforts to the extent that hardware has been modified to meet requirements as stated by different investigators.

A desire for the ability to use a systems approach in positioning operations was expressed. If such an approach is used, the various types of equipment and hardware employed (surface, subsurface, airborne, satellite, electronic, etc.) must be compatible and designed to operate in an ocean environment. Positioning accuracies of components should also be determined and evaluated using a systems approach.

Satellite use could also speed up information collection in the vast oceans. This rapid collection should be complemented by just as rapid a means of processing, analyzing, digesting, and evaluating the voluminous data obtained.

Geodesy

Precise Measurement Technologies. A need was identified for development of precise-measuring technology to be incorporated into all aspects of marine geodetic and oceanographic measurements, particularly to provide horizontal and vertical control on the sea floor for surveying, mapping, and other operations. The desired accuracy of measurements was often expressed by interviewees as equivalent to that on land. Whether or not this is achievable in marine measurements is yet to be determined. This cannot be established while standards at sea are lacking.

Marine Geodetic Standard. A need exists for establishing a geodetic standard at sea by which accuracy criteria and systems capabilities can be determined. A marine geodetic range, for example, could offer a "yard stick" for test, calibration, and evaluation of all types of positioning systems. Therefore, a marine geodetic range should be established and tied to the continental geodetic system. Major stations of the range should be so situated that short, intermediate, and long-range shore-based positioning systems can be tested, compared, and rated.

Marine Geodetic Control. No method of achieving an undisputed standard is envisioned that does not involve fixed geodetic control points at sea. Three or four of these points could form a useful marine geodetic range. Although the advantage of having marine control points would be numerous, as can be deduced from the usefulness of their counterparts on land, the hardware for their determination is not available and attainable and their accuracies are not known. Therefore, it is not possible to make evaluations and to definitely assess potential benefits. Whatever the hardware used and the design of marine control points chosen, they should be compatible with surface-based equipment and applicable for use by surface, submerged, and above-surface craft.

Although the accuracy at which marine control points can be established and the accuracy that can be achieved in their application are not yet known, potential users would like to have them placed in their areas of operation. Their possible use with satellite-based systems was often projected or stated as the ultimate in fulfilling the most stringent accuracy requirements, particularly for operations in deep water. A few of those interviewed were unfamiliar with the concept of marine control points, but they were aware of the advantages associated with land points and could infer the usefulness of such points at sea. Some indicated that they would like to see their capability demonstrated. Several indicated that they presently have no real need for marine geodetic control points; however, they said they would be able and happy to use them if they were available.

Boundary Determination. Disputes and litigation can arise over political boundaries and lease claims. A need exists for development of capability to mark and identify international, national, and local boundaries. A desire was expressed for having hypothetical lease boundary lines on maps correspond to actual bottom conditions. Marine geodetic control points could serve as the corner stones for identification. However, if such a system is to be completely operational and as good as the control-point system on land, the positioning capability needed for marking the lines between adjacent sea points must be developed. The areas of highest priority are those of immediate economic potential, nationally and internationally.

Gravity Measurements. Gravity measurements on a worldwide basis are required by the Department of Defense. The largest errors in gravity measurements at sea, whether measurements were obtained with shipboard or airborne systems, have been attributed to navigational uncertainties. Knowledge to 0.1 knot of E-W component in the velocity of surveying vehicle is desired. Open-ocean gravity base stations are needed for control, coordination, and improvement in the accuracy of ship-based and airborne gravity survey programs. Marine geodetic control points could serve ideally as gravity base stations. Positioning accuracy requirements for these stations have been stated as being between 15 and 50 meters. Satellites could be used in establishing these gravity base stations progressively and concurrently with marine gravity survey operations. Use of satellites could also make possible greater speed of operation, greater areal coverage, and probably greater accuracy.

Deflection of Vertical and Geoid. A need was expressed for the development and improvement of methods employing astrogeodetic measurements at sea from stabilized platforms aboard ships for direct measurement of deflection of the vertical and tilt in the sea surface. A need to obtain deflection of the vertical from inertial platforms and gravity measurements was also expressed.

There are also requirements for geoid determination at sea by direct altitude measurements from satellites to ocean surface. In addition, geoidal determination with satellite geodetic techniques and on the basis of surface gravity measurements is needed. Accuracy requirements of 1 to 5 meters are wanted by geodesists. In this area satellites hold promise for achieving requirements. Oceanographers, on the other hand, require even better accuracy (0. 1 to 1 meter). This must be a goal of the future, however, when satellite-based equipment becomes more refined.

Major Positioning Systems Available

Over 100 positioning systems have been or are in use at sea. They can be classed into five groups:

(1) Electronic
(2) Inertial
(3) Acoustic
(4) Celestial
(5) Satellite.

Analysis of the results of the study indicates that no single system can meet all the positioning requirements stated for the many ocean operations and missions of interest. Except for the continuity criterion, the Doppler satellite system apparently comes the closest to satisfying many of the stated requirements. The Apollo tracking ships contain many sophisticated positioning systems, including Doppler, radar, inertial/star trackers, and bathymetric systems. These could be of great importance for future marine geodetic applications.

Electronic Positioning Systems

Several types of surface-based electronic systems are used to position oceanographic and survey data which are ultimately displayed on maps and charts in terms of geographic coordinates. The positions assigned to these data, whatever the position fixing method and datum involved, are either converted to or arbitrarily assigned as geographic coordinates. Electronic positioning systems are subject to range, environmental, and/or geometrical limitations which act singly or in varying combinations to degrade the quality of positioning data.

Generally speaking, the rated capability of high-frequency systems is commensurate with or exceeds most of the accuracy requirements identified during the survey. Reported positioning capabilities vary between a few meters to 50 meters at distances 50 to 75 miles from shore. However, even at such distances, the occurrence of errors and uncertainties in positioning is not uncommon. Beyond 50 to 75 miles from shore, it is questionable whether or not the position fixes of most systems are of sufficient accuracy.

In the broad ocean areas only low-frequency and very-low-frequency systems such as Loran and Omega are available. These systems are used primarily for navigation. Reported positioning capabilities at long ranges vary between 200 and 2,000 meters.

At present there is seldom any independent means available for absolute accuracy determination and operational evaluation of electronic and other systems. Moreover, the lack of redundancy and the need for repeated observations are other factors affecting the evaluation of positioning data obtained. In general, positioning accuracies achieved are unknown and cannot be determined; only relative comparisons of systems are sometimes undertaken.

Inertial Systems

Inertial systems are looked upon favorably and can perhaps play an increasing role in future positioning and surveying programs. In particular, they can be useful for ship-velocity determination, continuous positioning between control points, and satellite fixes. Therefore, they have the potential for meeting the often-stated continuous-positioning requirements. Inertial platforms in current use accumulate errors with time due to gyro drift even in the absence of vehicle motion. Therefore, periodical updating of position information from external sources is necessary. The accuracy of inertial systems is affected by gravity, the accuracy of the external system used to update position information, and the frequency of resetting. Information obtained must be carefully used and corrections must be made for deflection-of-the-vertical effects if they exceed accuracy specifications. Growth rate of errors in information obtained with unclassified inertial systems was reported as between 200 and 2,000 meters per hour.

Acoustic Systems

For the purposes of this study the primary interest in acoustic systems is for local positioning, i.e., relating ship position or surface instrument-vehicle position to bottom-mounted acoustic transponders. Acoustic systems for geodetic application have not been fully evaluated. They have been used for local navigation and for search and recovery operations. Their use in surveying and mapping is just beginning. Reported rms errors in relative positioning of a ship with respect to underwater transponders are between 3 and 10 meters, with extremes of 50 to 100 meters.

Celestial Systems

A celestial system which has found application on board ships and is worthy of mention is a star-tracker system. Such a system is used on Apollo ships coupled with SINS. Potential application to marine geodesy has not been evaluated.

Satellite Systems

Results of the application of satellite methods are given in the following section which relates specifically to the GEOS-II satellite, the components of which represent five major methods. The GEOS-II contains Doppler equipment, the equipment on which the Navy navigation satellite system is based.

GEOS-II Satellite Capability – Application to Marine Geodesy and Positioning

The GEOS-II satellite, which was designed for land-geodesy purposes, contains the five major types of satellite equipment: Doppler, SECOR, radar, optical, and laser. All five were investigated for their possible application to precise ship positioning and establishment of geodetic control at sea. The main criteria used in evaluating the capabilities of these satellite methods are accuracy, areal coverage, and continuous positioning. Results of the study reveal that only the Doppler method offers potential for meeting the requirements of both positioning and control points establishment. For continuous positioning, however, a system of 24 Doppler satellites would be needed.

Doppler Method

For precise positioning, the Doppler satellite is the only operational system with which considerable experience has been obtained at sea. Present geocentric positioning accuracy is reported to be between 200 and 400 meters. It appears that for the near future use of the Doppler system in ship positioning will be accuracy limited to 100 to 150 meters, assuming that ship velocity is known to about 1/4 knot. The most serious accuracy limitations result from errors in extrapolation of orbital elements, from uncertainty about earth parameters, and from incorrect determination of ship velocity. The first two types of error are constantly being reduced. The ship velocity error, the largest, is a function of the geometry of satellite pass and is affected by ocean currents. The measured velocity of a ship going through water is not its true velocity over the earth. This error has been estimated as 400 to 1,000 meters at a velocity of 1 knot. Therefore, to improve the accuracy of Doppler positioning, errors in ship velocity must be minimized.

Existing satellite systems have worldwide coverage capability, but give position information only at fixed intervals. This does not satisfy the requirements of most surveying teams for continuous positioning. Either a system of 24 Doppler satellites or the use of existing satellites in conjunction with inertial, acoustic, or electronic positioning systems is required.

For establishment of geodetic control at sea, the Doppler method offers great potential for overcoming the limitations due to continuous positioning and uncertainty in ship velocity. In this case, positions at fixed intervals would be satisfactory. Fortunately, the use of bottom-mounted (fixed) underwater acoustic transponders, possibly the main elements of the desired marine geodetic control points, could make feasible determination of the true velocity of the ship over the earth. Furthermore, several satellite passes could be made over a period of time while a ship is positioned with respect to a bottom control point (local datum); thus allowing calculation of statistical averages. With this approach, the accuracy of the Doppler method can be improved by an order of magnitude. Accuracy approaching that achieved on land could be obtained to satisfy the more stringent requirements (10 to 50 meters) of marine geodesy.

SECOR Method

The SECOR method, unlike the Doppler, has not been used at sea for precise positioning. However, several approaches for its application at sea have been proposed. These approaches involve adaptations of the basic SECOR ranging technique. Unfortunately, the present cost and great size of a SECOR setup restrict its practical application by most potential users. Also, three satellite positions obtained from two different satellite orbits would be required for a position fix. This would limit use of SECOR while the ship is in motion.

For establishment of marine geodetic control, SECOR could present an opportunity. Since the highest precision is required for establishment of control points, the use of several independent measuring methods is desirable. The SECOR setup already exists on land and the GEOS-II satellite also contains a SECOR transponder. An experiment with this method at sea might prove useful if it could be conducted without excessive cost.

Radar Method

For precise ship positioning, only the ranging mode of C-band or S-band radar offers potential. For certain classes of ships, such as the Apollo ships which have radar on board, radar could be used as a back-up system for SINS/star trackers because of their small random error in range measurements (1 to 9 meters). As with SECOR, use would be limited while the ship is in motion. For establishment of marine geodetic control, the ship would be kept on station for a few days and several passes could be obtained.

Optical Method

For precise ship positioning the optical method, although having the advantage of using either types of active or passive satellites, appears to be impractical because of complexity of equipment, the need for favorable weather conditions, and the long time required to obtain observations and reduce data.

With respect to establishment of marine geodetic control, limited experiments have been performed on ships, and the results obtained indicate definite potential for such application. Accuracies of 10 to 20 meters in ship station location with respect to the North American Datum have been reported. The limitations of the method are not as serious in this case as in the case of ship positioning.

Laser Method

For precise positioning the same limitations are inherent as in the optical method. In addition, there are other limitations due to the narrowness of the laser beam.

Because knowledge of station coordinates would be only approximate, use for precise positioning would be restricted.

The use of laser method for establishment of geodetic control is just becoming operational on land; therefore, no attention has been given to its application at sea.

RECOMMENDATIONS

The following recommendations are made on the basis of information obtained and requirements and needs identified during the study:

(1) Precise geodetic measurement capability at sea should be established. On the basis of this capability, standards for testing, evaluating, calibrating, and comparing marine positioning and surveying systems should be developed. Efforts should be so planned that a marine geodetic range able to serve a majority of economic, defense, and other interests will be provided.

(2) A program to determine experimentally the feasibility of using GEOS-II satellite capability to establish a marine geodetic control point should be planned and carried out under controlled conditions that will permit meaningful evaluations of methods, systems, and off-the-shelf equipment. An Apollo ship would be ideally suited for this experiment from the standpoints of availability of appropriate on-board equipment and current mission accuracy requirements.

(3) Positioning capabilities should be expanded to involve multiple-system use. For example, satellite-based equipment could be used with geodetic control points at sea, inertial systems with these control points, satellite-based equipment with inertial and acoustic equipment, and satellite-based equipment with surface electronic equipment.

(4) The possible advantages of launching additional satellites to provide more optimum combinations of areal coverage and greater frequency of fixes (approaching continuous positioning capability) should be explored.

(5) Concentrated efforts should be devoted to referencing all ocean mapping and surveying to one datum.

(6) In collaboration with other organizations, NASA should make efforts to bring about some standardization in the expressing of accuracy ratings, requirements, and achievements.

SECTION III

REQUIREMENTS AND NEEDS - PRECISE POSITIONING AND MARINE GEODESY

Describing the positioning requirements associated with the many objectives and missions of the various organizations working at sea involves discussion of many permutations and combinations. The requirements described in this section are more appropriately considered as needs of individual organizations than as formally established requirements. The lack of formal agreement concerning what is needed is not surprising. Many thousands of people with a great variety of interests are engaged in collecting data at sea. Although annual multimillion-dollar expenditures are involved, the diversity of interests makes identifying common interests difficult.(32)

With some notable exceptions, correspondingly great interest apparently has not been shown in: (1) assessing the effect of positioning errors on the integrity of data and (2) maximizing the utility of the data from both the technical and economic standpoints, taking into consideration the facts of obsolescence and the large number of potential users of specific types of data. Testimony to this is the dearth of published material relative to positioning accuracies actually being achieved.

Development of a rationale concerning the significance of positional errors for the integrity of thematic data portrayed in terms of geographic positions on charts and maps seems to have been largely neglected in the literature. In contrast, analysis of discussions with numerous people (see Appendix A) suggests that they are concerned and that rationales do exist or have started to evolve.(86) The results of the survey represent a beginning toward formalization of requirements. In addition, the survey revealed a requirement for developing and applying standard evaluation criteria.

Most of the information relating to accuracy compiled during the survey is based on different standards and represents a wide spectrum of terminology. The numbers obtained can not be converted in terms of circular, spherical or map accuracy standards as defined by Greenwalt.(33) Therefore, it was considered best to report accuracy numbers as stated. Sometimes these accuracy numbers pertain to needs, sometimes to equipment ratings, and sometimes to achievements. In the field, however, operators have not been able to obtain the accuracies they have been led to expect by equipment ratings. Therefore, their needs are unsatisfied. Although requirements stated can not be readily interpreted in terms of an absolute assessment of needs, particularly for horizontal positioning, they offer proof that the technical community desires improved positioning capability. The numbers are valid in that they reveal a real gap between what is needed and what has been achieved. The scope of the anticipations associated with the Doppler satellite method of navigation and position fixing is concrete evidence of the desire for standards.

Discussions of the requirements for marine geodesy and precise positioning are presented as much as possible within the context of the following topics:

(1) Geophysics and Geology
(2) Hydrographic and Bathymetric Charts and Maps
(3) Physical Oceanography

(4) Tracking, Acquisition, Localization and Identification
(5) Equipment Test, Calibration, and Evaluation
(6) Geodesy

GEOPHYSICS AND GEOLOGY

The geologist, geophysicist, and those interested in soil mechanics deal with bottom and subbottom data versus position. All have the task of referring these data to a ship position. The ship, in turn, is positioned by one or more methods in some type of horizontal coordinate system.

Requirements

Positioning requirements vary according to the purpose and objectives of the surveys, both quantitatively and with regard to continuity (continuous positioning, day, night, etc.). In many cases, the most stringent needs were stated as recovery of a position after various time intervals, up to five years after initial surveys. Representatives of the industrial community characterized permissible errors in this need in several ways – "the best we can get", "reoccupy the same position", "±15 meters, ±30 meters", "±50 meters", "±100 meters", etc. This is particularly true in exploration for oil and gas, for which purpose the stated needs usually fall between the limits of ±30 and ±100 meters of error in recovery of position.

Members of the scientific and academic communities were often less explicit than industrial representatives, but some needs were described as "±30 to 60 meters recovery of position", "rms 15 to 30 meters in geographic coordinates", "±50 meters recovery when important features are discovered on ocean floor", "surface position ±1000 meters relative", and "±30 meters geographic". One user stated that an accuracy of 1 mile would be sufficient for gravity work.

Requirements in geophysical exploration have been treated by Burg.(21) For seismic work, for example he states the following:

Geodetic location – repeatability accuracy CEP
500 feet, 95 percent of the time

Position fixing – sequential position fixing
accuracy CEP 50 feet, 95 percent of the time,
20 feet preferred

Service area – 200 miles from the coast,
400 miles preferred

Utilization – 24 hr/day, all weather conditions.

These requirements are not being met. Burg has also pointed out that the performance of shipborne gravity meters has been improved to the point where accuracy is controlled by errors in determination of Eötvös effect. To meet minimum requirements, ship heading should be known to better than 1 degree and ship speed to 1/6 knot.

Oil and mineral leases are issued on the basis of acreage blocks defined by grid lines constructed and superimposed on a map in accordance with map projection procedures. These are hypothetical lines representing geographical coordinates in that their traces and intersections are not identifiable with physical markers or topographic features. In addition to the needs expressed for recovery of position, needs were also stated in terms of locating drill sites with respect to lease boundaries. In this case, actual geographic positions are desirable in order that drill sites are not closer than legally specified distances (often 300 feet) from a lease boundary. This is significant from several view points including the possibilities of leasing wrong blocks and drilling at wrong locations or in wrong blocks. It is also important when producing fields are located in more than one lease.

It is desirable when "staking" the location for drilling that the site, when possible, be positioned by relatively accurate optical or microwave methods. These methods necessitate line-of-sight observations between the site and offshore platform or land stations previously tied into geodetic control. Depending on the situation, this method can introduce uncertainties if the platforms and land stations are in geodetic system of coordinates and the drill site is selected on the basis of a geological structure compiled from data at many points positioned by electronic coordinates. Each of these points has an unknown geodetic error that arises from unevaluated combinations of range, geometry, and environment. Accordingly, the actual drill site could be staked at an unfavorable location if the geological structure is shifted (or distorted in shape) because of unknown bias (or varying geodetic error at each data point) in electronic coordinates.

Seismic lines can be run to check on the above situation. Also seismic tie lines are run during the surveying and exploration stage as a check to eliminate discrepancies in data. In either case, this is an added expense.

Other problems are unique to exploration in foreign areas. These include positioning equipment available, lack of land control, additional expenses of operating overseas, etc. In areas not covered by short-range surface systems costs can amount to $30,000 per month to install and operate equipment over and above costs of establishing land control, all within the assumption that foreign countries are cooperative and will permit land installations.

Requirements in geophysical exploration can be summarized as the desire for a single type of positioning system for all areas with errors in recovery of position within 30 to 100 meters or better, but first and foremost with errors that are known. Within limits, errors that are known can be taken into account in a methodical manner. The system should have 24-hour-a-day continuous positioning capability, have long-range coverage, and not require shore control stations (in the same sense as surface-positioning systems). Requirements for scientific work are similar. Positioning within 30 to 100 meters is wanted. Requirements for geographical accuracy were not too numerous but with one or two exceptions were between 15 to 30 meters.

Costs Arising From Errors in Position

Costs arising from positioning errors are not known. Examples have been reported, however, of test drilling being done in the wrong lease block; the wrong drilling could represent losses up to $2 million. If discrepancies in geophysical interpretations occur and can not be eliminated, it is necessary to perform additional surveys which can cost about 5 to 10 percent of the original survey costs. Associated costs fall between extremes of $50,000 and $1,000,000 per situation. From partial resurveys, when errors are discovered to be not too serious and when they have a systematic character, the cost of readjusting survey data from an area can range up to $100,000. Other examples of costs arising from positioning errors include the leasing of wrong blocks with associated costs of lease, surveying, and data analysis.

Accuracy

Positioning accuracy being achieved is generally not known and not evaluated. Only relative comparison of one method or system to another is usually possible. Areas close to shore have coverage available from electronic systems whose repeatability capabilities are usually stated to be about 25 to 50 feet or less over ranges out to about 50 to 75 miles from shore. Yet, the requirements for geophysical surveys, as stated above, usually are between 100 and 300 feet, and thus are less stringent by an order of magnitude than the rated system capability. Accordingly, if these numbers are reasonably correct, there should be, seemingly no problem with regard to recovering a position. The reasons for these apparent discrepancies possibly stem from a combination of factors, e.g., range, geometry, and environment; resolution or repeatability of geophysical methods; care and checks exercised by operators, plotting errors etc. Perhaps one of the most important factors is that system capabilities can be rated under idealized and controlled situations whereas the systems must be used under much less than ideal conditions.

The conclusion to be drawn regarding accuracy is that the present concern over errors in positioning is based on experience utilizing the most capable surface systems available under least stringent range conditions, i.e., at distances from shore less than 50 to 75 miles. Accordingly, a greater concern is that the distance from shore of the areas being subjected to economic exploration and development is constantly increasing. Oil production capability now exists to 600-foot depths. Drilling capability exists in much greater water depths. Technology-wise, then, oil and gas can even now be produced from 600-foot depths. In terms of distance, this includes areas of 200 to 400 miles from shore. The magnitude of errors at these distances can be expected to increase by several factors up to an order of magnitude. Every 100-foot increase in depth capability can increase these distances considerably. Oil companies now hold leases in 1200-foot waters.

Satellite Applications

The use of satellites for solution to positioning problems is being viewed with great anticipation and enthusiasm. Satellites at present can meet range requirements and have 24-hour capability because they are not environment limited. Satellites have an additional attractive feature in that all surveying data could be placed on a common reference system.

Satellite errors are expressible in terms of geocentric position. Opinions differ on the current maximum error magnitudes of a satellite used in the position-fixing mode, but generally they are considered as between 100 and 500 meters. If ship speed can be determined to within about 0.1 knot, the associated error under favorable conditions is reported to be reducable to about 40 to 50 meters. These latter values are about the same magnitude as other error components involved in a satellite fix (e.g., orbital, earth coordinate system, etc.).

On this basis satellites begin to approach only the upper limit of the 30- to 100-meter requirements in the ability to recover a position. If ship speed is known then the situation is greatly improved. Operationally, the use of only satellites to reoccupy a position has additional limitations, i.e., the time required to navigate and maneuver a ship to reoccupy a given position in an area of interest versus the time interval of and between a satellite pass.

Satellites have the potential to provide near-continuous positioning capabilities anywhere in the world if a sufficient number of satellites are in proper orbit simultaneously (e.g., a postulated 24-satellite system). At present, minimum time possible between fixes is in the neighborhood of 1 hour.

As would be expected, there is no single solution to all positioning problems. Rather, the answers lie in a series of solutions, often involving multiple systems to match specific types of requirements, e.g., satellites used in conjunction with surface-based positioning equipment, inertial systems, Doppler sonar, or acoustic beacons.

Marine geodetic control either in the form of a geodetic range (standard) at sea or of a temporary point(s) in an area of operation established by satellite or airborne distance-measuring methods are viewed as possible partial solutions, e.g., the use of such control for positioning in conjunction with inertial or satellites methods and for absolute comparison of surface-based equipment. In essence, then, numerous combinations of possibilities remain to be explored, evaluated, and optimized before available state of the art is exhausted. Applications of satellites constitute a significant part of this state of the art.

HYDROGRAPHIC AND BATHYMETRIC CHARTS AND MAPS

Probably the most important requirements for scientific investigations and effective exploration and exploitation of the oceans and their resources lie in the availability of accurate maps and charts. The most important criteria by which the value of maps and charts may be judged are their accuracy, adequacy and clarity.(45, 20) Accuracy depends on quality of field surveys. A nautical chart or a map cannot be more accurate than the hydrographic or bathymetric data from which it is compiled. In turn, these criteria depend on the availability and quality of geodetic control and the positioning systems used.

The distinction between hydrography and bathymetry is not constant among the basic treatises on these subjects. In some cases, the terms seem to be used interchangably. In general, however, hydrography refers to collection of basic data used to compile charts for the navigator showing point depths, shoal waters, currents, channels, hazards to navigation, etc. Also hydrographic surveys often refer to surveys within the 200-meter or 100-fathom line. Bathymetry usually deals with collecting depth data in order that the bottom can be contoured. Traditionally, bathymetric surveys have been associated with areas of deep water, but this need not be the case, e.g., C&GS 1967 series of bathymetric maps off the California Coast. Whatever the distinction between the two, both require the same type of basic data, e.g., a reference datum, geodetic control, and precise positioning.

Most of the U. S. nautical charts are based on the adjusted North American Datum which in turn is based on the Clarke's ellipsoid. This ellipsoid, however may not be a best fit for the vast ocean areas. For most U. S. hydrographic surveys, horizontal geodetic control which provides their datum is based at least, on third-order triangulation. Vertical control datum for depth and height measurements is determined by tidal measurements referred to Mean Low Water (MLW), Mean Lower Low water (MLLW) or Mean High Water (MHW).(45) In conducting hydrographic or bathymetric surveys, two important operations: (1) measurement of depth (soundings), and (2) determination of horizontal positioning are carried out simultaneously. Using the various positioning systems discussed in Section IV, marine surveys lead to maps and charts on which are displayed thematic data referenced to geographic coordinates.

Requirements

Mapping requirements vary according to purpose and scale. Most of the requirements were expressed in terms of needs for: (1) several types of maps of varying scales, (2) better positioning system accuracy, and (3) development of a means for better geodetic control, particularly in the broad ocean areas. Several statements were made in regard to map-accuracy requirements which varied from specific numbers of ±20 meters to ±300 meters to more general statements such as "as high as can be obtained approaching that of land requirements".

Increased numbers of surveys are being conducted and there is a trend toward larger scale maps and charts and greater detail surveys for use by numerous enterprises performing a variety of missions. A need was expressed by several organizations for several-purpose maps of large and medium scales. These maps ranged from scales of 1:2,000 to 1:40,000 with corresponding positioning accuracies (sometimes stated as standard map accuracies) of ±20 meters to ±200 meters for mineral exploration, deep submersibles, search and recovery, military and other uses. Smaller scale maps from 1:250,000 scales to 1:1,000,000 with corresponding standard map accuracy of ±200 meters for general use were also indicated. It was further stated that to achieve a 200-meter map accuracy, observations must be made to better than 100 meters. Since maps cannot yet be established overnight, as one investigator indicated, plans for actual systematic mapping of the ocean floor should start as soon as it is practicable. This observation is based on the results of an international conference on mapping which indicated that only 15 to 20 percent of existing ocean maps at the 1:1,000,000 scale may be "usable", and that even coastal maps in some foreign areas suffer the same problems.

Hydrography is usually applied progressively from the largest to the smallest scales delineating as much as possible certain information. Therefore, it may not be possible to establish the smaller scale maps before the larger ones.

One of the basic requirements for mapping is accuracy in positions. Obviously, a knowledge of the depth is useless for charting purposes without the knowledge of the geographic position at which the depth was measured. Therefore, a need was identified not only for continuous positioning information for depth soundings and in real time but also an instantaneously translatable electronic or other coordinate to geographic coordinates of maps. Often it was reiterated by some experts that the largest single source of problems confronting most marine operations and particularly mapping is the uncertainty in the accuracy of positions and that there are no means at present to definitely know the accuracy of positions at sea. Position accuracy requirements for maps varied according to map scales, but it was stated as a rule of thumb, the observational accuracy should be at least about one half the map accuracy requirement. For small-scale mapping, ±50 meters was stated as "more than we can dream for now". Accuracy of 10-25 meters may be desired for important areas, but these are for engineering scales and relative accuracy within the local area is all that is needed. Another operator involved in hydrographic mapping stated that the positioning requirements imposed on his operation are about ±15 to 20 meters in the broad ocean areas. Minimum acceptable accuracy is 300 meters which is often difficult to get.

The need for precise positioning capability is also expressed as the limiting factor in present systems for achieving the required accuracy particularly in broad ocean areas. To overcome some of these limitations a trend to use several positioning systems and impose several survey patterns is developing for precision surveys in the deep ocean. The purpose is to make these surveys at least internally consistent by applying adjustment procedures. The problem, of course, still remains as to where the survey is located on the earth's surface and with respect to another survey. By no means is the need for accurate positions universal for all missions. However, the opinion was often expressed that positioning requirements should be looked at in terms of all users collectively, with varying interests, rather than in terms of individual and parochial needs. Extreme accuracy out in the middle of the oceans by individuals or a single group may seem difficult to justify. It is doubtful perhaps, except for national defense, that any single operation or mission can justify the costs involved with highly accurate measurements in the open oceans. However, the U. S. alone is making measurements with over 100 oceanographic ships which are operated by various organizations and agencies for different purposes at a cost of $500 to $6000 per day for each ship. Some, by the nature of their work, have more stringent requirements for accurate positioning than others. These would represent a sizable total effort and expenditure. Therefore, in terms of total national interest the data obtained should be of such quality to satisfy the widest scope of present or future users interests. An interested user indicated that out of every four ships with oceanographic missions only one is involved in hydrography. Most of the oceanographic ships could make excellent survey platforms. Because of time and associated costs involved in marine surveying and mapping operations, oceanographic ships should have multimission capability.

Requirements for the development of marine geodetic points to control ocean surveying and mapping were expressed by practically all people directly involved in these operations. Some indicated that they have used underwater acoustic transponders for local control in detailed surveys which proved to be better than bottom features. However, their problems still relate to where the surveys are located geographically.

The importance of marine geodetic control was often compared to that of land. For example "at present there is no dispute about the need for control on land, why should it be any different at sea? Control points at sea in an area of operation are definitely desired". Others pointed out that the development of procedures for systematic ocean mapping in which positioning is coupled with marine geodetic points could be summed up as "otherwise we will have wildcat operations with everyone going in his own direction".

A need for identifying datums of various maps was also expressed, particularly, for foreign areas. The datum should be the same for near shore and for distant areas at sea.

General priority areas requiring accurate mapping are listed as continental shelf, slope, deep water, starting first with U. S.

Accuracy

The accuracy achieved was often not given because of lack of a standard for comparison or because the user did not know how to evaluate it. However, general statements indicated dissatisfaction with accuracies being achieved in the open ocean for detail work. One user stated 500 feet (150 meters) as repeatable accuracy was achieved using the best system (used most existing systems) compared with prominent bottom features. In special cases when repeatability of 300 meters (maximum allowable) was not achieved, the survey ship moved to a new location and started over again. In terms of cost this was estimated as a loss of about $5000 per day.

Generally speaking, most users were satisfied with existing positioning systems up to distances of 50 miles from shore even in some detailed surveys where geometry of systems were good. Beyond about 50 to 75 miles from shore, however it appears questionable whether the majority of electronic systems could meet the positioning accuracy requirements, particularly for large-scale mappings. As distances increased further to sea only the Loran and Omega positioning systems had the range capability but nowhere could they meet the accuracy of ±50 to 150 meters required for large scale maps.

Although some standards or rather specifications for hydrographic and bathymetric maps are available, only qualitative evaluation could be made by examining such factors as geographic datum, depth, plane of reference, purpose and character of survey, compilation procedures, etc. The U. S. proposed international accuracy standards(45) for hydrographic surveys are stated in terms of:

(1) Maximum errors for depth measurements

(2) Scale of surveys for coasts and oceans

(3) Spacing for intervals of sounding lines

(4) Frequency of interval of plotted soundings

(5) Sampling of bottom characteristics

(6) Position fixes (maximum spacing, maximum plotting errors and location of shore control)

(7) Reference of soundings to vertical datum.

Application of Satellites

Satellite applications to mapping operations were viewed favorably by most users particularly in the deep ocean. The use of one system such as the satellite to position the soundings and to establish the needed horizontal geodetic control would place all surveys and resultant maps on one datum and relate them together to a specified accuracy. Hence, the propagation of errors could be controlled and well distributed by adjustment procedures.

The use of different systems in positioning and datum reference of charts create additional problems which if not corrected could result in large errors. For example positions obtained by the Doppler satellite or astronomic methods refer to an earth centered reference system. Current maps based on electronic positioning are on the North American Datum which is based on the Clarke's ellipsoid. The two reference systems may differ considerably. A need exists, particularly in foreign areas, to identify the datum reference used on various charts and maps.

Not to be overlooked also is satellite capability to provide vertical control. Satellite altimetry, if successful could be very significant in deep ocean tide measurements. Contrary to the old belief that tides are negligble in the open ocean, values as high as 5.6 feet (quite significant) were discovered in an experiment by C&GS at distances of 100 miles from shore.(10, 41)

In summary, satellites can offer several advantages:

(1) Range can be extended to any distances

(2) Singular horizontal datum can be provided to all surveys

(3) Geocentric coordinate (absolute) system can be obtained

(4) Accuracy of the order of a magnitude or better than obtained by VLF and celestial fixes can be achieved.

PHYSICAL OCEANOGRAPHY

The ocean waters constitute a dynamic environment. The validity of their description rests upon the ability to ascertain, measure, or compute environmental descriptors (dependent variables) as a function of position in a three-dimensional coordinate system and of time. Problem solutions are sought either in terms of observations at given positions with time varying, or at instants of time with positions varying.

Requirements

Oceanographers characteristically have worked with one to five miles horizontal positioning capability in the open sea. Although not satisfied with this capability, they have "to get on with the tasks at hand" using whatever means of positioning that are available. As a result, limits in what they can do with their data has prevented them from maximizing the benefits of oceanography.

Oceanography deals with variables whose utility and benefit are sensitive to errors in position. The significance of this sensitivity, and thus positioning requirements, depends upon many factors including status of knowledge, objectives, phenomena being investigated, and map scales. Today's oceanographic literature abounds in research marking the transition from an era of gross areal or world-wide descriptions of the oceans to one of more detailed and comparatively minute descriptions of a local or regional extent. Evolving therefrom are more stringent needs for precise horizontal positioning at sea. As a general case, a horizontal positioning capability of at least 200 meters is needed for oceanography. As this capability becomes available, the utility and benefit of oceanographic data will increase in a proportional manner.

In underwater sound propagation studies, there are numerous variables affecting results, for applied and practical purposes. Assessment and evaluation of these results can be greatly improved if the distance or position variables can be held constant or accurately evaluated. Acoustic positioning is playing a greater role in the execution of numerous operations. Needs were expressed in various ways, e.g., positioning bottom installations to circular standard error (CSE) of ±50 feet relative to land points; positioning within an earth coordinate system, or positioning relative to features on the ocean floor. In some cases the requirement is more stringent by an order of magnitude.

Missions involving deep submersibles as a research or operational platform are becoming more numerous and complex. The success of some of these missions requires precise positioning in the horizontal and/or vertical with variations being positioning with respect to a surface support ship or to the bottom. Somewhat akin to this is the problem of determining positions for data obtained from measurements or sensors remote to a surface ship. As a ship is conducting a survey, ability to relate the position of the remote sensor or sensed data to the ships position determines or limits the ultimate usefulness of oceanographic data. This problem can become critical at large surveying scales.

Among the myriad of other activities in oceanography is the use of floating buoys to study ocean currents and of tracer dyes in diffusion studies. Problems in horizontal positioning can limit the effectiveness of these types of investigations.

Turning now to the vertical coordinate, referencing measurements at sea to a level surface has constantly plagued the oceanographer. Oceanographers work on or from a physical sea surface which departs in a time-dependent manner from an equipotential surface, e.g., the geodesist geoid, in four ways: periodic, synoptic, climatological, and secular departures.(97) The mean sea level is another surface of great interest. Although often called an equipotential surface, this is not strictly true because of differences in water densities and the effects of long term meteorlogical conditions. The Coast and Geodetic Survey readjusted 50,000 miles of continental first-order leveling holding fixed a single mean-sea-level station. Results showed that the Pacific Ocean at the west coast of the U. S. is higher by an average of 2 feet than water at the Atlantic Ocean and the Gulf of Mexico coasts.(40) Precise leveling across Panama gave height difference of 18 and 22 cm between the Pacific Ocean and Caribbean Sea sides.(40) Running a level line across a body of water is a different matter, however, and no method exists at present for comparisons of mean-sea-level datums across oceans and between islands.

The geodesist would like to know the geoid to 1 meter or less but would be reasonably satisfied with 5 meters on a worldwide basis. The oceanographer on the other hand needs to determine a mean sea surface to within a few decimeters or less. Using the Gulf Stream as one example Knauss, in some geostrophic calculations, showed that reducing slope value by one part in 18 (10^{-6} radian in this case) changed the computed volume transport by about 1 part in 4.(54) Further reduction in the slope by 10^{-3} radian caused a further change in transport in the same direction by about 1 part in 5. Moreover, this second change also introduced a counter current with transport in the opposite direction.

A direct method of determining volume transport reported by Richardson and Schmitz utilizes differences in position to compute a distance.(84) Considering this as the only source of error in the method, the relative error in volume transport is approximated by the relative error in the distance separating the points of submergence and emergence of the instrumentation. In areas covered by precise short range position systems this source of error should be quite small, the chief problem being operational in that position fixes of points of emergence and subsequent emergence downstream are made with respect to instrumentation on the boat. Error could increase to serious proportions if other than the most precise positioning equipment is used, e.g., at greater distance from shore, unless the downstream run of the instrument is increased. This in turn, however, would defeat the purpose of the method if much detail is to be retained.

Von Arx, in several works, has devoted much attention to the value of and need for a level reference surface at sea and for ability to determine regional sea-surface slopes.(95,96,97) Illustrating the difficulty of the problem, he cites sea-slope magnitudes to be expected from synoptic influences. These range from 10^{-10} to 10^{-4} radian (1 arc second is equal to about 5×10^{-6} radian). Using an inerto-optical technique, Von Arx reports sensing the direction of gravity at sea with an accuracy of 5×10^{-5} radian or about 10 arc seconds, and hopes that the future holds an improvement by two orders of magnitude to 0.1 arc second. If so, using direction of gravity as a vertical reference, he foresees the possibility in the future of measuring, by his technique of observing the horizon, sea surface slopes whose magnitudes are larger than 1 arc second.

Application of Satellites

The use of satellites as a platform for optical and microwave altimetry over the oceans is under investigation for application to determination of surface slopes, reference surfaces, and geoidal studies at sea.(6,34,62) The ultimate success of these methods will be determined by knowledge of the geocentric distance of a satellite and by the accuracy achievable in measuring the height of a satellite above the sea surface versus the magnitude of quantities sought, their rates of change, and the scale of interest. At present, the possibilities of measuring satellite heights above the sea with an rms error of ±1 meter are viewed with optimism.

Over the oceans the amplitude and wavelength of geoidal undulations derived from satellite methods represent smoothed features of the geoid. Thus, if by satellite altimetry, a surface of mean sea level can be determined the resultant will be an improvement over present knowledge of the geoid provided that the sum of differences between the geoid and mean sea level and of the errors in satellite heights is less than the errors in knowledge of the geoid.

Approaches in satellite altimetry include assignment of a statistically determined value to each of numerous areas (e.g. 1 x 1 degree, 2 x 2 degree, etc., squares) on the basis of a number of height measurements in each area. A gross feeling for the sensitivity of slope values to errors in position along a satellite height profile can be obtained by considering the differences in height of two positions on the sea surface converted to a plane. These differences can be approximated by the arc length of a circular segment whose radius is the distance $\underline{d}$ between the two positions* assuming errors in height to be equal. The maximum relative error in the slope is then approximately the first term, $\Delta d/d$, of a power series in the relative error of the distance. In this sense, slope error is sensitive to slope and distance magnitudes and error in position. The significance of the slope error depends on the phenomena and scale of investigation.

Among the numerous studies on the applications of satellites is that of the Interrogation, Recording and Location System (IRLS). In this system a satellite would be used to interrogate and transmit to a central station data from numerous sensors including ships and buoys. IRLS has a positioning capability of approximately 2 kilometers.(9) Should the capability of a version of this system be increased by a factor of 10 or more then systematic oceanographic studies at comparatively micro levels would be a distinct possibility through remote sensing.

Application of satellites to horizontal positioning and of marine geodesy are treated in other parts of the report, much of which is applicable to oceanography.

TRACKING, ACQUISITION, LOCALIZATION AND IDENTIFICATION

Various activities at sea involve tracking, acquisition, localization and identification require precise positioning. These activities are described under the following topics:

(1) Search and Rescue

(2) Deep Submersible

(3) Space Tracking.

Search and Rescue

The searches for the Thresher off the U. S. Atlantic coast, for the nuclear weapon off the coast of Spain, for the explosive ship, Stevenson, off the coast of Alaska, and for

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*Positions are actually an area illuminated by a wave front. Other factors are also involved in satellite altimetry such as sea state, stabilization of the satellite, pointing error, etc.

the nuclear submarine Scorpion somewhere in the Atlantic have proven the need for more accurate positioning capability and for some form of marine geodetic control in rescue operations.

The Thresher search and location operations took one year. The recovery of the nuclear weapon off the coast of Spain took about 3 months; significantly, it required about 3 weeks after the loss of the nuclear weapon before deep-ocean equipment and adequate surface-navigation techniques could be established. Even after the establishment of surface-navigation systems, large errors were reported when attempts were made to get back to the same position.

Positioning problems in search and recovery are many, as reported in the literature and as stated by people involved in these operations. The need and desire for positioning accuracy of the order of ±30 feet (10 meters) was expressed. This accuracy is required for a search pattern that will assure effective coverage of all details of an area, make it possible to avoid the cost of overlapping search, and eliminate the risk of missing an area. Searchers are often told to find an object of interest at any cost, particularly where international politics or national prestige or security are at stake. Needed accuracy should be achievable with surface-based electronic systems provided careful operations and necessary corrections are applied under idealized conditions such as, near coastal areas, short period of observations, proper transmitter geometry, etc. An accuracy in surface positions of ±12 feet (4 meters) has been reported as achieved during the search for the Thresher.

Statements such as "We were lucky in locating the bomb", were made regarding the discovery of the nuclear weapon off the coast of Spain. Perhaps such references were made to the fact that the bomb parachute left a trail on the ocean floor about 1000 meters long. This simplified the localization, once the trail was observable, by the deep-submersible vehicle. A surface-based navigation system had to be installed and become operational before effective search could begin.(90) Therefore for such operations it is desirable to have a positioning system independent of shore installations available at all times. Also a precise bottom charting and positioning system is needed.(90)

The most attractive solution for search and recovery problems in a general area is to establish a grid system based on a bottom-marker system.(90) Markers can be located speedily geodetically (in geographic coordinates to avoid duplicating the search area), or at least, with respect to each other. The best approach suggested is use of a satellite system to determine the coordinates of the control points and use of a combination of satellite and acoustic search patterns. Whatever the system used, a need exists for control points and for a satellite capability for their establishment.

Deep Submersibles

The role of deep submersibles in search and recovery operations continues to take on more and more importance. Obtaining the full benefits from use of these vehicles in exploration and in search and rescue missions is directly dependent upon accurate control and positioning in all three dimensions of the marine environment. When a ship is conducting a survey or is towing a submerged or surface sensor platform, the ability to relate the position of the sensor and the data generated to the ship's position bears directly on the integrity of the resultant thematic maps and charts. Statements made during interviews indicate some inadequacies of present systems and point out the need for new developments in this area.

A need exists to first locate an object intermixed with topographic effects and second to return to that point as required. Simultaneous accurate positioning in real time for surface, subsurface, and bottom vehicles and equipment in also needed. Also needed is compatibility of the equipment and systems involved so there will be no interference or hindrance of operations. The areas needing most attention are foreign coastal areas and the deep ocean.

The ultimate goal, as stated, is to develop a capability for positioning underwater vehicles to within 1 foot (0.3 meter).(90) To meet this type of requirement, the Navy has under development a local navigation system complex consisting of multisensors such as Doppler/sonar, an altitude/depth sonar, a miniature precision inertial platform, digitial computer and underwater acoustic transponders.(26) Although preliminary tests show the system is still far from achieving such accuracy goals, nevertheless, this Navy approach is a step in the right direction and some potential has been shown. Surface-positioning capabilities must also be perfected to provide an effective worldwide system.

Space Tracking

Several space operations which will take place in oceanic areas will require high accuracy in positioning; this requirement can be met only by application of marine geodetic methods. These operations include:

(1) Apollo ship tracking

(2) Recovery of lost objects and retrieval of space ships at sea

(3) Location of new satellite-tracking stations.

The location and positioning of the Apollo ships during the injection, insertion and reentry phases of the space craft in the earth-centered coordinate system will be quite important. Continuous spacecraft position and velocity information will be required with reference to both the earth and the moon. The role of shipboard tracking stations in the world wide tracking network will be vital for the success of the moon-landing mission and the safety of the astronauts. Five Apollo ships located at various areas in the broad oceans, within a few degrees from the equator and beyond the range of good surface-based positioning system, will have to meet the most stringent accuracy tests. The accuracy requirements for the Apollo mission are stated as ±300 meters in horizontal position with respect to an earth-centered coordinate system and 20 arc seconds in ship attitude with respect to the true vertical for about 99.95 percent of the time or (3σ).(23) The accuracy of measurement must be maintained for time periods approaching 2 weeks on station.

The need for establishment of a few marine geodetic control points with an absolute accuracy of at least ±150 meters, (in depths ranging from 1000 to 6000 meters) and 5 arc seconds from the true vertical has also been stated for marine geodesy.(23) The potential of marine geodesy and adequacy of the state of the art of off-the-shelf hardware should be explored in an experimental program.

The requirements for retrieval of spacecraft at sea are similar to those of search and recovery and will not be discussed further.

New tracking stations at sea will be essential for complete satellite orbital predictions. Orbit determination to an accuracy of ±1 meter or better is becoming a realistic goal. Tracking capabilities, particularly in the southern hemisphere, are quite limited due to lack of land areas for placement of sufficient tracking stations. Marine geodetic control points might provide the base from which such tracking capability could be provided through ships or platforms. These control points could, in turn, be positioned and included as an integrated part of the worldwide super-control-point system on land.

EQUIPMENT TEST, CALIBRATION AND EVALUATION

The trend in equipment and hardware is toward development of the system approach to positioning operations. A beginning in use of the systems approach, at least for a local-area positioning involving the Deep Submersible Program, is being made. The advantage of a system approach to positioning is that it can point out areas of lags in the design of various components or subsystems. One application of the system approach is in the area of surveying and mapping operations. The final results from such operations are usually portrayed on charts or maps for different purposes. The information on the charts must be compatible not only within the charts themselves but also with other charts.

Furthermore, the various types of equipment and hardware employed in positioning these surveys (for example, satellites, surface-based electronics, shipboard electronic and acoustic subsystems, sonars, underwater systems) must also be compatible with each other so that results can be obtained in an integrated fashion. The system approach helps to identify wide gaps in equipment and subsystem precision or accuracy. When multiple items of equipment are used in a single mission, which is often the case, the final accuracy of the product cannot be better than the accuracy of the least accurate component. Therefore, it is of little value to attempt to improve accuracy of all other components if one inaccurate component is so large that its contribution is dominating in the final results.

Also to be considered in the system approach is the effect of the environment. This is particularly important in positioning with surface-based electronic equipment. For most ocean areas, the largest factors affecting the accuracy of electronic systems, in addition to range limitations, are environmental effects.

The existence and use of many types of equipment for positioning requires a means for their calibration and evaluation against a standard. The desire for a marine geodetic range against which all equipment and systems could be tested and evaluated in an operational environment without any restriction was expressed by many potential users. The concern was of course, related to the ultimate use and purpose of the equipment. Many of those interviewed expressed their wish for as "good as you can get". In one instance, a user was interested in calibrating his acoustic system against a highly accurate microwave surface positioning system at a distance of 5 miles from shore. Although a ±1 foot precision requirement for his acoustic system was desired, he was unable to calibrate it to that precision. Others expressed the need for a standard so that they would better know the capabilities and limitations of their equipment. The lack of standardization has caused misinterpretation of data reliability estimates as well as duplication of efforts to the extent that hardware has been modified to meet requirements as stated by a different investigator.

The use of satellites to collect and transmit data from the oceans and to report information from land resources in a short time is desired because of the speed of acquisition possible. Acquisition data rates, however, impose several problems of their own; namely, (1) rapid means of processing in real time and on ship, using computers, and (2) quick means of analysis and evaluation of obtained data. The speed of information collection for the vast oceans should be complemented by just as rapid a means of processing and digesting it.

GEODESY

The following discussion deals both with the requirements of marine geodesy and with geodetic approaches to meeting requirements of other topical endeavors. Consequently, requirements are discussed within the context of

(1) Geometric measurements for description of the Earth's surface through a common reference system. These involve precision-measurement technology, establishment of marine geodetic standards (e.g., marine geodetic ranges), establishment of marine geodetic control, and boundary determinations.

(2) Physical measurements for determination of the gravity field of the earth, its deviation from normal field, and its effect on and support of geometric measurements. These involve determinations of the geoid and deflection of the vertical components.

Precision-Measurement Technology

Geodesy by nature deals with methods and systems for making precise measurements. Precise-measurement technology must be incorporated into all aspects of marine geodesy in proper perspective. To state the accuracy requirement of systems is not sufficient; the capability and limitations of these systems must also be known. For example, crude measurements can be made with a precise "ruler", such as a light interference comparator used for geodetic base-line measurements; however, to do so might not be economically advisable. Conversely, accurate geodetic measurements are not possible with crude "rulers". The ideal is to select and integrate the proper equipment and components for the specific task. But, what is the proper equipment? How precise is current measurement technology at sea? Can the precision of various systems be determined and compared in some absolute manner so that accuracy would be determined?

Established geodetic criteria on land based on many years of use, offer only a starting point for marine geodetic measurement. What is realistic at sea in terms of capabilities, realistic requirements, and economics? By accuracy criteria do we mean one part in 1,000,000, one part in 100,000, or one part in 25,000? In terms of accuracy orders at sea, are criteria of, first, second, or third order, etc, realistic? Many of those who are involved in sea operations want an order of accuracy at sea equivalent to or approaching that on land.

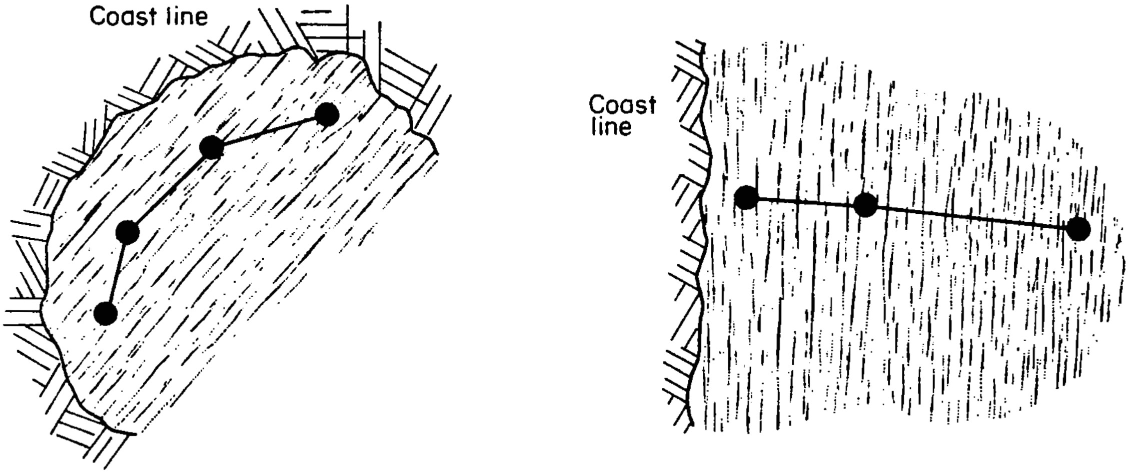
Should the orders of geodetic accuracy on land be applied at sea on an equivalent basis, or is first order at sea equivalent, capability wise, to third or lower order on land? Accuracy orders of precise measurement technology at sea need to be developed and defined for purposes of marine geodesy, but these orders can only be defined after marine geodetic measurements have been made. To provide a basis for definition, some standard must be available.

Land geodesy has had many types of systems available for precise measurements, i.e., surface-based, airborne, and satellites systems. With satellite systems, an accuracy of the order of a few meters has been possible on land in determination of coordinate of points separated by thousands of kilometers. High-accuracy land measurements have been made on the basis of established high-order geodetic standards. But what about the application of satellites and other measuring systems at sea? How can the status of measurement technology be evaluated and matched against marine requirements? The obvious approach is to eliminate present voids and establish a geodetic standard at sea as a beginning, i.e., a marine geodetic range.

Marine Geodetic Standards

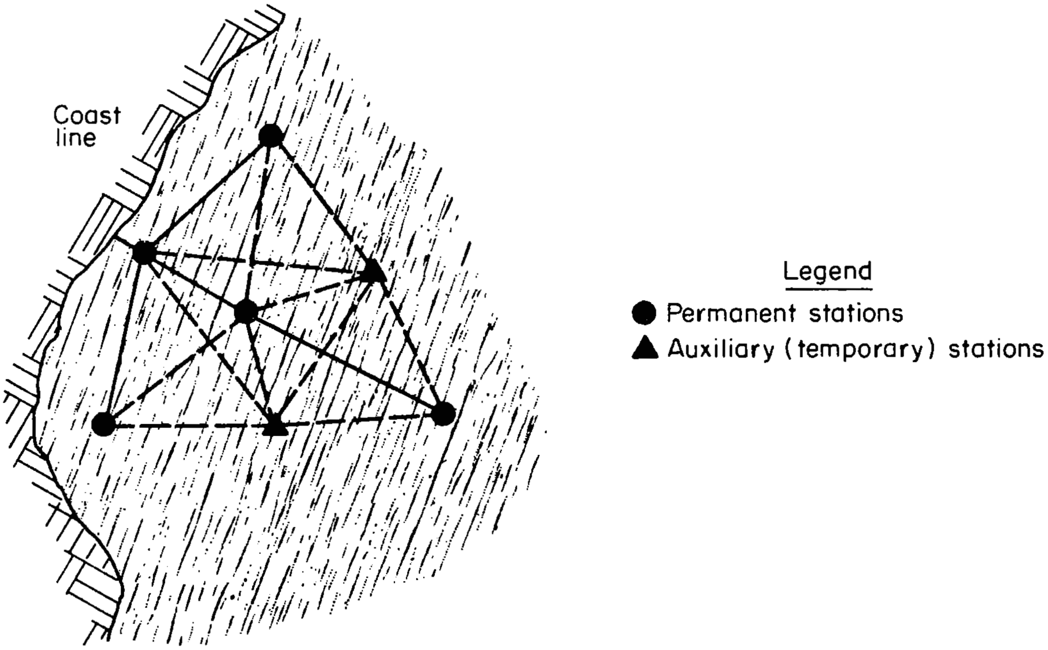
Several configurations of marine geodetic ranges are possible (see Figure 3). All involve a network of lines formed by connecting a series of permanent bottom reference points or surface platforms (stations). A number of temporary reference stations would also be required to achieve a specified accuracy. The reference stations could be so distributed that permanent stations would be located at distances from shore corresponding to short, medium, and long range positioning systems. The most important considerations with respect to the range are: location; orientation, direction and configuration; geometry; accuracy; hardware; cost and potential user benefits.

Many interviews afforded statements concerning the lack of a geodetic standard at sea and/or the desirability or potential advantages of establishment of a marine geodetic range. Such a range will not solve all of the problems related to precise-measurement technology, but it will certainly be a significant and first step in the right direction. On a short-term basis, the greatest single benefit to be derived from a range is likely to be the upgrading of positioning and surveying systems by providing a means for their calibration, test and evaluation. However, over a long term the usefulness of the range to the sciences and technologies involved in precise measurements at sea could easily be the greatest single benefit provided. Obviously, in the latter case it would be most difficult, if not impossible, to predict the quantitative benefits. Even so, this difficulty can not reduce the necessity for advancing the national capability for making precise marine measurements. Because of the serious push toward greater development of the sea which has already started, the subject of precise measurements cannot be avoided. Needs will create pressures. Planning in advance of pressure increase will permit an efficient approach.



a Coast-Parallel Range
Shelf only

b One-Direction Range
(shallow and deep water)



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c Multidirection Range
(shelf and deep water)

FIGURE 3. CONCEPTUAL RANGES

Marine Geodetic Control

The advantages of marine geodetic control points are easily recognized, but the accuracy with which these points can be established is not yet known. The applicability of various types of hardware for marine geodetic purposes has not been fully explored. Also, procedures available have not yet been used extensively at sea, and it is not now possible to evaluate them or to assess achievable accuracy and benefits.

The majority of the people interviewed during the survey were familiar with the meaning of marine geodetic control points. Many felt that the use of satellites for positioning along with inertial systems and control points will be the future trend for most accurate marine operations: "Satellites and marine geodetic points are here to stay". Such a combination should fulfill most of the requirements for detailed measurement and microstructure analysis. Some reported their need is for means for calibration of systems and equipment. Control of all ocean mapping operations seemed to be of primary importance in the estimation of many. A few of the interviewees were unfamilar with marine control points but knowledgeable concerning land geodetic control from which they drew inferences on the usefulness of marine geodetic points. Some indicated that they would like to see the capability of marine control points demonstrated. Others indicated no real present need for marine geodetic control points, but would be happy to use them if available.

It also seems apparent that a need exists for establishment of a few "super control points" in priority areas of the oceans. These would be particularly useful for ship tracking of low-orbit satellites (low-orbit tracking suffers because of lack of land-tracking sites). Control points should also be located in areas of specific operations. Such control points could be semipermanent or temporary, recoverable types. Since they could not be established at random but careful planning and site selection would be necessary, design criteria would have to be carefully considered and evaluation of every program would be necessary.

For any given class of requirements involving marine geodetic control points, certain steps must be followed to arrive at an optimum solution. For example, a given task must be characterized in terms of existing positioning methods, requirements, and cost. These approaches could involve one or more temporary points through consideration of several factors affecting the design, such as accuracy, physical parameters, preliminary solutions, and density and spacing of points. The optimization of results would then involve a trade-off analysis of requirements, cost of control points, and potential use. In some cases, the hardware and design of marine geodetic control points should be suitable for use by surface, submerged, airborne, and satellite systems.

In summary, marine control points would provide numerous advantages in that they have potential to:

(1) Serve as calibration points at great distances from shore in actual areas of operations and permit frequent updating or position fixing of surrounding surveys

(2) Furnish a yardstick for comparing and evaluating electronic positioning and inertial systems

(3) Furnish independent accurate control for bottom mapping and other oceanographic missions

(4) Provide gravity base stations in the oceans (needed but not now available for shipborne and airborne gravity measurements)

(5) Provide capability which should be useful in the establishment of a national marine geodetic range

(6) Provide a test range for improving SOFAR (long-range sound transmission and propagation)

(7) Provide precise positioning capability independent of time and environment.

Boundary Determination

Probably one of the most critical problems which will require the best marine geodetic techniques for solution is boundary determination. Geodetic networks on land serve for locating international, national, state, and local boundaries and determining positions and making maps with respect to them. At sea, boundary lines at present are drawn in accordance with map projection procedures. These lines, however, are hypothetical lines representing geographical coordinates. Unlike land boundary lines, their traces and intersections are not identifiable with physical markers or topographic features.

A need exists to have a capability to establish bottom control points as a means to identify boundaries and to provide a means of accurately positioning boundary lines between the established fixed points. There is much concern over the boundary problem. Litigation and disputes can arise over political boundaries and lease claims.

For example, at present determination of a lease boundary on the continental shelf is the responsibility of the leasee who is usually granted a number block on a map representing his lease. With oil leases, because of drainage, unexploited areas may not cause much concern until production approaches adjacent lease boundary lines of competitors. In such case, every meter of exploitation may be economically significant. On the other hand, in mineral exploration where drainage is not possible, every square foot of lease is economically significant.

Position errors can lead to undesirable and costly situations involving international and territorial boundaries and waters, domestic and international lease boundaries, surveying, military operations, and search and recovery missions. The ability to avoid error depends on positioning and geodetic capabilities. Over and above the military aspects, the areas of most priority are no doubt those of immediate economic potential, nationally and internationally.

Gravity Measurements

Gravity measurements are used for many reasons including determination of the figure of the Earth, establishment of an absolute coordinate system, and computation of satellite orbits and missile trajectories. For effective utilization of these measurements for such determinations, gravity surveys must be made everywhere on the Earth's surface, and the sea represents over 70 percent of the Earth's surface.(39) From the point of view of geodesy, the accuracy of gravity measurements must be between ±0.01 mgal and ±5 mgals, depending on the purpose.

Gravity measurements at sea are made with surface-ship, submarine, underwater, and airborne instruments. Most of these instruments are gravimenters used with stabilized platforms or gimbal suspension. Pendulum instruments have been used in submarines by several investigators, but only the Soviets have used pendulums aboard surface ships. Accuracies of gravity measurements at sea have been reported to be on the order of ±0.1 to ±1.0 mgal for bottom instruments, ±1 to ±5 mgal for submarine instruments, ±2 to ±10 mgal for surface-ship instruments, and ±5 to ±10 mgal for airborne instruments. Most of the errors in gravity measurement at sea on surface ships are attributable to inaccuracy in navigation.

Marine gravity ranges have been established on the continental shelf near shores for the evaluation of shipboard gravity-meter systems.(78) The most critical error in the use of shipboard gravimeters is due to inaccuracy in the determination of the velocity vector of the survey vehicle. The east-west component of this velocity vector (Eötvös correction) must be known to about 0.1 of a knot if one-mgal accuracy is desired. Such velocity measurements may be achieved at present only in reference to fixed points on the ocean bottom. Expressed desired accuracy for positioning shipboard gravity measurements varied between 100 feet and 600 feet (30 to 200 meters) with one extreme of 2000 meters. The most stringent positioning accuracy requirements in gravity measurements is being related to the establishment of base stations.

Gravity-base stations and ranges in the open oceans would be of great importance for the control, evaluation, and improvement of accuracies of marine gravity observations.(53, 69) In land geodesy and geophysics, many base stations are needed for effective measurements. It can easily be seen that for gravity measurements at sea, many accurate marine control points and gravity-base stations will also be needed if instrumental capabilities are to be fully utilized.

For gravimetric surveys, marine control points could provide accurate base stations to control open-ocean airborne and surface-ship-based surveys. The density and distribution of gravity base stations needed is not known, but this can be determined. As a first approximation, a station every 10° by 10° for the given area of operation may be considered as desirable.(69) At each base station, surface-ship or submarine instruments could be employed to measure in detail the gravity over an area of perhaps 1 by 1 degree. At the control-point station, for a more precise base value, an underwater gravity instrument could be used. The end result would be a systematic network of detailed gravity surveys over the oceans which could be used to control airborne measurements which have still more stringent position and velocity determination requirements.

The satellite, again, can offer the speed of operations, the areal coverage, and perhaps the accuracy needed for establishment of base stations. If a satellite technique and capability can be developed in conjunction with a bottom-mounted control system, base stations will be feasible and can easily be established progressively and concurrently with marine gravity surveys operations.

Deflection of the Vertical and Geoid

From measurement of gravity on the surface of the Earth, gravity anomalies (Δg's or differences between properly reduced observed and theoretical values) are determined, and the quantities N (geoid undulations), ξ, and η (deflection of the vertical components) are computed. These quantities are important in the accurate determination of the radius of curvature and shape of the Earth and could be important in the establishment of an absolute coordinate system and correction for inertial and star trackers.(39, 66)

On land, these quantities have also been determined by astrogeodetic methods (relative N, ξ, and η). A beginning toward utilizing the astrogeodetic technique at sea has been made possible through the use of an inertio-optical system to determine deflection of the vertical.(97) The method requires geodetic positions which are approximated by electronic or satellite methods. Currently the accuracy of the astronomic positions obtained in the open sea with this method is of the order of ±6 to ±10 arc seconds. This is of the same order as satellite positional accuracy of ±200 meters. This means only a large deflection of the vertical components can be detected. Improvement in the method to ±1 arc second is forecast.(97)

Deflection of the vertical components and geoid undulations are also determined from gravity measurements using Stokes and Vening Meinesz formulas. However, this requires dense gravity surveys around the point of determination to some distances from the point and lesser density of gravity measurements away from the area.

The determination of a surface approximating that of the geoid by direct altitude measurements from a satellite to the sea surface is under investigation.(6, 34, 62) This requires accurate determination of the satellite orbit and continuous ranging from a satellite-borne altimeter (laser or microwave radar) to the sea surface. Future precision in measurements to about ±10 centimeters would aid tremendously oceanographic work. Present studies indicate that precision of ±1 to ±5 meters is possible. This should be most welcomed by the geodesists for geoid determination. According to Lundquist, at Smithsonian Astrophysical Observatory, present computer programs for range measurements are being expanded to include altitude measurements.(62) This is possible since the range to the satellite is a function of station coordinates, orbital elements, geophysical parameters, and time. The altitude is also a function of orbital elements, geophysical parameters, and time. Therefore, measurement of altitude should not be a problem, since existing range programs are written for ±0.5 meter precision.(62) It is not yet determined whether marine control points could aid in these altitude measurements. Nevertheless, geodesy will benefit from such accurate and direct determinations of the geoid.

SECTION IV

MAJOR POSITIONING SYSTEMS

Positioning systems can arbitrarily be grouped under five types: surface electromagnetic or electronic, inertial, acoustic, celestial, and satellite. The role of these systems in ocean activities has been and will be of great importance. Without positioning information the value of all surveys would be useless and almost all purposes and objectives might not be realized. Over 100 positioning and surveying systems have been or are in use at sea today; all have strong points and limitations and no single system can satisfy all purposes. Various criteria are applied in evaluating these systems, e.g., accuracy, areal coverage, continuity of positioning, and reliability and maintainability. All of these criteria are of interest, but for purposes here the accuracy and areal coverage criteria are perhaps of greatest importance.

The accuracy of positioning and surveying systems on land, although not a simple procedure, can be and is often computed on the basis of established geodetic standards. There are no geodetic standards at sea. Accuracy statements or claims made with regard to marine positioning systems, unless caution and understanding is applied, can be interpreted incorrectly or in a misleading manner. These statements often represent instrumental errors which indicate the precision of the particular system and its ability to repeat measurements under similar and often idealized field conditions. Sometimes the accuracy of the system is given in terms of error contours which reflect only the effect of system geometry.

Position fixes at sea are normally obtained by the intersection of electronic lines of positions from basically a circular or hyperbolic geometry. The coordinates obtained by surface electromagnetic positioning systems are in terms of electronic coordinates. These coordinates are converted to geographic coordinates mathematically. Many factors must be considered in determining the accuracy of the resultant geographic coordinates with the precision of the electronic fix as only one factor. The accuracy of a fix could be determined, for example, in terms of geographic coordinates related to an established geodetic system (relative) or in terms of absolute coordinates (geoconcentric) related to the center of mass of the Earth. To get this type of coordinates from electromagnetic systems one must consider several factors (most of which are normally neglected in everyday operation) affecting the accuracy of the system. Examples of these factors are velocity along propagation path, atmospheric conditions, shore station and base-line accuracies, geometry, instruments, computations, procedures, operators, etc. Accordingly the reported accuracy of electromagnetic systems which may be stated in terms of a few feet could not possibly be the accuracy of the resultant survey or position fixes on a geographic chart. Moreover, a position fix is often the result of one observation (e.g., intersection of two lines of positions) for which there is no means to determine its accuracy. Therefore, the numbers related to accuracy reported in the following discussion will represent most often the system precision and/or repeatability.(15)

Areal coverage relates to the ability of the system to give reliable positioning information under normal operations in a given area. Coverage can be local or worldwide depending on the system. In a given area it is given in terms of distances from shore stations.

ELECTROMAGNETIC SYSTEMS

Electromagnetic systems depend on the propagation of radio waves which obey the basic formula $\lambda = \frac{v}{f}$, where λ = wave length, v = velocity of propagation, and f = frequency. The basic measuring techniques to obtain positions at sea involve time measurements multiplied by velocity of propagation. Two basic measuring techniques are available:

(1) The pulse technique – the time interval between a transmitted and a received electromagnetic pulse is measured

(2) The phase-comparison technique – the phase of continuous unmodulated electromagnetic waves is compared with the received signal to determine the time delay.

In both techniques the accuracy of measurements is dependent on the velocity of propagation of electromagnetic waves, the atmospheric conditions, land and water along the propagation path, timing, geometry of the transmitters with respect to the receivers, and several other factors.(55) Normally, the higher the frequency used, the better the accuracy of measurements and the shorter the range (distance). High-frequency systems use line-of-sight transmissions and employ small antennas. Lowering the frequency increases the range but decreases accuracy.

Circular systems generally consist of a master station aboard ship and two shore stations. The master interrogates the shore stations (shore control) which, in turn, generate circular lines of positions. Two intersecting lines from shore control are needed to determine a position fix. Circular systems transmit frequencies between 2 Mc/s and 3, 000 Mc/s.

Hyperbolic systems consist of one master and two secondary stations all located on shore. The system receivers are normally located on ships. To obtain a position fix, the intersection of two hyperbolas is needed. The usual procedure is for the ship to measure the difference in transmission times for signals from the master and from one secondary station. Thus, one line of position (hyperbola) is determined. The second hyperbola is measured from the master and the other secondary station. The intersection of the two hyperbolas gives the position of the ship.

High-frequency systems are used extensively for offshore oil explorations and in extending horizontal control from land out to 50, 75, or 100 miles from shore. Reported positioning capability of these systems varies from a few meters to 50 meters. The performance of these systems in near-shore areas is often reported as satisfactory. Errors up to a mile or so have been reported by various operators at about 50 mile distances, but some of these errors can be attributed to poor geometry, variations in propagation path, carelessness in operations, loss of lane counts, and lack of sufficient calibration points.

In one case, the difference between the indicated positions of two ships, side by side and equipped with the same system, was reported to be on the order of ±1000 feet at near-shore distances. Examples of high-frequency systems are the Tellurometer, Raydist, HiFix, LORAC, Shoran, Hiran, Lambda, etc. Some of these systems provide coverage at distances up to 200 miles from shore with positioning capability reported to be from ±30 to ±150 meters.

Low- and very-low-frequency systems, such as LORAN, Omega, and Decca, transmit waves along the curvature of the Earth's surface. These systems employ hyperbolic geometry which allows extended areal coverage making it possible for many ships simultaneously to use a single system. Positioning capabilities of these systems have been reported to be of the order of ±100 to ±2000 meters. Accuracy is sacrificed to achieve increased range, and large errors of the order of 1 to 5 miles have been reported at long ranges. The Omega system is the only surface system which has worldwide coverage capability once all transmitters are established. Its main purpose is general navigation at extreme long ranges (2000 to 6000 nmi). The Omega system may have application for determining ship velocity but only limited work has been done on this topic to date.

INERTIAL SYSTEMS

Shipboard Inertial Navigation Systems (SINS) are used on some ships as the primary means for position determination. They are self-contained and can be used worldwide. Starting from an initially known position, successive positions are carried forward through an inertial navigator which employs accelerometers to sense changes in motion and gyroscopes to provide direction references. Inertial platforms in current use accumulate errors with time due to gyro drift even in the absence of vehicle motion, and therefore, depend on periodical position updating information from external sources such as LORAN and star trackers. The accuracy of inertial systems is affected by the shape of the geoid and by the accuracy of systems used to update positions, and by the frequency of position updating.

The geoid surface, to which the direction of gravity is always perpendicular, is determined from gravity anomalies. The direction of gravity is then normal to the geoid and the deflection of the vertical (δ) can be shown to be $\delta = \frac{1}{\gamma} \frac{\partial T}{\partial S}$, where γ is the theoretical gravity on the ellipsoid surface, S is the horizontal direction to which deflection refers, and T is the potential due to the disturbing masses of the Earth which cause geoid undulations. Other means of determining the geoid at sea by direct range measurements from satellites or from astrogeodetic measurements are under investigations.(6, 34, 97)

The charts, maps, and mathematical computation models of navigational data are related to an ellipsoidal surface. The horizontal coordinates obtained from LORAN and other electronic positioning systems used for updating are also referenced to the ellipsoid surface of the earth but SINS refers to the geoid. This makes accuracy evaluation of inertial navigation systems quite complicated. If inertial systems are improved to near perfection, positioning systems used to update them should also be improved, and reduced to the same basis so that results obtained could be meaningful. Otherwise, to update SINS with a less accurate system would be like calibrating an "inch ruler" with a "yard stick".(70)

Published error growth rates in commercially available SINS have been reported to be about 200 to 2000 meters per hour.(24, 65) Extreme deflection of the vertical values of 1 minute of arc, which could cause a shift in geodetic position of 1 mile have been reported at sea near island arcs. Inertial systems which seek the local vertical could be in large error when reset if not corrected for these values. According to Macomber the average slope for a large ocean area, computed from the geoid undulations of the satellite gravitational field, is about 7.5 arc seconds.(63) This slope, if not corrected for when resetting an assumed mechanically perfect inertial navigator to the given geodetic position, would result in a position error of the order of 1/4 of a mile or about 450 meters after a period of 42 minutes. Similarly, for a 3-arc-second deflection, an error of 1/10 of a mile or about 200 meters would result. He further states that resetting the inertial navigator to the geodetic position is still unsatisfactory since the navigator's position will then oscillate with twice the amplitude of the deflection of the vertical. Instead, the navigator should be reset to the astronomic position and then the angular velocities to be used would be those defined by the astronomic latitude and longitude rates.

To obtain accurate geodetic positions, it becomes necessary to determine the deflection of the vertical angles and correct the astronomic positions by that amount according to the following well-known relationships:

$$\xi = \phi' - \phi$$

$$\eta = (\lambda' - \lambda) \cos \phi$$

where ξ and η are deflection of the vertical components in the meridian and prime vertical planes respectively, ϕ' and λ' are the astronomic latitude and longitude of the same point.

Obviously, use of the SINS in general navigation does not require all these corrections. However, if SINS is to be used in precise ship positioning or to provide control for certain advanced marine surveys which require a high degree of accuracy, either gravity surveys in the area of interest should be made from which deflection of the vertical charts would be prepared or other means of measuring directly the deflection of the vertical must be available to make the necessary corrections.(17) Additionally, for SINS to be effective worldwide, other positioning systems of worldwide capability are needed to reset the system.

ACOUSTIC SYSTEMS

Positioning with respect to the bottom topography or with respect to a set of underwater acoustic beacons or hydrophones on the sea bottom is accomplished by measuring depth to the bottom, the rate of change of depth, or slant ranges. One approach involves profiles referenced to a contour map of the area made from previous bathymetric surveys.

The primary interest in acoustic positioning is relating the ship's position or the instrument vehicle at the surface to an underwater control point. This can be accomplished by several methods. One method is similar in principle to the solution of a three-dimensional intersection problem in geodesy. Shipboard sonar measures at least three ranges to the underwater devices and the position is then computed relative to the bottom.(68)

Two basic transponder interrogation systems have been used.(89) In one method transponders reply to a ship at one of three frequencies (10.0, 10.5, or 11.0 kcps); the reply is at 12 kcps. In the other(27, 25), the ship interrogates at 16 kcps and the transponders reply at different frequencies varying from 9.5 to 12 kcps.(27, 25) Relative accuracies achieved in positioning a ship with respect to the bottom transponders in the deep ocean have been reported from ±3 meters to ±10 meters rms(93, 89, 25) to standard error of about 1 part in one thousand(38).

Other methods which have been applied involve acoustic line crossing techniques or variations of these techniques to determine minimum distance.(31, 38) The use of a single source unit is also possible, as was done in the Mohole Program(82), if interferometry-type equipment can be provided on the ship.

Another acoustic technique operates on the principle of dead reckoning; the ship's track is determined on the basis of the heading of the ship through water and current. This method involves Doppler sonar to determine the speed and, when used with a gyro-compass to determine heading, can provide the basis for continuous positioning information.(2)

The above methods are applicable for relative ship positioning over short ranges (10-20 miles) and can be applied in local areas on a worldwide basis. For long-range acoustic positioning, one method in particular, SOFAR, is a technique that can be applied for long-distance measurements and position fixes in the ocean. SOFAR propagation depends on the existence of a sound channel in the ocean. Sound from explosives is generated at the axis of the sound channel and can be propagated for thousands of miles. The sound rays are usually confined to a region of minimum sound velocity along the axis of the channel. The propagated sound is received at ship or shore stations through hydrophones lowered to or placed in the axis of the channel. Triangulation can be established through such a method. The relative accuracy of this method is about 1-5 kilometers in 1000-kilometer distances and is affected by the velocity of propagation of sound, time measurements, and distance variations. The application of this technique to marine geodesy will be very limited. On the other hand, marine geodesy, through the establishment of a fixed distance by other means, would aid in minimizing the errors due to velocity of sound propagation, the largest source of error in this method.

CELESTIAL SYSTEMS

Celestial navigation is the oldest and most used method of positioning at sea. Lines of position are determined by sighting at celestial objects such as the sun, moon, planets, and stars for which astronomic positions and relative motions are known as a function of time. Continuity is affected by weather but the method has been used worldwide for many years. The most common instrument used is the sextant. The accuracy of the method is of the order of 1-5 kilometers and is not satisfactory for marine geodetic applications.

A celestial system which has some applications in marine geodesy is the star tracker. Star trackers have been used in military aircraft navigation for position fixing and heading correction since 1946.(91) Star trackers have found their applications on board ships. For example, the Apollo ships employ star trackers which can be operated either manually or automatically and which are also coupled with SINS.

Basically, star trackers are devices that can detect, acquire, and track a celestial body. Position fix can be acquired by measuring and processing stellar angular arguments measured with respect to the local vertical and time. The on-board computer on the Apollo ships retains a 60-star catalog. Measurements with star trackers yield astronomic positions fixes the accuracy of which is of course affected by the deflection of the vertical. Accuracy figures on these systems were not identified.

SATELLITE SYSTEMS

At the present time satellites used for navigation at sea are based on the Doppler navigation satellite. The positioning accuracy is affected by the knowledge of ship speed, orbital uncertainties, and other factors. Accuracies reported range from ±100 to ±500 meters and depend on accuracy with which ship speed can be measured. One limitation is that most users are interested in continuous position information. With existing satellites a fix is possible only at intervals of 1/2 hour to 2 hours. Satellites are treated in more detail in the next section.

SECTION V

GEOS-II SATELLITE CAPABILITY - APPLICATION TO MARINE GEODESY AND POSITIONING

The GEOS-II satellite methods investigated for their potential applications to marine geodesy are: (1) Doppler, (2) SECOR, (3) radar, (4) optical, and (5) laser methods. Except for radar, these methods have been used extensively in land geodesy to establish a worldwide geodetic datum accurate to ±10 meter's in an Earth-centered coordinate system. Since the greatest possible precision is required for many types of marine geodetic measurements, the use of the GEOS-type satellite is desirable. Other satellites, particularly those with Doppler, such as the Navy Navigation Satellite System and the French Doppler Satellites, can also be used effectively. Special types of Geoceivers, already available, are required to receive the multiple transmitted Doppler frequencies from these satellites.

A review of the above methods, including discussion of their operation and characteristic errors, is given in Appendix B. These methods will be discussed here primarily in terms of their potential use in marine geodesy in two different, but related, applications:

(1) Precise ship positioning, where the ship obtains position fixes while in motion

(2) Establishment of marine geodetic control points, with the ship positioned relative to underwater acoustic markers for a given period of time.

Also presented is a summary of the opportunities for applying these satellite methods to marine geodesy.

DOPPLER METHOD

Of all the satellite methods, the Doppler is the only operational method which has been applied in precise ship positioning. This method has also definite potential for the establishment of marine geodetic control points at sea.

The Doppler method is used for determining both the orbit of the satellite and the location of points (positions) on the Earth's surface from observation of the satellite. Its use in ship positioning involves primarily a shipboard receiver to measure accurately the Doppler shift of radio frequency transmitted from the satellite and a computer to compute the geocentric coodinates of the observer.

The main source of error, in addition to those mentioned in Appendix B relative to land positioning, is the uncertainty with respect to ship velocity(35,76). This error is a complicated function of the geometry of the satellite pass (principally of the maximum elevation angle of the satellite). This error is also dependent on the direction of the error in ship velocity(51). For use in the computations, the ship velocity is resolved into its two components – one perpendicular to the path of the satellite (cross-track component) and the other parallel with the path of the satellite (along-track component). The effect of the cross-track error component, $\delta v_{\perp}$, is not as serious as that of the along-track error component, $\delta v_{\parallel}$(74,76).

The main problem is due to the fact that the measured ship velocity through the water is not the true velocity over the earth. The most serious problem is due to the existence of unknown currents(51).

The main effect of the component $\delta v_{\parallel}$ is to change the relative speed at closest approach from v to $v - \delta v_{\parallel}$. This results in an error in the slant range of $2\delta v_{\parallel}\rho/v$ and a cross-track error, $\delta r_{\perp}$, in the ship's position of:

$$\delta r_{\perp} = (2\rho/v)\,(\sec\chi)\,\delta v_{\parallel}\,, \tag{1}$$

where χ is the elevation of the satellite at the time of closest approach(74).

The along-track error in the ship's position, is given by:

$$\delta r_{\parallel} = (\rho_g/v)\,\delta v_{\perp}\,, \tag{2}$$

where ρ_g is the ground distance from the observer to the projected orbit of the satellite on the ground(74).

The cross-track error in positioning results from an along-track error in the ship velocity and vice versa. (The along-track error in ship velocity produces a negligible along-track error in ship position.) The factors $(2\rho/v \sec\chi)$ and (ρ_g/v) are given in units of time, the former being considerably larger than the latter. Typical values for $(2\rho v \sec\chi)$ range around 0.16 hour, but can reach as high as 0.5 hour for a pass with an elevation of 75 degrees. This would result in a cross-track error of 0.16 mile to 0.5 mile (400 to 1,000 meters) for 1-knot error in the velocity measurement. A typical value for (ρ_g/v) is 0.04 hour(74, 76). To obtain higher accuracy than presently possible in ship positioning, the error resulting from the determination of ship velocity must be minimized.

Besides the uncertainties in ship velocity, there are several minor sources of error such as the reflection of waves and angular motion of the ship. If radiation enters the receiver after being reflected and the reflected wave is measured, the result is an apparent displacement of the antenna from its true position. Reflection of waves should not be a serious problem with a suitably designed and located antenna, unless the ship is rolling heavily. Angular motion of the ship occurs when the antenna is not placed at the center of mass of the ship. This motion may be measured by the observer and included in the computations. The only error, then, is that due to error in the measurement. These errors are not as large as those due to ship velocity(76).

Relative positioning can be used to eliminate the errors due to the satellite's position (and atmospheric refraction). It provides a means of checking the internal consistency of the measurements, provided the measurements were made from the same satellite pass; or it can be employed for determining the position of an unknown station(77). For the former case, the positions, $\bar{R}_{TA}$ and $\bar{R}_{TB}$, or stations A and B would be required information. The distance between A and B would then be:

$$d = \left|\,\bar{R}_{TA} - \bar{R}_{TB}\,\right|\,. \tag{3}$$

Receivers situated at both stations can receive Doppler data. If the stations are close, the orbit of the satellite changes very little between measurements at the two stations. The measured position, $\bar{R}_{MA}$ and $\bar{R}_{MB}$, of A and B could be expressed as:

$$\bar{R}_{MA} = \bar{R}_{TA} + e_o + e_c + e_{r_1} \tag{4}$$

and

$$\bar{R}_{MB} = \bar{R}_{TB} + e_o + e_c + e_{r_2} \quad , \tag{5}$$

where $\bar{R}_{TA}$ and $\bar{R}_{TB}$ are the true positions of A and B, e_o is the error due to the incorrect satellite position, e_c is the error due to the coordinate system of the Earth, and e_{r_1} and e_{r_2} are random errors(77).

The measured distance, d_M, becomes:

$$d_M = \left| \bar{R}_{MA} - \bar{R}_{MB} \right| = \left| \bar{R}_{TA} - \bar{R}_{TB} \right| + e_{r_1} - e_{r_2} \quad . \tag{6}$$

As can be seen in Equation (6), when d is small, the only error present is that due to the random errors. Using Equations (3) and (6),

$$d - d_M = e_{r_1} - e_{r_2} \quad . \tag{7}$$

As "d" increases, the errors caused by the orbit contribution and the coordinate system in determining $\bar{R}_{MA}$ and $\bar{R}_{MB}$ will not "cancel" each other, and a maximum error will occur when these two values are opposite in sign for the two stations.

If the position of station A were known and that of B unknown, Equation (6) could be solved for $\bar{R}_{TB} + e_r$; i.e., the position of B, including a random error term, could be determined. Here, again, the total error would increase as the distance of the unknown station from the known marine control point increased, but most of the time this error could be expected to be less than that error if only one station measurement were used.

The main factors to be considered in using satellites for marine geodesy are:

(1) Accuracy
(2) Areal coverage
(3) Continuous positioning.

Ship-positioning requirements vary widely from one operation to another as noted in Section III. Present Doppler satellite use in ship positioning will be accuracy limited to about ±100 to ±150 meters in the geocentric coordinate system. It is possible, however, to obtain accuracies comparable to those achieved on land with the Doppler method (±10 to ±30 meters) only if used for establishment of marine geodetic control points.

The accuracy of the Doppler method on land has been reported to be ±10 to ±30 meters, depending on many factors including the type of measurements made, the number of fixed stations employed, and the number of satellite passes used in the analysis of data. The most serious accuracy limitations of the Doppler method result from errors in the extrapolated orbital information and from uncertainty about the parameters of the Earth.

Although the primary use of the Doppler method on land is for determining the coefficients of the gravity potential of the earth, its use at sea has been primarily for positioning. At sea, the most serious error is due to uncertainty in the velocity of the ship.(92) This latter error is dominating and it is of the order of about 400 to 1,000-meters-per-knot velocity.(52, 74, 76) At best, 1/4-knot error in the velocity of the ship, which is not easy to achieve, would result in about 100 meters component error in position. Therefore, including the other error components, the application of Doppler for positioning of ships will be limited to about ±100 to ±150 meters in geocentric coordinates. The error, although it appears large, is still less than that of any other available positioning systems – particularly at great distances from shore.

In order for satellite Doppler to satisfy the more stringent accuracy requirements (±10 to ±50 meters) of marine geodesy, the velocity of the ship must be determined accurately. Fortunately, it appears that the problem of ship velocity can be eliminated or greatly minimized if the Doppler system is used in conjunction with bottom-mounted underwater acoustic transponders, the main elements of the marine geodetic control points. Preliminary investigations indicate that for the establishment of these points not only is the problem of ship velocity minimized, but also several passes of the satellites can be measured while positioning the ship relative to the underwater transponders. This could be approached in either of two ways:

(1) The ship could be positioned relative to the ocean-bottom transponders with respect to time. This would yield the velocity of the ship to a high degree of accuracy. These data could then be combined with data from the Doppler obtained from many satellite passes using as first approximation the predicted satellite orbital elements as transmitted by the satellite. These data could be analyzed in the laboratory with corrections being made to the orbital parameters, and the final coordinates of the control point could be determined with an accuracy approaching that achieved on land.

(2) The position of the ship could be determined with respect to the transponders during the time of the satellite pass. Data could be collected from many such passes over the area and an average or mean position of the ship could be determined. The statistical average of many measurements should yield a reasonable accuracy for the position of the control point.

The nature of these two methods leads to two general conclusions:

(1) It is necessary to rely on some fixed points on the ocean bottom to achieve a high order of accuracy in measurements of coordinates of stations.

(2) It may be feasible to perform measurements using both methods and thus provide a means of comparison.

Other alternatives for minimizing the error in the velocity of the ship, although not as effective as that described above, are based on the use of other external means. For example, the use of inertial navigation systems, electronic positioning systems whenever available, and VLF or other systems could reduce the ship-velocity error.

Present satellite systems provide position fixes at sea at fixed intervals of time. This does not satisfy the requirements of most surveying vehicles for continuous positioning information. The use of other systems such as those mentioned above is therefore required, not only for ship velocity determination but also for positioning between the intervals of the satellite fixes. On the other hand, a satellite Doppler could provide continuous position information if more satellites were placed in orbit. A system of 24 satellites would be required. Several organizations favor the implementation of such a system because of their desire to have one universal system.

SECOR METHOD

The SECOR method is a space trilateration system. The SECOR satellite system employs electronic distance-measuring equipment whereby slant ranges between satellite and ground stations are determined simultaneously from the phase comparison of a transmitted and returned signal. (See Appendix B for detailed description.) Synchronization, which is essential for precision measurements, is established through a master ground station.

SECOR is not as sensitive to frequency stability as is Doppler, but it does depend on an accurate value of the propagation of light in a vacuum. The accuracy of the SECOR method also depends, in large measure, on the configuration and the strength of figure of the associated network. For best accuracy, one of the three minimum positions of the satellite must be on a different orbit than the other two in order to avoid collinear centers. Accuracy figures on SECOR are scarce.(3) Probable errors based on internal consistency of measurements on land have been reported to be less than 4 meters in determination of latitude, longitude, and height.(81) The main sources of errors are due to calibration of ground stations and the satellite transponder and to tropospheric and ionospheric refraction.

Unlike the Doppler method, the SECOR method has not been used for positioning at sea. Several approaches to the use of SECOR for determining the position of ships at sea have been proposed.(83, 85) These approaches employ adaptations of the basic SECOR technique. Two approaches, CODA (Consolidated Data) and ODVAR (Orbit Determination and Vehicle Attitude Reference) are considered.(83) An advantage of CODA/SECOR over the present system is the fact that the coordinates of the satellite are determined in real-time tracking at the master station. The master station has the only transmitter; the other ground stations serve essentially as transponders.

A signal originated at a master station, A, is received and transponded at a satellite. The transponded signal is received and transponded again at one of two slave stations, B, and this reply is received and transponded a third time at the satellite. The resulting signal is received back at station A, and a phase comparison of the transmitted and received signals at station A yields a measure of the range ($R_a + R_b$). Likewise the range ($R_a + R_c$) for a third station, C, can be determined by sequentially receiving and transponding the signal at station C. The satellite's response to station A's transmitted signal is used at station A to obtain a measure of R_a. The data are "consolidated" at station A yielding the ranges R_b and R_c and hence the coordinates of the satellite by "trispheration".

A fourth unknown station (a ship) could be included in the network. Three positions of the satellite for the same orbital pass could be determined by trispheration from the known stations and these in turn would determine the coordinates of the ship - also by trispheration. During the time between the determination of the satellite positions, the ship would be moving and hence errors would be introduced in the measurements. Another source of error, of course, would be that due to the CODA/SECOR system itself in positioning the satellite. Also, this type of solution does not lend itself to the most desirable geometric configuration since all three positions of the satellite are for the same pass, resulting in collinearity of centers.

An alternative approach would be to use only two positions of the satellite and an estimate of the geocentric radius of the ship to determine the ship position. The velocity of the ship would still have to be known, and an additional error would be introduced due to the assumed geocentric radius. The geometry would be somewhat better than that of the previous solution, however.

The SECOR/ODVAR approach requires that only one position of the satellite be known and, hence, the velocity of the ship is not required. In order to obtain the geocentric coordinates of the ship, however, it is necessary to obtain the geocentric coordinates of the satellite and the three angles which define the orientation of the satellite with respect to the geocentric reference frame. The former can be obtained by the CODA/SECOR approach or other means and the latter by ODVAR/SECOR which requires phase-comparison angle measurements at three antennas located on a set of orthogonal axes on the satellite. Accordint to Reid, however, high accuracy is not possible with SECOR/ODVAR.(83) Therefore, this system will not be discussed any further.

K. Rinner outlines an approach to the application of the SECOR satellite ranging system to marine geodesy - both for geodetic control and for positioning. He describes two possibilities for determining the coordinates of the marine geodetic control point: (1) using one underwater acoustic marker as the master station and (2) using the ship as a master station.(85) In (1) he reduces the SECOR range measurements from three separate surface positions of the ship to one of the acoustic markers. At the same time, each surface position of the ship is being determined by acoustic range measurements relative to several underwater markers. In (2) the ship is positioned relative to underwater markers by acoustic means while simultaneous SECOR ranging measurements are made to the satellite and three known ground stations. In either case, all observations of the control points with SECOR trilateration could be reduced and their coordinates determined by adjustment.

Rinner further presents an argument for using SECOR in positioning in a manner similar to the use of Doppler; i.e., the parameters of the satellite orbit would be determined by satellite tracking from known stations and stored in the satellite. Positioning of a ship would consist of observing at least two ranges to the satellite. Ideally, the satellite would transmit its own position when interrogated. The satellite position, the two ranges, and an estimated geocentric radius of the ship would be used in calculating ship position.

Rinner argues that the advantage of a SECOR system would be the strong geometry of the range networks as compared with results based on range difference as in a Doppler system. He states that, "Even if the accuracy of range difference measurements is n-times higher than the corresponding accuracy of range measurements the final results will have only the same accuracy as soon as the range is n-times the length of the difference. In addition, the geometry associated with difference measurements is typically weaker than for ranging systems. Therefore, ranging systems should provide better results when compared with systems using differences of ranges".(85)

Since the highest precision is required for establishment of marine geodetic control at sea, the use of several independent or semiindependent measuring methods is desired in geodesy. Therefore, SECOR could have a potential for use in the establishment of marine geodetic control points. As was pointed out in the discussion of the Doppler method, the approach for determining ship velocity and eliminating or minimizing its error could make this method even more useful.

The present cost and size of a SECOR setup, however, restricts its practical application by average users. Furthermore, none of the preceding approaches have been actually attempted and tested whereas the Doppler method is fully operational and its accuracy has been tested. The accuracy of SECOR on land is still a debatable topic. It would therefore seem logical at this point to experiment with the possible applications of the Doppler navigation satellite system to marine geodesy – leaving the SECOR system for future possible consideration. Its probable use would be by a government agency with ocean-mapping responsibility and capability.

The SECOR setup already exists on land and is being operated by the Army Map Service on a worldwide basis. The GEOS satellite also contains a SECOR transponder. Therefore, an experiment at sea could be made at a minimum additional cost to existing operations. Using at least three positions of the satellite in two orbits, or simultaneously from one orbit, the coordinates of the ship (positioned relative to the marine control point) could be determined. The process would be repeated for other control points until a small network was established. The final coordinates of the control points would be determined after the adjustment.

It must be mentioned finally that discussions with persons involved with observations and reductions of SECOR measurements indicate that they prefer the use of Doppler, already operational at sea.

RADAR METHOD

The radars considered in this discussion are those of frequencies in the C-band (FPS/16 or FPQ/6) and S-band radars (Unified S Band Radar-USB) which are available on board the Apollo ships. Each of the Apollo ships will carry a C-band radar and USB radar which could be used as a back-up to their SINS/Star Tracker positioning systems. In addition, the GEOS-II satellite carries a C-band transponder which would work well with the FPS/16 or FPQ/6 radars. At present the FPS/16 is used strictly for satellite tracking and not for determination of ship position. It gets the information "where to look" as the satellite comes over the horizon through a complex interconnection with SINS.

Ship positioning can be accomplished, however, with C-band radar by direct range measurement from the ship and known ground stations to the accurately tracked GEOS satellite C-band transponder similar to that in SECOR. With the availability of these radar systems on board five of the most sophisticated tracking ships, their utilization for marine geodesy could be of most importance. Analysis of such a C-band radar indicates that position accuracy requirements of the Apollo ships (±300 meters probable error in a suitable coordinate system(23)) would be met 99.95 percent of the time(24).

The technical characteristics of the C-band and USB radars are given in Appendix B. The ranging errors of these radars are reported to be as follows(1,61):

Radar	Random Range Error
AN/FPS-16	±9 meters
AN/FPQ-6	±3 meters
USB	±1 meter

The errors in radar measurements are normally much higher when all data obtainable from radar are analyzed. For example, random azimuth and elevation angle errors for the same radars mentioned are of the order of 0.2 milliradian or about 220 meters at the satellite altitude of 600 nmi. For this reason, the use of radar in the ranging mode is of interest to marine geodetic applications. Ship position could be obtained according to Calibria from the intersection of three or four ranges from the ground to the satellite.(24) The three-range solution would require preknowledge of the approximate coordinates of the ship. The four-range solution which could involve three ranges plus the earth radius is more accurate and would not require approximate coordinates of the ship. As in the SECOR, three satellite positions obtained from two different satellite orbits would be required. This requirement would therefore limit the use of radar in positioning while the ship is in motion. On the other hand, for establishment of marine geodetic control, this requirement would not be a limiting factor.

Analysis of error components (see Appendix B) indicates further that the use of USB would be superior even to use of the C-band radar system. However, the utilization of USB in the ranging mode would also require a satellite with an S-band transponder which is not available at the present time. The USB provides more accurate range information by virtue of its instrumentation. If it is desired to take advantage of this instrumentation it would be possible to modify the RF section of one USB. That is, it should or may be fitted with a C-band transmitter and receiver.

Although opinions were expressed that a single shipborne FPS/16 tracking a geodetic satellite could not duplicate the accuracy of ship position determination achieved by the Doppler method, nevertheless, the potential of C-band radar for ranging measurements must be considered, particularly for establishment of marine geodetic control points in the manners discussed above.

OPTICAL METHOD

Optical satellite methods involve the location of the camera stations by photographing the satellite against a star background and reducing the photographic plates to obtain the direction vector to the satellite as determined from the reference system of the stars. The optical method can use either one of two types of satellites, passive with sufficient brightness or active (flashing light) to make observations. The GEOS satellite is equipped with a flashing light-optical beacon system. The satellite is photographed from several observation points on land against the background of the stars. The optical methods are satellite triangulation methods, affected also by the geometry and strength of figure but independent of the effect of the gravity field of the earth. Details concerning the various methods, the cameras used, and their accuracy and other characteristics, plus available satellites and existing programs, are discussed in Appendix B.

The optical satellite methods have received the widest applications in geometric land geodesy perhaps because of the familiarity of the techniques involved and the simplicity of observations. Also, they give the highest accuracy achievable. Limited experiments have been performed on ships and the results obtained show promise for geodetic application of optical methods to the establishment of marine control points. Of particular interest is the experimental work of H. Jury at the Air Force Eastern Test Range with Photogrammetric Ocean Survey Equipment (POSE) – the details of which may be found in several reports.(47-50) The POSE system consists of a gyro-stabilized stellar-oriented camera with associated timing equipment mounted aboard a ship. The ship station was used as an unknown station, but its relative position to either underwater acoustic beacons(49) or land-based theodolites and cinetheodolities(47) was known. Using simultaneous observations of a satellite from the shipboard and several land-based camera stations, the geographic position of the ship was determined by triangulation.

To use a camera at sea, the effects of ship motion must be overcome. The mathematics involved is essentailly an extension of the land-based camera situation accounting for the relation of the camera to a stable platform mounted on the ship with the equations describing the displacement of the photographic image due to:

(1) Ship translation
(2) Platform random, steady, and enforced drift
(3) Earth rotation
(4) Apparent stellar and satellite motion.

One of the main problems is the overlapping of a stellar (or satellite) trail upon itself. This occurs when there is poor platform stabilization and no enforced drift. Use of a three-axis stabilized platform that can be separately torqued in roll, pitch, or azimuth to enforce drift such that the optical axis of the camera can sweep through a given angle per unit of time seems to reduce this problem. The stellar and satellite energy sweep across the photographic plate at a uniform rate resulting in a slightly sinusoidal star trace and linear target trace. Positioning accuracies as high as 30 to 60 feet relative to the land-based camera stations on the North American Datum have been claimed with the use of a camera mounted on a stabilized platform.(47) Furthermore, these results were obtained under controlled test conditions where the desired geometry and the coordinates of the ship were known by other means and hence may have influenced the analysis. Discussions with persons involved with the optical methods of satellite observation on land only (and with no experience at sea) disclosed two main objections:

(1) Instability is a problem. Even on land it is very difficult to achieve the stability desired.

(2) Operational feasibility is questionable.

Others with some sea experience, and hence a familiarity with the problems involved, seemed to feel that a camera system could be operated from a stabilized platform on a ship. They feel that as long as the star and satellite traces can be prevented from overlapping, this method has definite potential and should not be overlooked.

The use of optical methods for positioning at sea appears impractical when one considers the complications involved due to waiting for favorable weather conditions and obtaining simultaneous observations with suitable geometry. Also, it would be impossible to satisfactorily reduce the photographic plates and compute the position within any reasonable time span.

The use of optical methods for establishing geodetic control, however, is an entirely different matter. This has definite potential whether or not 30 to 60-foot relative accuracy is now obtainable. The drawbacks mentioned earlier would not be critical factors since the ship could stay on position obtaining other needed measurements until favorable observing conditions occurred several times. All data could be archived and analyzed later in the laboratory. Since the ship would not stay exactly at one point for all observations, it would be very helpful to have some accurate record of its movement. This could be obtained if the ship were continuously positioned relative to ocean-bottom transponders.

In geodetic work, it is desirable to use several systems independent of each other for analysis of new systems; therefore, the optical method may demand some further consideration for marine geodesy.

LASER METHOD

The GEOS satellite is equipped also with quartz prisms so that an incident laser beam from ground equipment is reflected back to its source. Using this method, an interrogating ground station can determine the distance to the satellite by measuring the time taken for the beam's round trip. Also the direction angle from which it comes can be determined. The use of this method in the determination of marine control would require special cameras and a stabilized platform, as with the photographic method. There are certain difficulties associated with this method because of the narrowness of the laser beam.

The main problem associated with the use of a laser for marine geodesy would be the stabilization of a platform to such a degree as to be within permissible tolerances for aiming the beam.

In a visual tracking situation, a laser beamwidth of 1 milliradian (or 3 minutes of arc) is usually transmitted.(16, 46, 68) This beam spreads 1 part in 1,000; therefore, the beam width is 1 kilometer for a distance of 1 megameter. This is 1,000 times the diameter of the GEOS satellite. To illuminate the satellite, the center of the beam must be pointed to within one-half the beamwidth or 1.5 minutes of arc; i.e., the satellite position must be known to about 1.5 minutes of arc. Once the satellite is seen, it can be tracked visually to within 1 or 2 minutes of arc. It seems reasonable, therefore, to estimate that the platform would have to be stabilized to within a fraction of a minute of arc. Of course, the beamwidth could be widened, but each time this is done the system is degraded somewhat. It then becomes a matter of determining just how much degradation is acceptable(57).

Another factor to be considered is the observer's position since this must be known to determine the satellite's position. If visual tracking were used, this would not appear to present too great an obstacle. If "preset" tracking were to be used, however, the observer's coordinates would have to be known within a few hundred meters. Also, the beamwidth could be widened slightly to compensate for any large uncertainty in the observer's position since a laser beam of 1 mrad. beamwidth will illuminate an area of only 100 meters diameter upon its return(57).

The development of the laser for geodetic applications on land is just beginning. Consequently, no attention has been given to its application to marine geodesy. Therefore, at the present time, the laser system appears to have some potential for the determination of geodetic control at sea, provided that accurate estimates of the coordinates of the control points are determined by other means.

For positioning ships at sea in a navigation sense, the laser method will apparently have limited applications as in the case with optical methods.

OPPORTUNITIES PRESENTED BY GEOS-II

On land the capability of satellite geodetic techniques has been demonstrated. For example, a system of three-dimensional coordinates of selected points all over the world is being established with the geometric solution of satellite triangulation. Such solution is executed independent of the effect of the gravity normal and without any assumption as to the Earth's density structure. Several other solutions involving both the geometric and dynamic satellite methods are being analyzed to arrive at a unified world geodetic datum.(71) Once such a system is established, it will provide an absolute reference frame of stations around the globe to which can be tied both the predominantly geometrically oriented mapping programs and the evaluation of satellite orbits for determining gravitational and related geophysical parameters(88, 71).

Marine geodesy is now being presented with similar opportunities brought about by satellite capabilities in conjunction with other technology. Satellite and other prerequisite technologies give every reason to believe that geodetic control points can be established at sea. For positioning, satellites have several advantages over other positioning systems, particularly those operating at long ranges. In conjunction with the potential of other positioning systems, the potential for satellites use in marine geodesy and precise positioning is almost without limit. Satellites should make possible a relative or an absolute geocentric-coordinate system based on an accurate bottom-control system. This system can be used then with other available surface-based systems to provide geocentric positions of surface ships.

Satellites offer a single reference datum for worldwide ocean activities. The establishment of marine control points could be made progressively or simultaneously in different areas of the world oceans using the same technique, with each control point referenced to the same coordinate system. In time, this would improve capabilities for ocean mapping and surveying and for other operations being conducted on the basis of criteria amenable to realistic accuracy evaluation and standardization. Meaningful comparisons between sets of data would be possible. The benefit of satellites for control is obvious. Charts and maps being prepared today could be made compatible with those that will be prepared in the future. This would eliminate the traditional but always current problem of conversion of maps and data from one reference system to another.

Satellites could provide world-ocean coverage both for positioning and for establishing marine geodetic control. Depending on the altitude of the satellite, position determinations and distance measurements on the order of thousands of miles are possible. The potential for establishing super-control points at sea within a world geodetic net exists using satellites, for example, at deep-ocean ship-tracking sites in space programs.

Satellites provide the best achievable accuracy at long ranges anywhere in the oceans. Satellite systems at present, and in the foreseeable future, are the only available means of approaching the positioning accuracy needed.

Marine geodetic control points established by satellites and configured as a geodetic range at sea could go far toward elimination of the confusion and uncertainties in accuracy claims and statements by providing a reliable measuring standard at sea.

APPENDIX A

COMMENTARIES ON POSITIONING AND MARINE GEODETIC REQUIREMENTS

This Appendix contains extracts from 27 trip reports prepared by Battelle staff members who interviewed various individuals within a number of industrial, government, and private research organizations interested in a spectrum of ocean activities involving positioning information requirements. At the beginning of each extract is a general subject heading representative of the interests expressed by an individual or by a group of persons questioned in the organization referred to in the trip report.

The topics listed below formed the basis of discussion during the interviews.

- Type of activities or operations in the oceans.
- Annual dollar volume of marine activities.
- Marine area of interest- shelf (U.S., foreign), deep water (where), etc.
- Positioning system(s) or methods used.
- Type of positioning information required: fixed, continuous, both, etc.
- Time-span required to perform operation(s).
- Positioning accuracy requirements – present and future.
- Positioning accuracy achieved with current systems.
- Importance of positioning.
- Costs in terms of loss (dollars, degradation of survey, etc.) if required accuracy is not achieved.
- Desirability to employ a more effective or accurate system.
- Familiarity with marine geodetic control, its purpose and use.
- Desirability to have geodetic control in area of operations and estimate of accuracy required.
- Major technical and operational problems of positioning used, systems accuracy, range limitation, singularity of reference, reference system, continuous fixes, geometry, area, etc.
- Major problems in establishment of accuracy criteria and requirements.
- Flexibility to change if better means are available to improve positioning capabilities.
- Role of satellite – present and future.
- Role of geodetic control in the future.

Interview 1 - GEOPHYSICS

International operations impose certain positioning requirements for geophysical surveys which are different than those in the U. S. continental shelf, e.g.,

(a) Lack of any geodetic control and transmitting stations in foreign areas is often the case.

(b) Cost of operations increases due to installation of transmitters, establishment of land control, and transportation of equipment and personnel for foreign land.

At present time concerned with foreign exploration at distances up to 200 miles from shore and shelves which may extend up to 400 miles for which there are no effective positioning systems at that range. Company invests about $5-6 million/year for foreign geophysical operations.

Company has used several navigation and surveying systems to position their surveys; Shoran Raydist-N, Decca, LORAN, Toran, and Omega (on occasion). The geophysical surveys are made for them by contractors.

Positioning information required must be continuous. Operations may last from 30-day intervals to eight months. Sometimes only a few days. Perform on the average of 25 to 30 miles of seismic lines per day. Common depth point recording of shot points presents problems especially if continuous positioning is not available, such as is the case with satellite. Six traces from six different seismic shots made in succession. Therefore, any error in consecutive positioning will complicate matching the results from the traces which must all be reduced to one common point.

Positioning requirements vary from 200 to 400 feet, depending on the operations performed. For lease boundary identification this must even be much better, especially if the block leased just borders on a producing field adjacent to another company's lease (e.g., see map in Offshore, June 20, 1967).

Accuracy achieved is of the order of 400-1000 feet. This is what we like to think we are getting but there is no way of knowing for sure. Omega, which has been used, has perhaps the least accuracy figures (about 1500 feet perhaps).

The most serious problem which can be caused by a large error in positioning would be that which affects drilling a well. The cost of drilling such a well is about $2 million. Other problems would involve resurveying the area (cost - about $1.2 million). If it is not too serious and the error is systematic then all that would be necessary is to readjust the survey in the office which may cost up to $100,000.

Also it is very important for us to reoccupy a station at a later time (perhaps five years later). Therefore the accuracy of the system employed must be such that we can recover our operations successfully.

Company always searching for a better and more accurate system at a reasonable cost. Our cost at present in foreign operations is several times higher than domestic ones.

Oil companies are flexible and are always looking for something more suitable for offshore positioning everywhere.

We are a little familiar with geodetic control. We must see its practicality and demonstrated usefulness. Since geodetic control is not an operational system at the present time, we can't suggest anything in regard to its accuracy or practicality. Most oil companies can tell the geophysical contractor the equipment and system that he must use through contract. If a useful system is available they can use it and they are to use one system everywhere if possible.

The major problems and limitations of present systems are: range, accuracy, loss of lane count and useable time per day because of environmental conditions. We have no problems when using one system. If several systems are employed, then comparison is all you can obtain.

If the satellite can be used continuously or perhaps with another system like Doppler sonar or inertial, and can give 400 feet, it will be desirable because of its use anywhere in the world (singularity of system). It is also believed that it can also compete in cost with present foreign operations. For example, for one type of system the cost of three transmitting stations is about $30,000 per month using an eight-man crew, one supervisor, and one draftsman. Cost of mobilization to foreign land is about $15,000 to $25,000. Cost of establishment of land control, if not available, will certainly increase this. In addition we are assuming that foreign countries are cooperative with us and permit land installations. Also new transmitters must be used at other areas. If satellites can be married with another system for continuous positioning, this will definitely change the whole picture. The same can be said with geodetic control, particularly for defining block boundaries and obtaining an operational system.

Interview 2 - GEOPHYSICS

Company is involved in the exploration and exploitation of oil resources all over the world. Positioning information required for geophysical surveys and location of drilling wells. Marine area of the Company's operation is anywhere in the continental shelves worldwide. The Company's expenditure for marine operations is on the order of $100 million per year which excludes $20 to 30 million – the cost of a platform when in production.

Positioning systems used are: LORAN, Raydist, Decca, or equivalent, etc. If a new system is better than existing ones and available at a reasonable cost we will use it immediately. Our Company is quite flexible to changing to a new system if it is better. However, in some foreign areas we cannot be flexible because of monopoly. Eventually, the satellite will be a very important tool for survey all over the world. We are looking into it now.

For exploration purposes we need continuous positioning information. As long as a positioning system can allow us to go back to a previous location this should be satisfactory. In lease boundary location we are allowed to drill 300 feet away from the next lease. Seismic operations are conducted all year long. These operations are plotted and then two to three months later they are followed to check them. Instantaneous positions are needed everywhere.

The positioning accuracy requirement can be stated as that needed to allow the crew to go back at a later date to the same position. The final well location, however, must be 300 feet away from the next lease (what the government allows for drainage). In the North Sea one company has already drilled in someone else's lease. Fortunately or unfortunately it was a dry hole. This will happen again. Positioning accuracy is also important for determination of common depth point of seismic shots. Also in gravity measurements.

The positioning accuracy achieved with present systems is quite variable depending on the location and the conditions. The variations range from poor to sometimes good. Nothing is constant, however. There is no doubt in "my mind" that positioning accuracy is primary - fundamental.

It is difficult to estimate the cost due to poor positioning information. Normally, we have to reinterpret the data and go back and check some stations to know the crossings. If we find it, this can cost about five to 10 percent of the original operation. If we can't find it, we must shoot again. In any case, they are time consuming and troublesome.

Geodetic control on the ocean floor will be needed especially when we progress out to sea. The farther we go out to sea the more it will be needed. A spacing of 10 to 20 miles may be required for certain areas. Geodetic control, I think, will be very important for mapping as it is on land.

The major technical and operational problems are:

(a) First of all, the difference between theory and operations. The accuracy that matters is that what is achieved in operations and not what is stated in papers. ("We care less about stated accuracies".)

(b) Time of day or night that affect certain positioning systems.

(c) Personnel - most of available systems are not automatic. You must have several personnel tied up to the operations.

(d) Surface-based electronic systems when used in foreign land are not as convenient and certainly are more expensive because of transferring of equipment and personnel.

We really don't know where we are at sea, therefore, how can you establish accuracy criteria? If you have a base line established, at least we can compare the measurements to it.

Interview 3 - GEOPHYSICS

Company engaged geophysical operations concerned primarily with seismic, magnetic, and gravimetric surveys for oil exploration. Areas of operation are primarily the continental shelves of the world.

We would like to have positioning capabilities up to 400 miles from shore everywhere. The positioning systems used are: Lorac, Shoran, Raydist, Decca, LORAN, Omega, etc. We can now survey on a 24-hour basis around the clock with latest energy sources. We require fixed and continuous positions: (a) geodetic static and (b) dynamic.

Positioning accuracy requirements are: 100 feet to 1,000 feet. It is hard to say the positioning accuracy achieved. It depends on area which many times is not good. Need accurate and continuous system up to 400 miles.

Costs of poor positioning associated with degradation of survey and repeatedly checking of surveys. If a new system would have accuracy and range available, we could employ the new system. It is desirable to resurvey an area or go back for detail. So if geodetic control is available, it can be used. Accurate geodetic control is needed for accurate surveying and mapping on land as well as in the ocean. We have to operate with what we have got. We would like one system if available. However, a combination of systems will have to be the solution. All systems available have some kind of limitations. We are flexible if not prohibitively expensive. We need a standard for evaluation of work at sea.

The satellite may be good if enough fixes and/or continuous information are obtained. A combination of systems is the answer. Perhaps satellits plus acoustic Doppler or satellite plus inertial may be the only way to meet our requirements. The Omega system combined with others would appear to be of much lesser accuracy. If improved through monitors, it may be possible. Most important is velocity of ship. It should be known to 1/6 of a knot for both gravity and positioning information. Available systems may be satisfactory up to 150 to 200 miles, but they have their limitations.

Interview 4 - GEOPHYSICS

Involved in exploration and exploitation of oil and mineral resources. Annual investment in the ocean not known.

Area of operation primarily the continental shelf of the U. S. and other areas where oil is expected to be found. Progressing toward the slope in the near future. If we can exploit oil from the deep waters and still compete with oil obtained from land or shale oil, it is possible then for the oil companies to go into the deep water.

Has used many positioning systems. Mostly through contract for geophysical surveys where contractor usually provided the positioning systems. The types of positioning information required are both fixed and continuous. Positioning is required to locate platforms and drill for oil. Continuous positioning information is required particularly for geophysical surveys. Perform geophysical surveys around the clock.

Would like to have as accurate positioning information as possible, but operate with whatever can get. The positioning accuracy achieved with current systems varies with the system, its location, the type of operation, and other factors. In many cases, the information obtained has not been satisfactory as to accuracy and coverage.

Positioning system employed is of greatest importance to all geophysical surveys. Without positioning information, the oil companies are not able to perform useful surveys. The accuracy is of particular importance in foreign operations because of costs. The cost of operation in foreign areas multiplies by a factor of two or three over that in the U. S. This is due to transportation of operators and equipment to the areas of interest which often require the establishment of actual geodetic control on foreign land if not available. In addition, restrictions on transmitter locations create unfavorable geometry which degrades the accuracy. It is desirable to have a system most useful everywhere in the world and, if possible, not depending on shore installations. If this system is not prohibitively expensive, the oil companies are easily adaptable and very much interested in buying it if it has the accuracy and reliability.

Familiar with marine geodetic control, its purpose and use. Believe that control points would be of importance definitely in the area of deep waters, if an operational system of control points can be developed economically and established quickly in the survey area with a means of positioning between control points. The speed of installation and operation is important because geophysical surveys are expensive and are conducted on a 24-hour basis. For future positioning and mapping will undoubtedly be required especially in the deep water. It is not known at the present time the effectiveness of such a system in actual operations.

The major technical and operational problems facing the oil industry are those associated with the expansion of drilling into deep water. The limitation of existing positioning systems due to loss of lane count, sky waves effect at night, and distance covered from shore are among the problems requiring immediate attention. A few majors can afford to do more research into these areas and come up with more effective systems. Most of the other operating companies will have to depend on the geophysical contractor. If satellites proved to be reliable and effective for continuous positioning even in combination with another system, it is felt that most of the companies will request the contractor to adapt such a system.

Accuracy evaluation of existing systems has not been the easiest thing in the world. Such evaluation is possible only through the comparison of one against the other which is not effective. Other means are to check the positions against seismic or buoys.

The oil companies, in general, are quite flexible and they would obtain any system if it is accurate and reliable and not too costly. Believe satellites will be employed more in the future for positioning and other operations. Several companies are looking into satellites and other combinations that would be most effective for oil explorations.

Interview 5 - GEOPHYSICS

Activities involve marine surveys and research using the data collected, and include gravimetric, magnetic, topographic, coring, and hydrology. Area of operations is primarily in the deep waters.

Main positioning was by celestial methods; now are using satellites. The type of positioning information required is that for determining the E-W velocity of the ship (for Eotvos correction) and to be able to go back to the same spot. Satellites and ship gyro compass (good to 1/4°) are satisfactory. The positioning accuracy requirement is on the order of one mile; coverage is more important. The positioning accuracy achieved using satellites is on the order of .2 nm; using celestial fixes is of the order of two to five miles. Accurage positioning systems are nice to have but they are not absolutely necessary.

The accuracy of gravity measurements was improved to present 1 mgal using satellites from five to 10 mgals with celestial fixes. Can definitely get two to three mgals now and this is satisfactory.

Have heard discussions about marine geodetic control but do not believe it is needed for his operations. Sometimes need accurate geodetic control especially if drop bottom seismometers on the ocean floor. If could use nearby geodetic control it would be nice. Not familiar with mapping methods and can't comment on geodetic control for mapping.

Does not see any particular problems in regard to positioning. Only minor problems related to instrument breakdown which are common to all systems. Satellites in future positioning at sea is definitely the thing to use. Establishing an accuracy criteria at sea is very difficult. Have no means to evaluate any system. Have to be very careful in comparisons. Flexible to use new and better systems if cost is reasonable and reliability is good.

Interview 6 - GEOPHYSICS

Company involved in oil exploration and production. Area of operations includes the continental shelf of the U. S. and of the world. No leases are being given beyond the shelf in Louisiana at the present time. However geophysical surveys have been carried out throughout the whole Gulf area. This would include, of course, the shelf, the slope, and the deep water. Believe that about $1 million per day is being spent in the Gulf of Mexico alone by the oil industry and its supporting companies, such as drilling, positioning, surveying, etc.

For fixing of rigs and platforms, visual and microwave systems are usually used to obtain a geographic position with respect to another platform or to a land site. Most companies usually depend when possible on visual methods for final layout of their structures "because it seems that is the only way to be sure of putting it in the right place".

The types of positioning information required are continuous for exploration purposes, fixed for geological and platform locations. The time span of operations dependent in many cases upon the weather. For rig or platform installation this is usually a 24-hour-per-day job which also depends on the distance from shore. Often, buoys are installed during the day to establish some kind of positioning reference for continuing the operation at night. For geophysical surveys require continuous observations and if possible on a 24-hour basis for several days until the job is done. Systems used to date are susceptible to skywave effects thus reducing the efficiency and accuracy. If satellites can be used, this problem can be avoided and can operate over 50 to 100 miles from shore with no such problems at all.

The positioning accuracy requirements are or should be as good as we can get them. For practical purposes may be satisfied with 200 feet if we can be sure of it. We are normally pleased to obtain 200 feet; this has been accomplished with some systems in certain areas at the present time. In the past, errors of the order of thousands of feet were quite common using these systems. Have improved the accuracy and the use of these systems by taking many other precautionary steps, such as providing check points and ties and relying somewhat on our geophysical surveys to discover some of the errors.

The positioning system used is without a doubt of great importance. Without the positioning information have nothing. More than five years ago several oil companies made many mistakes in buying "wrong blocks" due to errors of about 0.5 mile in positioning of surveys. These errors caused also companies to drill outside the desired area or in the wrong lease. Some of these problems can be avoided by going into extensive field programs both in education and training and obtaining better equipment. In Louisiana, for example, geodetic control is available through existing platforms for most of the area to 600-foot depth. Beyond the 600-foot depth will, no doubt, require help from other positioning systems, such as "satellites". Another approach would be to establish electronic systems on base stations (existing platforms) to extend the range of the positioning systems to cover the slope and even the deeper water.

The company is always interested in better systems and at the present is interested in satellite for positioning. Realize that the satellites may not give pinpoint accuracy at the present time but are certain that it is the tool of the future. Obviously, may have several problems due to inaccuracy of the satellites, both operational and inherent to the system, but can be satisfied with ±300 feet if we know this is what we are getting. Eventually, would like to get positioning accuracy better than 300 feet from the satellite. Would like to have eventually an accuracy of ±50 feet with reliability of being able to go back to the same location.

Familiar with marine geodetic control from the use of horizontal control on land in planning his operations and in Gulf platform ties. Desire to have control points in the area of operation. The example of tying the platforms for extension of control closer to areas of operations demonstrates the importance of control points and their use. Marine control points will become necessary especially in areas where we have "big jumps" that cannot be related to a platform or when operating in deep water. However, an operational system must be developed to demonstrate their capability. Control points placed in the deep water, particularly in areas where no other control is within site of land or reach of microwave electronic positioning systems will definitely have a major role in controlling surveys and improving the accuracy of positioning operations.

With regard to accuracy criteria, believe the industry can be positive of positions only when have either visual or microwave equipment and at short distances from known structures and then can get within a few feet of the desired location. In addition, can employ two boats full time with positioning equipment on board and make continuous checks on these systems by visual means in order to control errors. Geologists normally provide the surveyor with acceptable tolerances for location of drilling sites or platforms. The surveyor must, however, work to keep within these tolerances. In off the shelf of Louisiana exploration we are lucky by having these platforms where we can make the siting on them.

Company is quite flexible in adopting any new system that meets the requirements. Also welcome all suggestions and ideas leading to improvement of capability and reliability of existing systems. Looks with favor on the role of satellites in the future of positioning. Hope that satellites will be used for all purposes, e.g., positioning tools for pipelines and for geophysical surveys, fixing structures, and bathymetry. Willing to state any type of requirements needed to justify the launching of any additional new satellites that will give either better positioning accuracy or additional coverage.

Interview 7 - GEOPHYSICS

Company involved in exploration and production of oil and minerals. No estimates available for company expenditures in offshore operations. Area of operations includes U. S. continental shelf and slope.

The positioning systems used are those of an electronic type. Other types of positioning involve visual sighting especially for precise location of structures. The type of positioning information required is both fixed and continuous. Fixed positions are needed for structures and barge installation, and continuous positioning information is required for exploration and pipelines. The time span of operations is continuous - sometimes five to six days, sometimes much longer depending on the purpose and location of the operation.

Positioning accuracy requirements also differ depending on the type of operations performed. For drilling, structures, and barges - 10 to 20 feet are required. For exploration purposes generally depends on the type of survey. For example, detailed surveys require higher accuracies which are "as good as possible". System accuracy is of importance, especially in production operations. Wells must be located exactly at the desired site within the lease boundaries. We must also be able to correlate two or three sites, which becomes critical in areas surveyed earlier with large errors.

Positioning accuracies of ±5 feet have been achieved in tying the platforms and locating drill sites. This is accomplished only by visual observations using theodolites and microwave equipment. Such accuracies have also been accomplished at about 80 miles from the coast. This was done easily because of the availability of platforms which can be observed visually. Visibility of up to 30 miles has been possible in some areas. The accuracy achieved in explorations varies with the scale. Checking the measurements against buoys, 50-foot accuracy can be obtained within 30 miles. At 70-mile distances, accuracy of the order of 300 to 400 feet has been accomplished in seismic line shooting (50-mile-long seismic lines).

The cost of operations resulting from large errors, say 1,000 feet or more, could lead to drilling in the wrong block and might amount to $2 million or more, depending on the location and equipment. The cost of drilling is of the order of $500,000. In some cases the company is reimbursed for some of the costs of drilling in the wrong lease by the rightful company, especially if it resulted in a producing well. It is very difficult sometimes to estimate the cost due to errors in positioning. In some cases errors in these surveys resulted in the company buying the wrong block. Company is getting as much information as needed for production purposes at the present time. However, for exploration we don't really know. How much the positioning information is really worth is difficult to estimate. Definitely a more reliable system is desired. We are about to go beyond 600-foot depths. In some U. S. areas we are already stretching the limit of equipment.

Familiar with marine geodetic control. Satisfied at the present time with the availability of surface control for surveys, but stated that if company is to go into deep water (which is expected in the future provided that oil production is feasible from these depths) control points must be moved out there or placed on the ocean floor. The role of geodetic control in future positioning and mapping operations believed to be that of calibrating the satellite receivers and other systems. However, in the Louisiana offshore exploration, not needed because of the availability of platforms and other visual means of providing the check and calibration of the positioning systems used.

Several problems common to most oil companies. Bad weather cuts down on the visibility and limits their positioning capabilities to electronic means. Electronic positioning cannot be relied on alone for drill and derricks locations. These locations must be known accurately and cannot be stopped or postponed because of weather, unless it is a hurricane. Often the company does not know when these operations are to be started. The cost of these operations is about $30,000 per day and therefore they must be continuous. Although electronic positioning systems have advantages against the weather, they are not as reliable. Most of them also suffer from skywave effect which causes errors and sometimes loss of signals and lane counts.

The location of the platform is most critical. Once a platform is located, it can be used then as a fixed control point on the surface. Company contracts most of the geophysical work. Very difficult and quite expensive for the oil companies to buy several types of equipment or several receivers for one system to operate only occasionally when needed. Prefer that contractors own and operate the best available positioning systems on a lease basis.

As to accuracy comparison or establishment of accuracy criteria, this has not been a problem for visual observation or in areas close to shore or fixed installations. It is; however, a different problem for geophysical surveys at areas where no visual means are available. In these cases, only comparisons or checks by crossings, or from seismic, geomag, and gravity records can be made. Since these are not accurate methods, we must continuously keep adjusting and correcting the surveys.

Company quite flexible and would desire a better positioning system, if available, at a reasonable cost, that would meet the requirements. As to the satellite role in the future positioning and oceanographic operations in offshore exploration, it will be the tool of the future.

Interview 8 - GEOPHYSICAL SURVEYING

Use available positioning systems to execute surveying operations. Believe that present positioning systems are adequate for most part. Does not think that there are any major problems but company is buying satellite receivers primarily for lane identifications of electronic positioning systems. For lane identification the satellite will be used to check the count at perhaps two-hour intervals, thus increasing the reliability of the systems. Satellite will not come to its own until a long time in the future, perhaps 10 years hence. A satellite system coupled with an inertial system will be an ideal positioning system provided that the "bugs" are eliminated from the inertial systems. The use of inertial systems will be limited in accuracy due to the effect of gravity anomaly on them. If the inertial system is to be used to determine the velocity of the ship which is needed to improve the accuracy of satellite positions, this again will still have inherent errors due to the gravity anomaly effects. Have not used satellites yet but existing electronic systems employed are very convenient.

Interview 9 - GEOLOGY

Main interest is marine geology with related interests including buoy surveys, core samples, dredge samples, sea mount surveys, and deep sea drilling. Perform operations all year round.

Decca and Hi-Fix and LORAN-A have been used in close-to-shore areas but beyond these areas only radar and mostly celestial navigations are used. Believed that in one area of operations an accuracy of about 100 meters has been achieved based on the information obtained from manufacturer of equipment. There is no way to know for sure though.

The positioning information required varies with the work that is being performed. With sea mount surveys both continuous and fixed interval are required. For target area location, need "as good as you can get it". At present and beyond radar range, plant buoys, although do not know where the buoys are. Estimated that 200 to 400 foot accuracy of control would be required, especially for deep sea drilling where sites have been determined hopefully by satellites.

The positioning system employed is very important for his particular operation. Fifty percent of the time it is difficult to make surveys compatible with other surveys. At present, can determine bottom depth with few feet accuracies. If not able to get close enough to this accuracy in positioning the determination of the geological information is degraded considerably. Generally speaking, people in oceanography do not have a good grasp of the importance of positioning accuracy in their work. In order to make useful marine geological surveys, the accuracy must be as good as the land surveys which, in turn, require highly accurate positioning.

Accuracy of short range system used is satisfactory but is limited in areas of operation; therefore, if a new system exists which can give as good data on worldwide basis, we can be satisfied. If we can obtain accuracy by the satellites of ±300 feet, which is not unusual as I hear, we will definitely increase the value and importance of the work we are performing by 300 to 400 percent. If such accuracy is achieved, the information will always be useful. It can also be stated simply that on land we require high degrees of accuracy to perform most of our operations, and I don't see why we should have any lesser requirements for the same type of work in the oceans. Oceanographers will eventually come to realize that their work will be of the same importance as ours (meaning geology), and accurate positioning is a must. In any case, in marine geology it is of most importance. "We are very much interested and flexible to use a better system if available". Familiar only with land geodetic control, but can see a correlation with marine geodetic control and its importance. It is desirable to have geodetic control in the area of interest, especially for drilling operations. Marine geodetic control will no doubt play as important a role in the future for mapping and other oceanographic operations as land mapping.

Have had limited association with the positioning systems available. However, can state that most of these systems are limited in range and useable area because of low accuracy. Celestial positioning, although worldwide, is limited by weather conditions and accuracy. Therefore, it is most appealing to have a unique system which can be used everywhere. The work that was done in one location last year had only celestial fixes. When bad weather occurred it was really "ridiculous" to know where you were.

Have not been involved in the accuracy evaluations and organization has no one working on this important problem; but people talk a lot about the subject. Looking ahead, a check in terms of fixed points for physical and chemical oceanography will be important. If accurate work is performed now it will always be useful in future detailed work. Furthermore, a knowledge of the systems' ability and capability would also be of importance.

Interview 10 - GEOLOGY

Involved in varying degrees with all U. S. continental shelf. Annual volume of activities related to the shelf work amounts to about $2 million per year. Believe positioning accuracy requirements should be as good as that of land, but not sure when this will be needed. In general, depending on situation, think recovery of position should be within 100 to 200 feet. Satellites are believed to be most accurate but also expensive. Topographic mapping, particularly micro-topography requires definite precision in navigation. The use of buoys as bottom markers to support existing navigation systems will be required. If geodetic control is available and if satellite systems are to be used with such systems, will definitely be interested in using such technology. Satellite positioning will be of greatest importance especially if the given positioning information is to be related to geographic latitude and longitude.

Interview 11 - OCEANOGRAPHY

Involved with sound transmission (shallow and deep water), reverberation, scattering, environmental measurements, gravity, magnetic, and many other experiments. Accurate positioning is most important for executing their operations. Never in a position where we can't have better ship positioning. Have requirements for positioning the ship relative to an earth coordinate system and also relative to bottom of the oceans. Have used LORAN-A&C, Decca, VLF, Omega, dead reckoning and satellites. Have had reasonable success with VLF but it was affected severely by diurnal effect which could introduce few miles errors. Satellite is most impressive and gives best results. A combination of satellite and Omega may be a very good thing. The highest accuracy requirement is ±50 feet (CEP) in locating bottom installation relative to a known point on land or in the vicinity of operation.

Usually, if can locate a general area within one-half mile, can get to specific points of interest after some search. Have had some success with SLS (side-looking sonar); its resolution is fair; no verification of interpretation yet.

Lack a means of evaluating properly the accuracy of measurements. Only have been able to repeat some of the measurements and compare the results. A lot of operations in the past have been involved with large areas and general surveys where accuracy was not critical. Experiments on sound transmission so far have not been very effective because of too many variables. A controlled sound experiment in fixing one or more distances between marine geodetic points could yield an improvement of what is known today.

In oceanography the z component of coordinates is most important as far as accuracy concerns in comparison to horizontal x and y components. If we know the z component accurately in geopotential terms, we can measure tides anywhere. If we know isobaric surfaces and gravity potential and relate it to a physical surface, we can advance oceanography and geodesy. Three accuracy requirements most critical for ocean measurements:

(a) Accuracy of ±1 meter for eustatic changes of sea level or land level.

(b) Accuracy of ±10 cm for ocean surface including tides, tsunami, barometric loading, tilt in sea surface, etc.

(c) Accuracy of ±1 cm for dynamic oceanography to determine level surfaces.

Interview 12 - OCEANOGRAPHY AND GEOPHYSICS

Involved in the studies of underwater sound propagation path, ocean floor, subbottom, water mass movement and geophysics. Annual budget for marine work something over $5 million.

Use Autotape for short-range positioning (20 miles); Raydist, Decca, and Shoran for medium range; and LORAN-C, Omega, and the Transit for long range. Also, use a relative positioning system.

Positioning information required is usually limited to what is available. Have a "good appetite" for any good positioning systems to give both fixed intervals and continuous information. Most of operations require to be out at sea on the average of about one month at a time.

The position accuracy requirements vary according to the type of operation performed. For example, require ±1 m standard deviation relative to a land mass about 10 miles from shore and down to depths of 6,000 feet of water. Are interested in knowing the velocity of the ship to ±0.1 knot by the time derivative of position changes. In many instances, require that the geographic coordinates of the ship be known to RMS of 50 to 100 feet. Some of these accuracies have been achieved at the short ranges involved and in the relative mode. If the geographic coordinates can be determined at long ranges from shore "it will be nice".

The positioning system used and its accuracy are of greatest importance. If accuracy requirements cannot be achieved operations in some cases would have to be discontinued. If operations are stopped, cannot estimate this in dollars. In search for the bomb, for example, the existence of the bottom trail left by the bomb in the search for it was a lucky thing. Would like to have a positioning system that can give absolute positioning (in the same land geodetic reference system), but if not available must rely on relative positioning systems as exist today.

Familiar with marine geodetic control and its use similar to land control and believe that it is needed. If geodetic control is available in the area of operations can use many systems available and particularly acoustic system to achieve high precision in local operations. Marine geodetic control should be of great importance for obtaining fixed station coordinates over a long period of time.

One of the major problems is due to the stability of an acoustic path and more work is needed in this area. Accurate information on the velocity and thermal structures of water is needed.

Since there is no standard to establish accuracy criteria of measurements it is quite expensive and don't know how to measure it.

The satellite will have a great role in future positioning; however, it has limitations at the present time in that must use dead reckoning computers to interpolate between fixes. But the satellite can be used on a worldwide basis which is very important.

Interview 13 – OCEANOGRAPHY AND GEOLOGY

Most important areas of activities which require precise positioning information are towed unmanned vehicle, side-looking sonar (SLS), acoustic propagation, and ocean bottom studies (taking samples beyond line of sight). By SLS can penetrate 20 feet into the bottom. Studies involve dropping a transponder in a given area, use overlapping scan to identify the transponder and obtain bottom data, then fly the fish (towed SLS) and drop another transponder, and so on. The transponders' positions must be determined relative to each other and surface positions must also be obtained to relate the transponders' locations so that they may be able to return to the same place at a later time. SLS can identify a transponder if its surface position is determined to ±1000 yards relative. But if the transponder position is given in geographic coordinates (from a chart) then ±100 yards is needed.

Underwater acoustic propagation studies also require positioning information to determine accurately the dispersion effect, arrival point and time. If the points transmitting and receiving pulses are known then sound propagations and variations can be determined more accurately.

The use of satellite for positioning along with inertial systems and marine bench marks (control points) will be the future trend of most accurate marine operations. This combination should allow detail measurements, heat flux and total heat flow, thermal structure, air-sea energy exchange and many other operations of increased value. "To know where you are depends on what you do". Ideally, it is best to record all information on tape with good time base and coordinates (latitude and longitude) cranked into them including ship heading, speed, and acceleration so that you can refer to and analyze them later. Therefore, positioning is among the major requirements for effective sea exploration and exploitation.

Interview 14 – OCEANOGRAPHY AND GEOLOGY

Organization involved in physical oceanography, marine geology, and meteorology. Annual dollar volume of work is about $1.8 million, not including ship operations. Area of operations includes continental shelf and open ocean.

The positioning systems employed are almost everything available, including satellites. The type of positioning information required varies with the type of operations. For example, for scientific requirements maximum control is needed which is why the Doppler satellite is needed. Of course, the secret of the positioning system is to enable the ship to get back and reoccupy the same place. Some operations do not require high accuracy.

The positioning accuracy requirements are also different. When working in one square mile area cannot tolerate as large errors as can in general mapping on 10-mile spacing. It is not possible to give the positioning accuracy achieved because it varies with the instrument, the model number, the operator, and also from one system to another. Accurate positioning systems can be important, e.g., for detailed surveys they want the best they can get, preferably 0 error if possible.

The loss in cost of operations in case of large errors in positioning can only be guessed. The rule of thumb method is about $3,000 to $5,000 per day. This happens quite often, and the surveys are sometimes useless. It is important to employ a more effective and reliable positioning system, but again this depends on purpose. For example, in ten-mile spacing one mile may be satisfactory. But, if the cost of the positioning system is not prohibitive, a higher degree of accuracy would then be desired and they would be willing to use such a system to raise standards.

Familiar to a certain degree with marine geodetic control points, but is not an expert but can appreciate, at least, their use for military purposes which in itself should be enough justification to do more work in this area and find better means for their establishment. Can foresee some legal problems between states, counties, and even international organizations for boundary determinations. The accuracy needed for this control can be stated in two categories: (a) need of a standard for exploration, and (b) need of another standard for exploitation.

It is advantageous to have geodetic control or any other form of control for positioning oceanographic operations; in general, oceanography will use marine geodetic control points but may not necessarily have the requirement for their establishment. The role of the geodetic control in future positioning and mapping operations is definitely of most importance. Geodetic control has always been the most basic element in economic developments. It has to be, or it will be disastrous to think of making all types maps and getting all types of positioning information without relating them to each other. I think you lie to yourself if you think otherwise. Geodetic control will be important for determination of the shape of the ocean surface and ocean floor. Scientists are looking at each of these categories separately. Others are looking at the relative position of the ocean floor with respect to the ocean surface and vice versa. It is startling when you realize that 75 percent of the Earth's surface is water, and do not know much about it geodetically or accurately. Geodesists are the first to come up with four or five decimal places in measurements based on a few measurements which can only indicate that geodesy is behind time in ocean investigations.

The major technical and operational problems are of three types: (a) maintenance, (b) reliability, and (c) complexity. I am always dubious when a new man is operating an instrument, or a new person who does not care about a reference system. It would be difficult to find one system which can be used effectively anywhere and everywhere. For example, may need one system of a high degree of accuracy for the continental shelf areas, and another system such as the Transit which can operate satisfactorily everywhere. The disadvantages of using many systems, of course, are complexity of operations, maintenance, etc. On the other hand, satellites can be used everywhere and it is one system; however, for charting a bay, for example, satellite cannot be used. The reason is obvious that the higher degree of accuracy required can only be obtained by surface systems.

A standard range is definitely needed for geodetic and oceanographic work. This range may not solve all the problems but certainly will go a long way in solving or eliminating many of them. Most of all, however, we need some type of authority who can make decisions and also can enforce them. Flexible to adopting a new system for operations if it is reliable and accurate. May not buy such a system but can recommend it; it is always a function of money. The satellite has already demonstrated its capability in the ocean buoy systems, in communication to the satellite, interrogation of the satellite, and in relaying the data back to earth. There is no end to more effective use of the satellites because everything has been successful to date.

Interview 15 - OCEANOGRAPHY, GEOLOGY, GEOPHYSICS

Organization conducts oceanographic, geological, and geophysical research in the oceans. Interested and operate in all oceans but principally in three or four areas.

The positioning systems used include Decca, LORAN-A, LORAN-C, Hi-Fix, and celestial navigation. Have requirements for fixed and continuous positioning information. Operate year round, day and night. The average cruises are about three to four weeks, with longer cruises on occasions.

The positioning accuracy requirement varies with the individuals and the type of research problem conducted. While a 1/2 to 1 mile error in positions was acceptable in the past, it is now necessary to recover positions within 150 feet, especially when important features are discovered on the ocean floor. The 150-foot accuracy is needed to get the details and perform satisfactory research. Reconnaissance and general surveys can tolerate larger errors. But the problem still remains to be able to return to 150 feet of the same place and particularly to tie seismic lines.

Don't know accuracy achieved because no efforts were made to evaluate the system accuracies. On one occasion, 100 feet was achieved with one system based on past experience using another system for which ±50-foot accuracy was claimed.

Positioning data are of prime importance to oceanographic surveys; in fact, as important as the data collected. Couldn't assess costs due to bad positioning but estimate that losses could amount to $3,000 to $5,000 per day if the ship is unable to operate.

Interested in more effective systems for positioning. Best systems limited to use in small areas. Outside these areas other methods available are not satisfactory.

The major technical operational problems as can be seen by the user are due to limitation of some of the existing equipment in range, accuracy, reliability, and environment. The accuracy that has been achieved by one system in current operation is definitely desirable. Future positioning requirements will demand still higher accuracies.

Can't answer this question on accuracy achieved and establishment of accuracy criteria from experience because we have not had this problem before. During work for the oil industry, the companies used to test their equipment with respect to buoys and ran seismic lines to closest check points. There is a need for a standard range to calibrate equipment. Preferably a need exists for having check points with known exact locations in the area of operations. Such calibration points could serve to test equipment. The only available means at the present time to check these operations are visual sightings on lighthouses and other known features which are limited only to coastal areas. At sea, we have no way to calibrate or test our equipment.

Have flexibility to use a new system which can give better accuracy and reliability. Although the cost will be a major item to be considered, must not forget that the cost of use of the present equipment is expensive.

Believes that satellites will solve problems in regards to all types of oceanographic surveys and will give accurate information that cannot be obtained at the present by other systems. In the long run, satellites are believed to be more economical because no shore networks are needed.

Familiar with marine geodetic control, its purpose and use, and interested in having geodetic control in the area of his operation to reference accurately his oceanographic operations. Regarding marine geodetic control points, their most important use in the future will be for calibration of systems and equipment. These points can provide exact references tied to a common system. When technology reaches the point that mining operations are economical in the oceans, geodetic points will be of greatest importance.

Interview 16 - OCEANOGRAPHY, MAPPING, CHARTING

Having difficulties with regard to the determination of accuracy requirements. Apparently, what is required in terms of accuracies is stated differently even by members of the same organization. The lack of common standards and education in the subject is probably the main source of confusion.

Use all types of positioning systems that are available. Objectives require continuous position information at all times while at sea. The positioning accuracy requirements will depend on the purpose and type of operation performed. It can safely be stated that accuracy requirements are as high as can be obtained approaching that of land geodetic accuracy requirements.

Bathymetry, gravity, and bottom mapping have probably the highest accuracy requirements as far as surveying is concerned. Gravimetric measurements, in particular, are conducted as part of the geophysical and oceanographic surveys. Although gravity measurements require a high degree of accuracy in positioning, this accuracy is unfortunately not really realized yet. Oceanographic surveys for collecting data on the structure of the water and its organisms may not require better than one-mile accuracy. However, these surveys are sometimes concerned with microstructure oceanography. If so, then "micro accuracy" in positioning should be required, otherwise it does not make any difference what you collect and where you collect it.

The positioning accuracy achieved varies and depends on the type of operation and on the one making the survey. Often enough the accuracy stated is misleading, exaggerated, or without any basis. In regard to positioning systems used, they are very important but can't estimate their value in dollars. Regards the use of satellites, ship velocity can be determined from acoustic control which should improve the satellite results. Another possibility to determine the velocity of the ship is perhaps through the use of the Omega system. Omega appears to be very stable for a short period of time. Therefore, through differential positioning at 15-minute periods, the ship velocity might be determined with sufficient accuracy thus eliminating the use of acoustic transponders especially where they are not required.

Familiar with marine geodetic control. Believe that marine geodetic control will be needed in many operations:

(a) Control of survey (minimum spacing required)

(b) Deep submersible

(c) Transcontinental cable laying, particularly in an area where cables must go over a ridge or a rise or meander in topography, where tension over a rise could snap cable. In such areas, the control is essential. Of course, if we are to depend on satellites in the future for communication rather than transcontinental cables, then this need is omitted.

(d) Precise search and recovery

(e) Detailed surveying and mapping.

The role of satellites in marine geodesy probably will be most essential in conducting accurate surveys, especially when used with bottom acoustic transponders for control.

Interview 17 - MAPPING AND CHARTING

Company operations include hydrographic surveys and special site selection to construct charts for navigation aid. Area of marine operation is worldwide. Almost all available positioning systems have been used.

The positioning information required is continuous for all hydrographic and geophysical surveys. The operations at sea are conducted continuously or about nine to 12 months per year. The positioning accuracy requirement for these surveys is ±50 feet. Need 2 σ repeatability. The minimum acceptable accuracy is ±1000 feet.

The best accuracy achieved with one system has about 500-foot repeatability from one year to another. This is assuming that the bathymetry is correct which it is compared with. However, changes in geometry and lack of prominent bottom features in the surveyed area and other reasons degrade the accuracy considerably. The positioning system used and its accuracy are of great importance to our operations.

If required accuracy cannot be achieved, it means we must move to another area. This may cost about one week of ship time or more. These ships cost about $5,000 per day to operate. Certainly would like to have the best systems available. Most of the problems are in regions far from land. It appears we are limited now and in the future.

Familiar with marine geodetic control in concept. Believes that cannot go wrong if control points are established and then use them. This should be more accurate than bottom features and echo sounders. Need something like geodetic control in the area of operations. Need geodetic control for maps if know how to establish it at a reasonable time and cost.

Some standards must be established. The order of accuracies must be determined and evaluated for surveys. What does it mean and what does it take to get it. The datum must be the same in near shore and also far out to sea. If everyone uses the same standards then all maps can be usable. In most cases the latitude and longitude of a navigation aid is given on a chart, however, there is no information indicating the datum on which that chart was based on. This datum problem affects also the type of electronic surveying system you are using especially when establishing a chart related to it. If datum is known, then you discover that it is in error of say one mile, then you can shift everything on the chart systematically.

Can change if the cost of a better system is reasonable. The satellite appears to give best accuracy now out in the oceans. However, we need continuous position information at least every three minutes. Perhaps satellite can be combined with inertial systems.

Interview 18 - RESOURCES

Interest includes those pertaining to commercial and sports fishing, discovery and development of mineral resources beneath the sea, water pollution and hydrology.

Positioning information required varies. If a fish finding satellite is to be used, a quick means of reporting the position of schools of fish is required. This information must also be relayed rapidly to fishing boats so they can converge on the area. The accuracy requirements are about 1 mile. On the other hand, for mineral exploration and exploitation, a higher accuracy in positioning is required. This accuracy must be good enough to allow returning and reoccupying the same position. It should be as good as we can get it. It is essential to have an accurate positioning system to exploit mineral resources even if it doubles the cost. For mining operations fixed locations are probably all that is necessary. For submersible vehicles, positioning information must be accurate in 3-dimensional cases. For pollution problems and this is especially for dumping materials, and so on, it is necessary to know position within plus or minus half a mile and be able to map currents. Positioning accuracy required can thus range from few feet to one mile. The positioning accuracy currently being achieved is not known.

Familiar with the geodetic control only as it is on land. As to marine control, it may be needed for photography and to obtain position information of first order accuracy. Do not know the accuracy requirements for the various operations and how they would be affected by the control. Expect that several problems would be associated with locating a vehicle with respect to discoveries on the ocean bottom, etc.

It is necessary that some type of control be established to stake out claims and also be enforced on an international basis. The more precious and valuable the claims, the more accurately the stakes should be located. It is like a city property. If it is in a downtown area every inch counts, and thus a highly accurate survey is required. Their use in the future will be certainly of great importance.

Interview 19 - MAPPING AND RESOURCES

Fifteen to twenty percent of existing ocean maps of the 1:1,000,000 scale may be usable (it is not known how "good" these maps are). Other maps are either insufficient or non-existent. Even coastal line maps suffer similar problems as to their quality and accuracy. This problem was dealt with last year during an international conference, and a resolution was passed to study the problem. Since maps cannot be established overnight, plans for actual systematic mapping of the ocean floors should start as soon as it is practicable. Accuracy is of most importance. Of course, it depends also on the scale of maps made. Positioning systems' accuracy is of greatest importance. The best systems available should be employed. Accurate geodetic control at sea similar to that on land also must be provided for these maps.

Marine geodetic control will soon become as important as land control for mapping and economic development. People and organizations must be educated first in geodetic work so they can recognize the problems involved. For example, at present there is no dispute about the need for control on land, why should it be different at sea? Control at sea in an area of operation is definitely desired.

Foresee problems of physically identifying boundaries in the ocean both as international boundaries and as lease granting concessions for exploration and exploitation of ocean resources.

There is no means at the present time whereby you can definitely know the accuracy of positions at sea. Accuracy requirement should vary with scale of maps - for 1:1,000,000 scale 0.2 mm on the final chart, 0.1 mm = 100 meters. For actual observations the figure should be about half as much or 50 meters. However, 50 meters is more than we can dream for at the present time. In the areas of importance 10-25 meters may be required. Of course, you are then reaching the engineering scale. At that stage local or relative accuracy is needed. Accuracy for operational purposes is also required especially when moving from one control to another.

Quite flexible to use better means of positioning if necessary, if mission requires, especially if you have to protect economic rights of one person or country. International conflict can also cause quite a bit of discomfort which no one country can afford.

Satellites have proven themselves for land geodetic use. They should definitely be explored and utilized in the establishment of ocean map control and also for positioning.

The major problems are:

(a) Lack of information and knowledge of sea floor, its structure, and property.

(b) Need first general map as on land, 1:1,000,000 scale.

(c) Procedures for establishing these maps, positioning must be coupled with control. Otherwise we will have wild-cat operations with everyone going in his own direction.

(d) Fast ocean mapping system. Echo sounders are too slow.

(e) Theoretical work must be established now. Example, the basic mathematics involved in the use of satellites for resection in space for geodesy was developed much before the launching of satellites.

(f) Priority areas may be listed in the following orders: the shelf, slope, then deep water - South Africa and North Sea are already priority areas.

(g) Means of predicting ocean resources.

(h) Means of positioning accurately boundary lines between established fixed control.

Interview 20 - FISH RESOURCES

Interested in marine biology and the effective monitoring and locating of schools of fish. Eighty percent of the time spent at sea is wasted in hunting for fish. Looking for better means of identifying and of locating schools of fish on the high seas. Area of interest includes all the oceans, and thus all sorts of navigation and positioning systems are used.

For research purposes position fixes are required something on the order of every one to six hours. The position accuracy requirements are on the order of one-half mile. With submersibles there is a need for higher accuracy. It is nice to know the position very accurately; however, such is not usually required.

Interested in satellite positioning and believes the satellite will become an efficient tool to locate and to monitor the schools of fish in the oceans. No information on the cost of operation in terms of dollar losses due to inaccuracies in positions.

Can be considered as a user of marine geodetic control if such were available, but have no requirement of need for such control. If it is there, would be very happy to use it.

The major technical operational problems that the user can see have nothing to do with positioning. Lesser problems can see, are related to the precise position of the submersible vehicles when surveying on the bottom to locate fish, also improving the accuracy of positioning particularly for research vehicles.

Interview 21 - EQUIPMENT AND SYSTEMS

Believe that satellites will be the best tools ever used for oceanography. It may take another five years, however, before the government agencies realize the full capability of satellites, their accuracy, and speed of collecting information from the vast oceans. In regard to needs of other positioning systems and their accuracies, we are expected to explore the oceans, the development of satellites and improvement of their accuracy must be pursued continuously.

Interview 22 - EQUIPMENT AND SYSTEMS

Company involved in almost all types of ocean operations, both defense and commercial. Budget in ocean-related activities is of the order of $60 to 70 million per year. For commercial purposes, interested primarily in the continental shelf at the present time. For defense and R&D, interested and operating in the deep water.

The positioning systems used are acoustic and electronic systems. The latter were not satisfactory for precise positions when calibrating an acoustic system. Requirement was precision of ±1 foot. Surface positioning at five miles from shore did not give this accuracy due to multipath reflection effect. Accuracy in any case deteriorates as distance increases from shore. Surface positioning is important in an acoustic system if have to relate its position with respect to land or an earth coordinate system.

Familiar with marine geodetic control, its purpose and use. State of the art is now such it is possible to establish control at sea starting out with continental shelf areas and progressing to other important areas in the deep ocean. Geodetic control will be required certainly for mapping and perhaps some other operations requiring high precision in location.

Major technical problems are associated with how well do we know our systems. Interested in determining the accuracy of acoustic positioning methods with some known standards but unfortunately this has not been possible. The electronic systems used appeared to lack calibration standards themselves. This points out the need for a precise geodetic standard for test and calibration of available positioning systems in the environment for which they are designed to operate.

As far as known, there is no good absolute basis for establishing accuracy criteria. All that can be done at present is compare one system against another or determine the internal consistency of measurements.

The satellites' role in future positioning may be satisfactory for fixed stations but it will be limited in accuracy for navigation because of the inaccuracy in knowing the velocity of the ship. Do not know of any good means to determine the velocity of the ship when moving.

Interview 23 - EQUIPMENT AND SYSTEMS

Operations at sea related to underwater sound operate everywhere in the oceans.

The positioning systems used are those that are available at the present time plus acoustic navigation systems. Both continuous and fixed positioning information required. The time needed to perform operations varies from weeks to months.

Need high accuracies of the order of ±30 feet if performing search and recovery. With this accuracy can be more effective in search and can eliminate going over the same area or overlapping for fear of missing. At present must overlap tracks because of inaccurate surface navigation. The accuracy of the system employed is essential as in the case of the bomb off Spain. Costs are not important in such cases where politics, international situations are at stake. If an accurate system is available we will use it with no limits. We can adopt easily if a satisfactory system is available.

The accuracies achieved vary. However, these accuracies are not really known. How do you know that the given position information indicates exactly where it is supposed to be? Need some fixed references to calibrate with and to evaluate the systems.

Familiar with geodetic control which would be desirable to have. If a grid system is established in a given area with good geodetic accuracy will certainly simplify acoustic navigation positioning operations. With such points available can then obtain ±30 feet desired accuracy. Were lucky in locating the bomb. Geodetic control for mapping is important. However, for positioning you need many points.

The major problem is that there is no satisfactory system at the present time. Acoustic systems are now available with one transponder. Such a system, however, is relative and you can't get the geographic coordinates of the points. Don't think that inertial systems are the answer although not an expert on them. Perhaps a combination of systems such as the satellite plus the acoustic navigation will be the best thing. Satellite is not continuous and the acoustic system can help in between perhaps. The satellite may give good accuracy if can be on station for a long time. It could be great if you get sufficient fixes.

Interview 24 - EQUIPMENT AND SYSTEMS

Activities involve instrumentation for ship and/or vehicle control, navigation, surveillance.

Positioning systems used are hyperbolic radio systems, inertial, and dead reckoning, and transponder net interrogation. Continuous positioning is required in all cases (LORAN, inertial). Accuracy requirements depend on the operation performed. The positioning system used must be important since it costs a great sum of money and effort. Have had no dollar losses from bad positioning. Directional problems at sea are of great importance, just as important as positioning - precise azimuth reference.

Not very familiar with geodetic control except in name, but familiar with bench marks, but could provide a reference system.

Establishment of accuracy criteria and requirements. Yes, this is an important thing to consider. We need some reference systems. Limited access to one is not sufficient.

Interview 25 - EQUIPMENT AND SYSTEMS

Involved in developmental work leading to equipment and methods for production. Particular program is the order of $1/2 million. Interested in the deep water everywhere. Use LORAN-C mostly; radar is used close to land but not all of the time. Require continuous positioning information when at sea which varies between two weeks to four weeks per year.

Nice to know positions 50 to 100 feet but we can't get it. The accuracy achieved is that of whatever LORAN-C can provide, perhaps 1,000 to 1,500 feet. Important to have an accurate system because it could restrict operations. Usually we try to relate to bottom topography as a check. If have accurate systems don't need this additional work.

Costs of poor positions associated with degradation of data. Must depend on other forms of navigation. Local acoustic net may be required which may cost about $100,000 to achieve the desired accuracy. Cost not a factor for more effective system. Place many transponders just to pick up a site now.

Familiar with geodetic control, and local geodetic net within area of operations is desirable. Need geodetic control so that we can calibrate with it.

Have many problems. Must use whatever is possible. Omega and satellites not accurate enough. Satellites good for a singular reference system but need continuous information; maybe system can be used with other systems.

As to accuracy criteria and evaluation of positioning systems, can only compare with something else sometimes, but who knows which is correct.

Interview 26 - EQUIPMENT AND SYSTEMS

Involved in all types of navigation experiments and have used most of the available systems, including surface electronics, satellite, inertial, star trackers, and acoustic systems. In the deep ocean, most of these systems except satellite navigation are unsatisfactory. Have experimented with positioning the ship over three acoustic transponders and have never been able to achieve the accuracies (few feet) claimed by supposedly leading organizations no matter how many corrections were applied.

Satellite Doppler navigation, although in the middle of the ocean is better than anything available at present for positioning, is still affected by errors in ship velocity. Would like to determine ship velocity to better than 0.1 knot. Accuracy requirements in positioning are of the order of ±100 feet rms in an earth coordinate system or ±25 feet relative. No doubt that satellite navigation and marine geodesy will play a big role in advancing positioning capabilities. Major problems associated with present surface-based positioning systems are due to nighttime activity (skywave effects), geometry, range limitation, and lack of calibration points in the areas of operations. A marine geodetic range of the type mentioned in article by Mourad and Frazier is needed.

Interview 27 – EQUIPMENT AND SYSTEMS

Involved with deep submersible vehicles and all types of navigation relative, absolute, and close to shore. Marine activities total about $1,500,000 per year, including close to shore work. The area of operations is mostly deep water for submersibles.

The positioning systems used are the Transit satellite plus inertial systems. The type of position information required is fixed positions by the satellites up to ±300 feet and then interpolation between fixes to 30 or 40 units. The time required to complete an operation is dependent on the type of operation.

The positioning accuracy requirement is also dependent on the type of operations; for example, exact locations are needed for geological and geophysical surveys. For oceanographic and meteorological data collections, lesser accuracy is required. In some operations the positioning system is essential, in others not so.

The accuracies achieved with LORAN, radar, and SINS are not satisfactory. Radar may be okay for some operations. Accurate SINS is expensive and needs to work with other systems for absolute positions. NAVOCEANO data collected are not good. They are built on different standards. To establish standards one must be able to get few feet accuracies first.

Familiar with marine geodetic control and its purpose but does not need it for operations close to shore. In other areas of the ocean, it may be required for certain surveying and mapping. In the future you will require geodetic control for accurate mapping. The major problems are those of cost of systems. To get adequate fixes from satellites every 10 minutes or so will require many satellites and many black boxes and these may not be satisfactory from the taxpayer's viewpoint. To be honest about it, if 100 feet can be obtained from satellites fixes, then we can use inertial systems in between fixes (precise dead reckoning) to obtain satisfactory results when needed. You don't mind the cost if you can get what you want if you need it.

APPENDIX B

DESCRIPTIONS OF SATELLITE METHODS

A review of the available literature pertaining to satellite geodetic methods revealed the lack of comprehensive technical coverage. Discussions were usually found to be either too general to provide useful information for the reader already somewhat familiar with the subject or too narrow and specific, concentrating on a special aspect of a method and/or methods and obscuring the overall picture. Therefore, it was necessary during the investigation to make an organized compilation of the materials found in a more useful form. That compilation is presented here in the hope that others with similar interests will find it helpful.

Five satellite methods are discussed:

(1) Doppler

(2) SECOR

(3) Radar

(4) Optical

(5) Laser.

DOPPLER METHOD

One possible procedure for positioning and/or establishing geodetic control is based on the measurement of the Doppler shift of radio frequency transmissions from a satellite. This Doppler shift is actually a change in the measured frequency of a constant signal as transmitted by the satellite and received by the observer. This change or shift results from the relative velocities of the observer and the satellite. It is illustrated graphically by the Doppler curve in Figure B-1. The point of inflection of this curve corresponds to the time of closest approach, t_C. The basic property of the Doppler curve is its symmetry relative to the time t_C for uniform satellite motion. As the satellite approaches the observer, the received frequency is greater than the transmitted frequency and the Doppler shift is positive; as the satellite recedes, the opposite is true and the Doppler shift is negative.

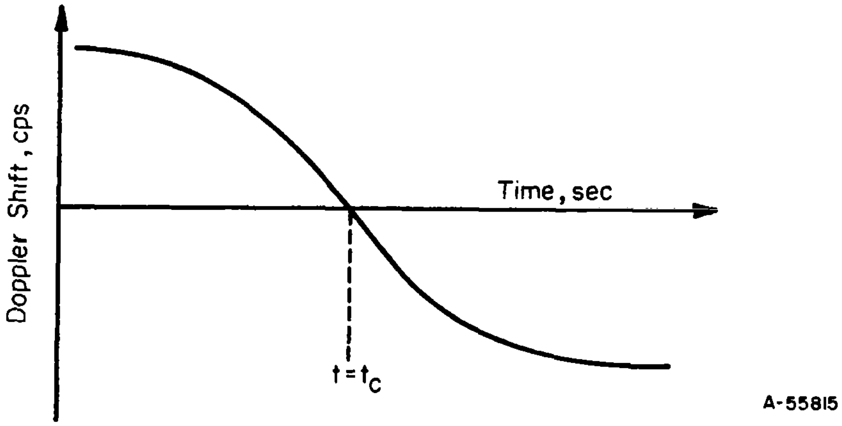

FIGURE B-1. DOPPLER SHIFT CURVE

Two types of satellites are available for obtaining Doppler data – the GEOS-type satellites, including the French satellites Diademe I and II, and the Navy Navigation Satellites (Transit) (see Table B-1). Associated with these are two types of receivers – the Geoceiver which can receive signals from both types of satellites and the navigation receiver (AN/SRN-9) which can receive signals only from the Navy Navigation Satellite System. Since the GEOS-II has no memory to store updated orbital data, as in the Navy Navigation Satellite system, it does not transmit orbital data to the observer to permit an accurate position fix. Consequently, it is used in this mode primarily for establishment of geodetic control rather than for positioning* Thus the Doppler data obtained from many passes of the GEOS satellite over a certain area are later combined at the computer center with accurate orbital data received from satellite tracking stations to obtain station coordinates.

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*Other applications of the Doppler data, i.e., dynamic geodesy, are not discussed here.

TABLE B-1. SATELLITES AVAILABLE FOR OBTAINING DOPPLER DATA

	Navy Navigation Satellites	GEOS-II	Diademe I Diademe II(44)
Frequencies transmitted, mc	150, 400	162, 324, 972	149.97, 399.92
Interval between timing signals, min.	2	1	
Memory equipment to receive, store, and transmit orbital data	Yes	No	No
Inclination, degrees	Near Polar	$i \approx 80$	$i \approx 40$

The Navy Navigation System presently includes thirteen fixed tracking stations located worldwide and used for geodetic Doppler applications. There are presently three operational Navy Navigation Satellites. Since they transmit orbital data, they can be used for positioning as well as for geodetic control. The satellite's orbital parameters are originally determined from Doppler data obtained from four fixed satellite tracking stations and transmitted to the Central Computing Center, which updates the orbital parameters and extrapolates the satellite's trajectory for at least a day into the future. The new orbital parameters, along with a time correction from the U. S. Naval Observatory, are transmitted to one of two injection stations, which injects them into the satellite's memory. Shipboard navigation equipment receives and records the Doppler shift and the orbital information from which the latitude and longitude of the ship can be determined.(35)

The use of the Doppler shift has many favorable aspects. Unlike optical techniques, this system is all-weather. The equipment is compact, transportable, and relatively easy to operate. Since no angular data are needed, special antenna arrays are not needed nor do the problems of antenna bore-sighting or stabilization arise. Furthermore, when the system is used for positioning, the navigator can employ various degrees of sophistication in his instruments and computing equipment to obtain the degree of accuracy required(36).

Like any method, the Doppler has its drawbacks. One main problem is positioning between satellite passes. Continuous fixing would be possible if 24 satellites situated in orbital planes at 45° angles to each other (six satellites in each of four such planes) were launched.

Mathematical Representation of Doppler Shift

The received frequency, f_r, is given by the relationship:

$$f_r = f_t - (v \cdot \cos A/c)f_t = f_t - (\dot{\rho}/c)f_t \quad , \qquad (1)$$

where

f_t = frequency transmitted by the satellite

f_r = received frequency

v = velocity of satellite relative to observer

c = velocity of light

ρ = slant range from observer to satellite

A = angle between velocity and range vectors

$v \cdot \cos A$ = radial velocity, taken positive away from the observer (see Figure B-2).

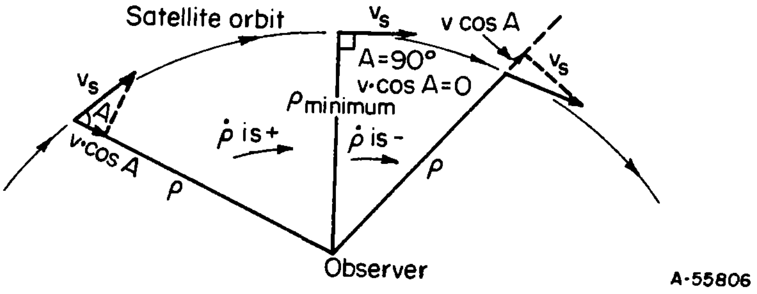

FIGURE B-2. DOPPLER PRINCIPLE

The terms $(v \cdot \cos A/c)f_t$ and $(\dot{\rho}/c)f_t$ are two different ways of writing the Doppler frequency. The frequency, f_t, in this case is considered to be propagated through a vacuum and the Doppler frequency referred to is the vacuum Doppler. At the point of closest or minimum approach, $\dot{\rho}$ is zero and hence the Doppler frequency is zero, or in other words, the received and transmitted frequencies are equal. If the satellite orbit is approximated by a straight line over the short portion near closest approach, $\dot{f}_D(t)$ is given by:

$$\dot{f}_D(t) = -(f_t/c)(v^2/\rho) \quad . \tag{2}$$

Hence,

$$\rho = -\frac{f_t}{c} \cdot v^2/\dot{f}_D(t) \quad . \tag{3}$$

Equation (2) is typically in error by 15 percent for an actual satellite, which is not accurate enough to use in navigation computations(74). In practice, the Doppler data is subjected to a least-squares fit to obtain the latitude, longitude, and the difference between the frequency of the observer's local oscillator and that of the satellite.

Ionospheric Refraction

The effects of ionospheric refraction must be considered if high accuracy is desired. In correcting for ionospheric refraction, use is made of the fact that the Doppler effect is directly proportional to the frequency, whereas the refraction effect is inversely proportional to the frequency, to first order accuracy(8). The Doppler shift in the presence of the ionosphere is of the form(36):

$$f_D(t) = -\frac{f_t}{c}\,\dot{\rho}(t) + \frac{\alpha(t)}{f_t} + \frac{\beta(t)}{f^2{}_t} + \ldots \qquad (4)$$

By simultaneously measuring the Doppler shift at two different frequencies, the first order refraction term is eliminated. The result is the vacuum Doppler shift and only second and third order contributions of refraction.

The Navy Navigation Satellites transmit two frequencies of approximately 150 mc and 400 mc. These two frequencies are controlled by the same highly stable oscillator so that although one frequency nominally set at approximately 400 mc varies slightly from satellite to satellite and drifts slowly within one satellite, the second frequency is always accurately kept at 3/8 of the higher.

The GEOS-II satellite is presently transmitting three frequencies which will be employed to further ionospheric refraction studies. The third frequency is used to eliminate third-order ionospheric contributions from the desired terms since these contributions are considerably larger in magnitude than second-order effects. The three-frequency solution for the vacuum Doppler shift should eliminate all significant ionospheric contributions. (99)

Operational Procedures

Measurement of the Doppler Frequency

The acquisition of Doppler data involves either a measurement of the instantaneous* Doppler frequency or a measurement of the integrated Doppler frequency. In either case, the measuring equipment receives two frequencies (three with GEOS satellites) along with their corresponding Doppler frequencies and ionospheric refraction effects. After a series of dividing and mixing operations, the result is the same as that which would be obtained if a frequency, f, had been propagated through a vacuum producing the vacuum Doppler, f_D. The received frequency could then actually be referred to as $f + f_D$. This notation will be used throughout in order to simplify the explanations, with f referred to as the effective frequency.

The output of the converter in the instantaneous Doppler measurement is the time interval Δ that it took to count N_c cycles of the vacuum Doppler, where N_c is some chosen number. The average frequency measured is then easily obtained by dividing N_c by Δ. This average is assigned to the time:

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*Instantaneous means measuring the average frequency over an interval so short that the average value can be taken as the true value at the center of the time interval, with negligible error.

$$t = t_0 + \frac{1}{2}\Delta + \frac{1}{2} N_c - 1 \quad ,$$

where t_0 is the time the count was initiated and the term $\frac{1}{2} N_c - 1$ is a corrective term. (76)

The integrated Doppler measurement, which is performed by using the AN/SRN-9 equipment, is simply a count of the number of cycles, N_c, of the measured frequency for a two-minute time interval. Since operational navigation satellites transmit accurate time markers every two minutes, these time markers are used to control the stop and start of the Doppler counter automatically. The number N_c is printed out on a tape along with the ephemeral data and Kepler parameters for the satellite(35). During one pass of the satellite, five to seven integral values are usually obtained.

The actual frequency measured is not the vacuum Doppler frequency but rather this frequency plus some constant. This is due to the fact that there is a frequency offset between the frequency transmitted by the satellite and the standard frequency of the observer's oscillator. The procedure involved in the AN/SRN-9 equipment will be discussed to explain this. The standard frequency, f_g, is kept equal to 400 mc as accurately as possible and the satellite frequency is kept lower by 80 ppm or 32 kc. The measured frequency, f_m, then becomes:

$$f_m = f_g - (f + f_D) = (f_g - f) - f_D \tag{5}$$

or,

$$f_m = 32 \text{ kc} - f_D \quad .$$

Since the frequency offset varies slightly from 32 kc, it is treated as an unknown parameter in the computations.

At the time of closest approach, t_c, the Doppler frequency is zero and the measured frequency is approximately the same as the offset frequency (32 kc). Data collected from a pass of a satellite would result in a Doppler shift curve as shown in Figure B-3.

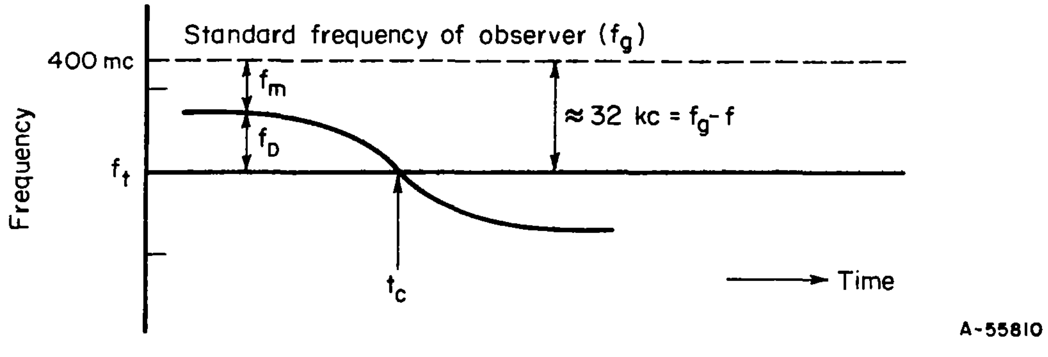

FIGURE B-3. MEASUREMENT OF DOPPLER SHIFT

The volume of data gathered in Doppler integral measurements is much smaller than that for instantaneous measurements, being contained in five to eight data points per pass as compared with 200 to 400 data points per pass for instantaneous Doppler measurements. The three best data points can be used for immediate positioning and the others archived for an analysis of the data at the lab.

Determination of the Observer's Latitude and Longitude

In Equation (1) the vacuum Doppler frequency, f_D, was shown proportional to the range rate according to,

$$f_D(t) = -\frac{f(t)}{c}\dot{\rho}(t)$$

In order to be more precise, the time required for the signal to travel from the satellite to the observer and the fact that the observer is also moving must be considered. The mathematical notation used here to describe this situation closely follows that of Newton.(76)

Let t_i be the Universal time of the satellite at which a signal is transmitted and $\bar{r}(t_i)$ its position at this time. Let τ_i be the time the signal arrives at the observer and $\bar{R}(\tau_i)$ his corresponding position.

The range ρ is a function of both times and is defined as:

$$\rho(t_i, \tau_i) = \left| \bar{r}(t_i) - \bar{R}(\tau_i) \right| \tag{6}$$

Figure B-4 shows range considered as a function of time. At time t_i the satellite's position is $\bar{r}(t_i)$. The signal transmitted at time t_i arrives at the observer at time τ_i when the observer's position is $\bar{R}(\tau_i)$. At time τ_i, the satellite's position is now $\bar{r}(\tau_i)$ and $\tau_i - t_i = \Delta t_i$ where Δt_i is the time it took the signal to travel the distance ρ to the observer at a rate c. Therefore, $\Delta t_i = \rho(t_i, \tau_i)/c$.

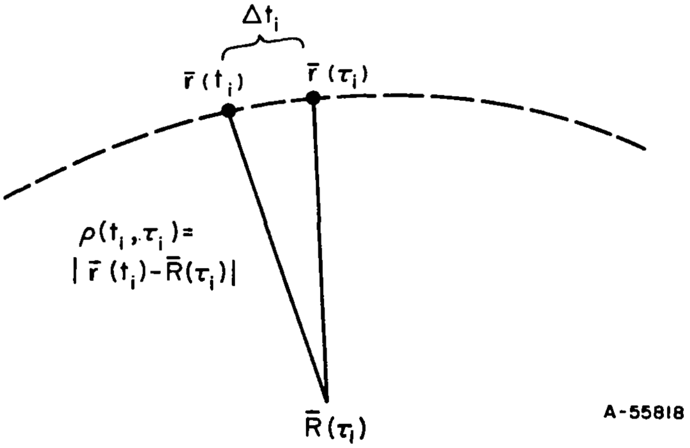

FIGURE B-4. RANGE AS FUNCTION OF TIMES

Whether t_i or τ_i is the independent variable depends on the method of measurement used. $\dot{\rho}$ will mean the rate of change of ρ with respect to the time adopted as the independent variable. The (vacuum) Doppler frequency, f_D, can then be written as:

$$f_D(\quad) = -(f/c)\,\dot{\rho}(\quad) \quad , \tag{7}$$

with the appropriate time inserted in the parentheses.

As was previously mentioned, the integral is performed between the times when two successive timing signals emitted by the satellite are received by the observer. The times these signals are emitted will be denoted as t_i and t_{i+1}, and the times of their arrival at the observer will be denoted as τ_i and τ_{i+1}. The value of the integral will be N_i. The frequency integrated is the difference, $f_g-(f+f_D)$, between the standard frequency, f_g, and the received frequency $f + f_D$. The integral may then be written as (regarding τ_i as the independent variable for the time being):

$$N_i = \int_{\tau_i}^{\tau_{i+1}} (f_g - f - f_D)\, d\tau = \int_{\tau_i}^{\tau_{i+1}} f_g\, d\tau - \int_{\tau_i}^{\tau_{i+1}} (f + f_D)\, d\tau \quad . \tag{8}$$

As accurately as possible, f_g is held constant and it will be treated as a constant in the integration. The first integral then becomes $f_g(\tau_{i+1}-\tau_i)$. Now the frequency multiplied by any time interval equals the number of cycles received during that interval. The second interval above means physically the number of cycles received between the times when two timing signals are received. But this is the same as the number of cycles of the frequency, f, emitted by the satellite between the times of emission of these signals, t_i and t_{i+1}. Hence,

$$\int_{\tau_i}^{\tau_{i+1}} (f + f_D)\, d\tau = \int_{t_i}^{t_{i+1}} f\, dt = f(t_{i+1} - t_i) \quad , \tag{9}$$

where f is constant to a high accuracy. Therefore:

$$N_i = f_g(\tau_{i+1} - \tau_i) - f(t_{i+1} - t_i) \quad . \tag{10}$$

Using the relationships between the times, this becomes:

$$N_i = (f_g - f)(t_{i+1} - t_i) + f_g(\Delta t_{i+1} - \Delta t_i) \quad . \tag{11}$$

Which, in turn, becomes:

$$N_i = (f_g - f)\,\Delta T + f_g/c\,[\rho(t_{i+1}, \tau_{i+1}) - \rho(t_i, \tau_i)] \quad , \tag{12}$$

where the interval $(t_{i+1} - t_i) = \Delta T$ is two minutes.

Expressing the distances in terms of the positions of the observer and the satellite:

$$N_i = (f_g - f)\,\Delta T + f_g/c\,[\,|\bar{r}(t_{i+1}) - \bar{R}(\tau_{i+1})| - |\bar{r}(t_i) - \bar{R}(\tau_i)|\,] \quad . \tag{13}$$

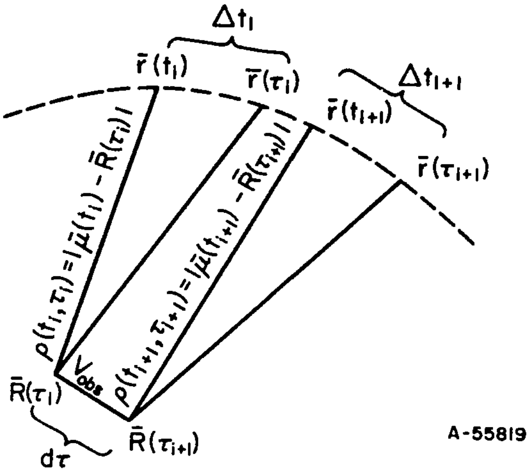

FIGURE B-5. MEASUREMENT OF DOPPLER INTEGRAL

In Equation (13), the positions of the satellite $\bar{r}(t_i)$ and $\bar{r}(t_{i+1})$ are determined from the orbital parameters transmitted by the satellite and hence are known. The only unknowns are the frequency offset, $(f_g - f)$, and the positions of the observer $\overline{R}(\tau_{i+1})$ and $\overline{R}(\tau_i)$. All the positions of the observer must be expressed in terms of two unknowns, namely the latitude and longitude of the observer at some specific time.

The times at which the frequency was measured will be denoted by τ_μ. Selecting one of these times as τ_o, the ground coordinates of some position of the observer $\overline{R}(\tau_o)$ can be written as a function of the observer's latitude φ_o, longitude λ_o, and time τ_o. The other positions of the observer at times τ_μ are then expressed in terms of the unknowns φ_o and λ_o and the known τ_o:

$$\overline{R}_1(\tau_1) = f(\overline{R}(\tau_o)) \mid \tau_1 = f(\varphi_o, \lambda_o, \tau_o) \mid \tau_1 ,$$

$$\overline{R}_2(\tau_2) = f(\overline{R}(\tau_o)) \mid \tau_2 = f(\varphi_o, \lambda_o, \tau_o) \mid \tau_2, \text{ etc.}$$

If the observer's position were fixed, the only change in his earth-fixed coordinates would be that due to the rotation of the Earth. The situation is complicated somewhat when the observer is moving and knowledge of his motion between Doppler integral measurements is required. The observer's velocity is an input to the computation of position. Any error in the estimate of his motion will lead to an error in his position determination. Assuming for the present that the velocity of the observer is known, the solution is the same as before with allowance being made for this motion, i. e., some time epoch τ_o is selected and the coordinates of the observer at this time, φ_o and λ_o, are the unknowns. The coordinates at any other time are written as functions of these unknowns. Each integral measurement of N_i results in an equation with three unknowns, Δf, φ_o, λ_o, where $\Delta f = (f_g - f)$. If the values of three integrals, N_1, N_2, and N_3, are used in the computations, a unique solution results for Δf, φ_o, and λ_o. To obtain an immediate position fix, three such integrals are usually chosen. For a more accurate determination of these unknowns, all the integral values obtained during a pass are used and a least-squares adjustment performed. Preliminary estimates of φ_o, λ_o, and $(f_g - f)_o$ are formed for some time epoch, τ_o, lying within the time spanned by the values of τ_μ and not necessarily being the same as one of these values. The estimated values for φ_o and λ_o can be determined by dead reckoning from a previous fix or from an independent navigation method. The positions, $(R(\varphi_o, \lambda_o, \tau_o) | \tau_\mu)$, of the observer at times τ_μ are estimated followed by an estimation of the values of N_i. The set of parameters which makes the estimates best fit the measurements is then determined.

Accuracy

The sources of error in the Doppler system include those which are effective regardless of the location of the observer (land or sea) and those peculiar to shipboard operations. Only the former will be discussed at present leaving the latter for a discussion of the application of the Doppler system to marine geodesy.

The accuracy of the Doppler system for positioning is presently ±25 meters for a fixed station on land from data obtained from a single pass of a satellite. The errors in positions obtained from a single pass of the satellite are due to:

(1) Measurement contribution

  a. Random: ±5-10 meters

  b. Upper limit to bias (bias caused mainly by refraction): ±3 meters

(2) Orbit contribution

  (i. e., incorrect positioning of satellite): ±20-25 meters

(3) Coordinate system for the earth: ±10-15 meters(77).

As can be seen from the preceding, the largest error is that due to the determination of the satellite orbit and its prediction for a day into the future. Satellite position errors result in an error in the observer's position in roughly a 1:1 ratio.(75) The satellite position errors are due mainly to a lack of knowledge of the earth's gravity field. Through the continued efforts of satellite geodesists in this area, however, one can expect a continual reduction in this error*. This factor, coupled with the recomputation of the data at a later date after better satellite orbit parameters have been provided, will provide higher accuracy(35).

A secondary source of error in the satellite's position is due to air drag. This presents a somewhat different problem since air drag is unpredictable, being influenced by solar activity. Future research does not promise to reduce air drag errors. However, satellite position error resulting from the errors in the force of air drag may be reduced by obtaining retracked satellite orbits, i. e., by archiving the data for further reduction after considerable improvement in geodesy has been made(35).

The random errors can be reduced by increasing the number of passes for which Doppler data is obtained. (This would be done especially when establishing geodetic control.) Accuracy is gained by adding more and more data only up to the point where unknown biases in the data produce errors comparable to the accuracy obtained by using redundant data. For this reason, many studies have been done regarding these biased errors, such as frequency drift and ionospheric and tropospheric refraction.

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*This error has already been reduced from ±75 meters in 1964 to its present value(75).

As was previously mentioned, a correction is made for the effects of ionospheric refraction by using two frequencies and eliminating the first order refraction term. The residual refraction errors are usually negligible, but they do vary widely with position and solar activity, being exceptionally large at low latitudes.

Tropospheric refraction contributes to the Doppler shift on each transmitted frequency also. However, this refraction is almost independent of frequency and thus is not affected by frequency mixing as is the ionospheric effect. In order to make a correction, a model of the troposphere is used along with meteorological observations at the time of the satellite pass. This method has been successful except when a weather front is near the observer.

The angle of elevation, χ, of the satellite also affects the accuracy of a position fix. For low values of χ, the satellite is not above the horizon long enough for the Doppler frequency to depart significantly from a linear function of time. Consequently it is not possible to deduce the frequency offset accurately and the time of minimum approach. This causes an error in the along-track component of the observer's position. When the satellite passes directly overhead, the errors in the cross-track component are large since the slant range changes very little for changes in cross-track position when near the plane of the satellite. Also, ionospheric refraction effects are greatest for low elevation angles and affect positioning accuracy.

In order to minimize these effects, only passes for $15° \leq \chi \leq 75°$ are used, although those near 15° are somewhat poorer. In order to improve on the coordinate system for the earth, the motion of the North Pole will be considered in the next analysis of data performed at the Applied Physics Laboratory of the Johns Hopkins University(77).

SECOR METHOD

The SECOR (SEquential COllation of Ranges) system, operated by the Army Map Service is a ranging system operating on the physical principle that modulation of an electromagnetic wave through space will undergo a phase shift proportional to the distance traveled and proportional to the modulation frequency. A measurement of the difference of phase between the transmitted and received electromagnetic wave provides a means for determining distance. A CW (continuous wave) is transmitted at one location and is received by a transponder. The transponder retransmits the received signal (without changing its phase). The retransmitted signal is received at the original location where its phase is compared with that of the transmitted signal. This principle is illustrated in Figure B-6 where the phase difference between the outgoing and incoming frequency with a wavelength of 512 meters is 270°. The total distance, 2D, is equal to the total number of cycles times the wavelength; i. e., 2D = (V + 3/4) (512 m) where V is an integral number of cycles.

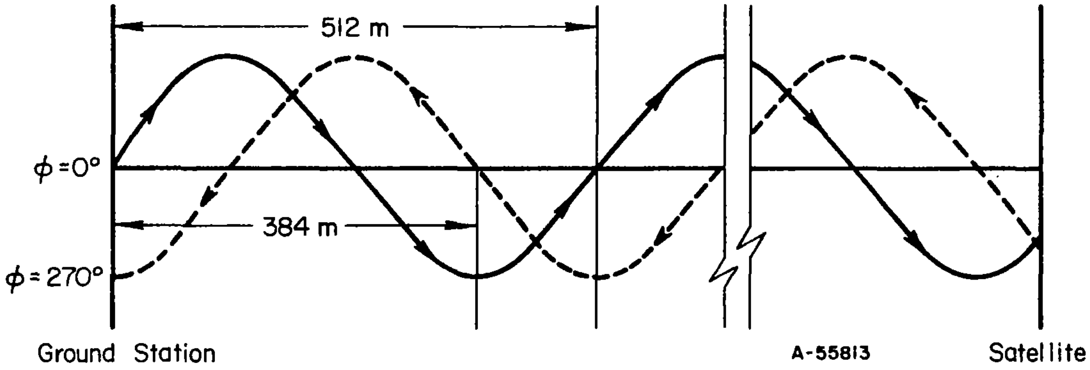

FIGURE B-6. SECOR PHASE MEASUREMENT(28)

The main advantage of the SECOR system, as in all electronic systems, is the fact that it is an all-weather system. The vast redundancy of data available, coupled by position checks through multiple determinations of range, has been SECOR's most prominent claim to achievable accuracy.

On the liability side, there is the fact that SECOR requires an active satellite; i. e., the satellite must be equipped with a transponder. (The only electronic technique which uses the satellite merely as a reflector of energy is radar, but this has had limited use for geodetic purposes.) Also, the simultaneous method of observation requires that four ground stations and a satellite meet certain geometrical requirements for good results. The orbital mode is used most frequently although the geometry of the situation has slowed down progress somewhat. This is due to the fact that the satellites now being used have a near polar orbit whereas the network is being extended in a west-east direction. Consequently, distant stations cannot observe the satellite and distance progress is slower.

SECOR allows for only the measuring of distances and neither angles nor directions. However, there has been mention of combining range and direction measurements. (Simultaneous SECOR and optical measurements were attempted with the ANNA satellite, but failure of the SECOR equipment prevented measurements.)

SECOR is not as sensitive to frequency stability as Doppler, but does depend much more on an accurate value of the propagation of light in a vacuum.* If four known stations were used instead of three, this source of error would be eliminated(80). However, the total number of ground stations is restricted by the number of channels provided; this is four in the Army Map Service SECOR system(85).

Measurement of Phase Difference

The basic equipment for the SECOR operation consists of an artificial earth satellite bearing a transponder or radio relay and a minimum of four ground stations. The SECOR transponder may be mounted in its own separable satellite or it may be installed as an integral part of a larger satellite. The SECOR transponder is composed of a receiver, transmitters, and power supply which converts the satellite battery voltage to the voltages required.

The four ground stations are equipped with a radio transmitter, radio receiver, precise time clock, an antenna array with servos for manual tracking, a magnetic-tape data recorder, and radio equipment for voice communication within the system. Three air-transportable shelters are used to house this equipment.(30)

Each SECOR ground station measures and records the difference in phase of the outgoing and incoming ranging signal. This phase difference is recorded on a magnetic tape in binary digital form.

In the SECOR system, the transmitter frequency modulates a 420-megacycles-per-second continuous wave with four different measuring frequencies. (See Table B-2.)

TABLE B-2. SECOR RANGE MODULATION SIGNALS(28)

Ranging Frequency Designation, kc		Wavelength (λ), meters	Nonambiguous Range ($\lambda/2$), meters	System Resolution, meters
Very Fine	585.533	512	256	0.25
Fine	36.596	8,192	4,096	16
Coarse	2.287	131,072	65,536	256
Very Coarse	0.286	1,048,576	524,288	2,048
Extended Range 20 Pulses/sec		15,000 km	7,500 km	41.83 km

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*The current tendency in data reduction is to disregard scaling error through the device of considering the value adopted for the velocity of light as being perfect by definition(18).

A number of different ranging signals are used so that an unambiguous range can be obtained; measurements at the successively lower ranging frequencies are used to resolve ambiguities in the measurements at the next higher frequency. Also, the extended range is measured by the time the signal takes to travel to the satellite and back using a scale of 20 pulses per second. The topic of unresolved ambiguities will be mentioned later since this has led to an unexpected source of error. The transponder in the satellite strips the modulating frequencies off the 420-megacycle carrier wave it receives and returns them, without changing phase, on carriers of two different frequencies. All four of the modulating frequencies return on a 449-megacycle carrier and the very-fine, or highest frequency, modulation also rides on a 224.5-megacycle carrier. The difference in the observed length from the very-fine riding the high-frequency carrier and the very-fine riding the low-frequency carrier is used to determine the ionospheric portion of the atmospheric refraction(28) (See Figure B-7.)

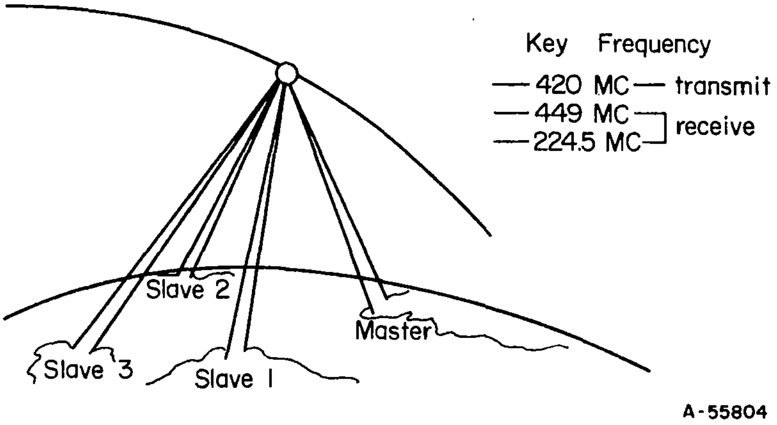

FIGURE B-7. SECOR TRANSMIT-RECEIVE PATTERN(28)

Operational Procedures

Modes of Operation

Three methods of observation are used with SECOR – simultaneous, orbital, and line crossing. The simultaneous method is the most desirable but is not always possible. The line-crossing technique is the least accurate and is not used for geodetic work. The orbital mode is used whenever the geography of the situation does not permit simultaneous observations.

Simultaneous Mode. In the simultaneous operation of SECOR, three ground stations are placed on points of a single geodetic network for which the latitudes and longitudes on the horizontal datum and the elevation on the vertical datum for that network are known. The geodetic coordinates of the fourth station are not known. The purpose is to determine these coordinates and then consider this station a fixed station to be used in further work.

The transponder in the satellite remains in a standby condition until activated by a select call signal generated by a SECOR ground station. The station nearest the approaching satellite is designated as the master station and the other three are referred to as slave stations one, two, and three. The master station interrogates the satellite first. The return signal is received by all four ground stations and displayed on their oscilloscopes. Operators at the slave stations adjust their transmission times for their signals to arrive at the transponder in numerical sequence in order for the transponder to be relaying the signal from a single station for 10 milliseconds, rest 2-1/2 milliseconds, and relay the signal from the next station for 10 milliseconds. In a seven-minute period of simultaneous tracking, each ground station measures and records 8,400 ranges, making a total of 33,600 for all four stations. This time-sharing method permits simplification of equipment and the use of a single transponder and a single set of frequencies instead of four of everything for an exactly simultaneous system(28, 29).

Precise time clocks at each ground station enable one to collate the measurements and determine at any instant the range from each station to the satellite. The three ranges (R_1, R_2, R_3) from the three known ground stations to the satellite at some time, t_i, form a tetrahedron, the basic figure in the process of solution. Computations are performed in a three-dimensional, Cartesian coordinate system by first converting latitudes, longitudes, and elevations to X, Y, Z coordinates. If the coordinates of the satellite at time t_1 are $(X_s(t_1), (Y_s(t_1), Z_s(t_1))$ and the coordinates of the three known stations are (X_i, Y_i, Z_i), where i = 1, 2, 3, then the Ranges R_i at time t_1 may be written as:

$$R_i(t_1)^2 = (X_s(t_1) - X_i)^2 + (Y_s(t_1) - Y_i)^2 + (Z_s(t_1) - Z_i)^2, \qquad (14)$$

$$i = 1, 2, 3.$$

These equations are the equations of three spheres of radii R_1, R_2, and R_3, which intersect at the point $(X_s(t_1), Y_s(t_1), Z_s(t_1))$. The simultaneous solution of these three equations would yield the position of the satellite at time t_1. (Actually, the three spheres intersect in two points but one of these points would be a ridiculous solution since it would be below the surface of the earth.) The fourth range to an unknown station would be:

$$R_4(t_1)^2 = (X_s(t_1) - X_4)^2 + (Y_s(t_1) - Y_4)^2 + (Z_s(t_1) - Z_4)^2 \quad . \qquad (15)$$

If two more positions of the satellite at times t_2 and t_3 are considered, eight more equations are determined:

$$R_i^2(t_2) = (X_s(t_2) - X_i^2 + (Y_s(t_2) - Y_i)^2 + (Z_s(t_2) - Z_i)^2 \qquad (16)$$

and

$$R_i^2(t_3) = (X_s(t_3) - X_i)^2 + (Y_s(t_3) - Y_i)^2 + (Z_s(t_3) - Z_i)^2 \quad , \qquad (17)$$

$$i = 1, 2, 3, 4.$$

These equations yield two more positions of the satellite. Two positions of the satellite may be determined on the same orbit but the third must be determined from another orbit to avoid having nearly collinear centers. Each new point of the satellite position is at the intersection of three spheres and the process is therefore called "trispheration". (See Figure B-8, a & b.)

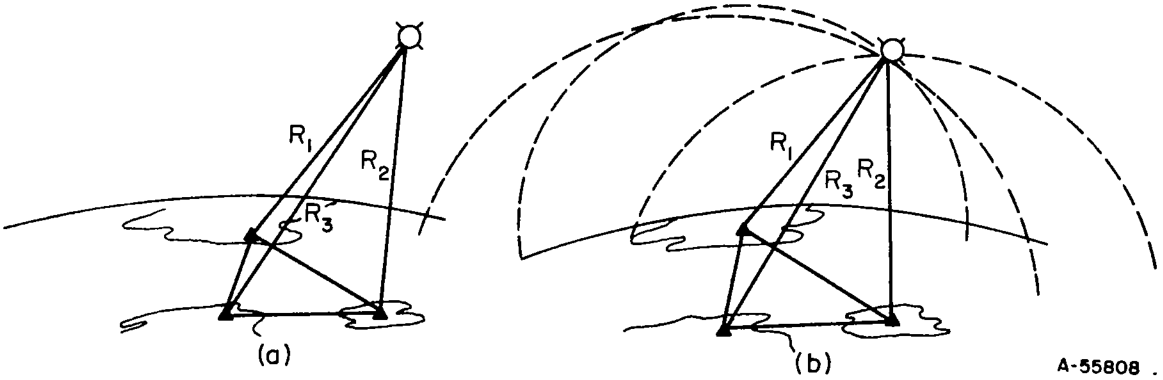

FIGURE B-8. TRISPHERATION

This process is now reversed to determine the position of the unknown station; i.e., the satellite positions are regarded as the centers of three spheres of radii $R_4(t_1)$, $R_4(t_2)$, and $R_4(t_3)$ and Station 4 is at the point of intersection of these three spheres. (See Figure B-9.)

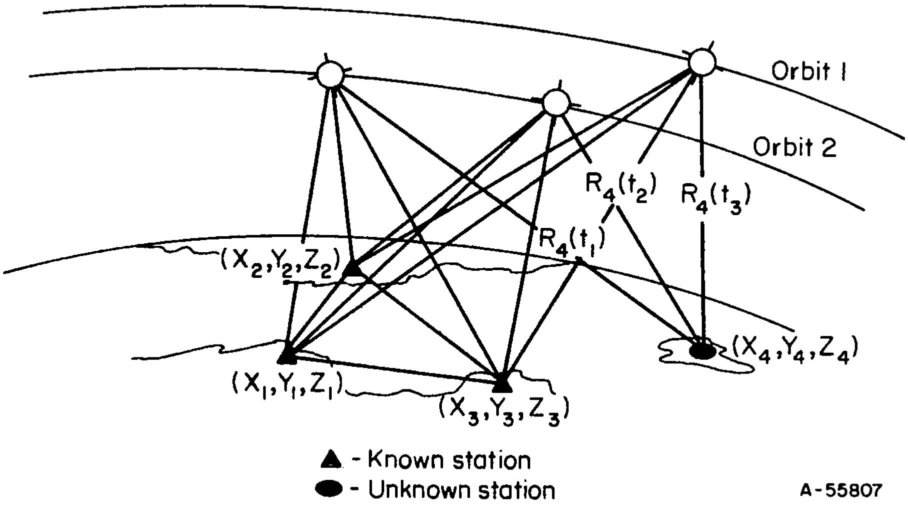

FIGURE B-9. SIMULTANEOUS OBSERVATIONS

All twelve range equations in the twelve unknowns may also be solved simultaneously with an electronic computer(28, 29).

The preceding explanation presents the minimum requirements for obtaining the position of the fourth ground station from the known positions of the other three ground stations. In actual practice, the data collected from many sattellite passes are used in a least-squares solution to obtain the most probable values. Trial point-coordinates available for the unknown station are used as a first approximation. The satellite positions are held fixed and only the unknown station is allowed to adjust.

Orbital Mode. The orbital mode of operation is used whenever existing geography prohibits the use of the simultaneous method. In this case, the measured ranges from the known positions of three ground stations are used to determine the satellite positions for a small segment of the arc. Extrapolation then provides the positions of the satellite at given times when passing the unknown point. These positions are used as the centers of the spheres with the corresponding ranges as radii to compute the position of the unknown point. This mode of operation is illustrated in Figure B-10, where S_i, i = 1, 2, 3, are the positions of the satellite computed from observations at three known ground stations and S_i' are the extrapolated positions of the satellite used to determine the coordinates of the unknown station.

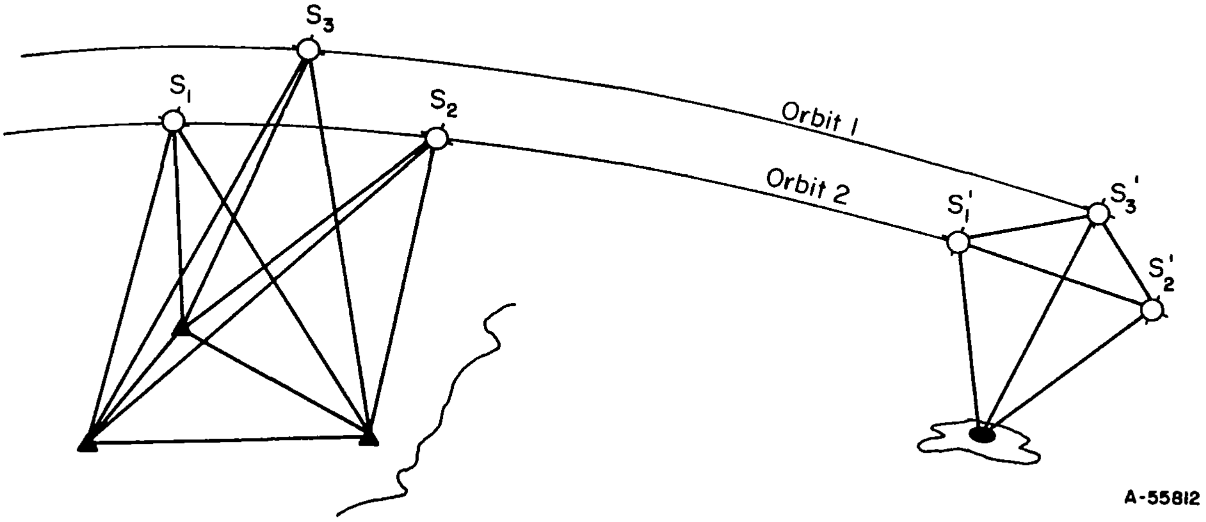

FIGURE B-10. SECOR ORBITAL METHOD

The simultaneous mode is preferred since the satellite position is of no consequence, serving merely as an auxiliary target. In the orbital mode, however, the extrapolated position of the satellite is a further source of error. Also, accurate timing is important in this situation for the satellite position at the time it was ranged upon from the unknown point must be known. An advantage of this method is the fact that earth-centered coordinates for the unknown station are obtained directly(22).

Line-Crossing Mode. This mode is analagous to the aircraft line-crossing mode employing the HIRAN and SHIRAN surveying systems. The satellite replaces the aircraft in the operation; i. e., the minimum range sum from two ground stations to the satellite is obtained. When a satellite pass is of nearly constant height above the spheroid, the minimum range sum occurs very nearly at the instant the satellite is directly over the base-line between the two ground stations (in practice, corrections must be made for the eccentricity of the orbit of the satellite). If the height of the satellite were precisely known at the instant of line crossing, the minimum range sum could be converted to the length of the spheroidal arc joining the stations. The need for precise heights is the major weakness of the line crossing method; for with satellite geometry, errors in height propagate unfavorably into the reduced spheroidal arcs. Theoretically, satellite heights can be recovered by means of three station trilateration. In practice, errors in locations of widely distributed stations combine with systematic errors of tracking to render such heights of marginal value for solid geodetic results(18).

Geometrical Requirements

There are several geometrical factors which must be considered in trispheration; for, as in triangulation, the accuracy of the ground points depends upon the geometric strength of figure to a large degree. One of these has already been mentioned, i. e., the fact that at least one of the three positions of the satellite must be on a different orbit than the other two in order to avoid collinear centers. Also, the reciprocal distances of the three ground stations should be about one to two times the height of the satellite in order to avoid poor strengths of figure. Likewise, the new station being positioned should not be more distant from the fixed points than the mutual distances between the fixed points themselves. The mutual distances between points in a "trispherical" survey is thus governed by the height of the satellite(28, 81).

The angles at the satellite formed by the rays from the ground stations to the satellite should not be small. If these angles are small, the surfaces of the spheres approach concentricity resulting in the changes in the coordinates being large compared to changes in the radii. Likewise, angles at the unknown point between range lines to the satellite position must not be small(28). With three basic points, rays intersecting at right angles provides optimum accuracy(85). Of course, this situation is almost impossible to achieve in practice. The satellite point is fixed most strongly when it is over the center of the base triangle and accuracy falls off as it moves away.

N. J. D. Prescott(81) has outlined the following considerations that affect the selection of stations in a framework (apart from those of logistics);

(1) Available satellite height

(2) Good intersections from all ground stations

(3) Extension of control – each new station should be suitably placed so that, when established, it plays a useful part in fixing the next unknown point.

Reduction of Data

The reduction of the data resulting from SECOR observations seems to be one of the main areas of the process undergoing constant revision and improvement. A report by D. C. Brown[18] develops a new error model for Geodetic SECOR. "Comparisons with the conventional reduction indicate that the new reduction should (a) provide higher accuracies from less data; (b) produce a far more realistic error propagation; and (c) lead to a more efficient field operation. Because it also automatically solves the problem of unresolved, constant ranging ambiguities, the new reduction promises a much shorter data reduction cycle than the conventional method"(18).

Initial data reduction procedures did not explicitly recognize the possibility of significant systematic error in SECOR ranges and thus the statistical treatment of observations was limited to the consideration of only random error.

The error model outlined by Brown is entitled NEO-EMBET (N-Epoch Orbital-Error Model Best Estimate of Trajectory). Brown's investigation indicates that NEO-EMBET may well promise an order-of-magnitude improvement over original SECOR reductions. NEO-EMBET differs from a geometrical reduction in that it effectively utilizes tracking data from those portions of a pass that are observed by only one, two or three stations. Horizon-to-horizon tracking from all participating stations is, therefore, best. All quads are adjusted simultaneously in the general NEO-EMBET reduction, and hence, fewer passes than in the independent adjustment of each quad are needed to produce acceptable results.

The results of the initial tests of the SECOR system indicated that the simultaneous mode of operation was a great deal more accurate than the orbital mode – the data being subject to a geometrical reduction only. Therefore, only data from good simultaneous observations with four stations was used in the reduction process. The problem has been under constant study, however, and orbital techniques enabling any good data in a pass to be used were developed recently. These techniques are now being employed by the Army Map Service.

Accuracy

Published results for the SECOR system are now outdated and a lack of publication has prevented an up-to-date accuracy determination. Many of the observations are being updated through recently developed data reduction techniques. With these new techniques, fewer passes may be used to obtain very acceptable results. Approximately 10 passes are now used in the adjustment reduction techniques previously mentioned instead of 20-25 passes as before. Erich Rutscheidt, Chief of Research and Analysis Division, Geodesy Section of the Army Map Service, will publish an article in the Canadian Surveyor by early fall 1968 stating the updated results of SECOR.

The Army Map Service began the development of SECOR in 1961 – the instruments being developed by the Cubic Corporation. The first SECOR satellite (EGRS-1) was launched in 1964 at which time an ETST (Engineering Test Service Test) was conducted involving five stations in the U. S. The results of this test were first presented in early 1965(28).

The fixed stations were near Las Cruces, New Mexico; Colorado Springs, Colorado, and Austin, Texas. The station treated as the unknown in the simultaneous operation of SECOR was near Stillwater, Oklahoma. The discrepancy between the SECOR result and that from the Coast and Geodetic Survey triangulation was 6 meters(12).

The orbital mode was also tested at this time by using a fifth station at East Grand Forks, Minnesota. The discrepancy between triangulation and orbital trispheration at East Grand Forks was 55 meters(12).

During the fall of 1964, the SECOR network was extended from Japan southeastward through Iwo Jima, Guam, Midway, and Maui, being tied into the South Pacific Hiram network wherever possible. Table B-3 outlines the results of this work.

TABLE B-3. RESULTS OF THE SECOR OPERATION IN PACIFIC

Starting from three known stations on Tokyo Datum (Bessel Spheroid), unknown stations on the following islands have been fixed.

	Probable Error, in meters		
	Latitude	Longitude	Height
Minami Daito Shima	±1.6	±1.6	±1.0
Iwo Jima	±2.1	±2.2	±2.8
Guam	±1.3	±1.5	±2.7
Marcus	±3.7	±2.2	±0.5

The probable error has been obtained from the internal agreement between the solutions[81].

The main sources of error are caused by calibration within the ground stations and the transponder, tropospheric refraction, and ionospheric refraction. Using a satellite at a height of 500 nautical miles above the earth's surface, Prescott(81) estimates the probable error of a single range measurement to be (for the various sources) as follows*:

Sources	Elevation (slant range)	
	60° – 90° (1000 km)	15° (2230 km)
Calibration – satellite transponder	1 m	1 m
Calibration – station	2 m	2 m
Tropospheric correction	0.25 m	1 m
Dual frequency ionospheric correction – night	0.25 m	1 m

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*These estimates of probable error are very approximate since it has been very difficutl to check the precise accuracy of SECOR range measurements.

Sources	Elevation (slant range) 60° – 90° (1000 km)	 15° (2230 km)
Dual frequency ionospheric correction – day	1.5 m	6 m
Random electronic noise	1 m	1 m
Frequency and light propagation errors	1 m	2 m
Combined (day) error	3.0 m	6.9 m
Combined (night) error	2.7 m	3.5 m

Zero Set Error

The signal spends some time going through the circuits of the ground station and of the transponder. The distance it would travel in free space during this time must be subtracted from the observed range. This is called the calibration correction. This correction is measured in the transponder before launching. It is measured in each ground station before and after each satellite pass by ranging on a transponder at a known distance from the ground station thus obtaining the difference between the measured and known distances.

Unavoidable errors in the ground station calibration and the unknown delays in the satellite transponder are known as the zero set error. When the system is functioning properly so that phase ambiguities are successfully resolved, zero set error is likely to be no more than a few meters. Experience has shown, however, that it is a fairly common occurrence for ranging ambiguities to remain unresolved throughout a pass. In this case, the zero set coefficient also contains an integer multiple of 256 meters(18). The zero set correction is applied to remove ambiguities in these multiples of 256 meters.

Refraction

A correction is computed for tropospheric refraction according to an empirical formula based on a tropospheric model. The troposphere does not change much and many studies have been made of its effects on light rays and radio waves; hence, the model is quite accurate.

The dual frequency method of correcting for the ionosphere is used unless the second frequency isn't received due to low frequency interference. In this case, an ionospheric model is used. Whenever both frequencies are received, the ionospheric model correction is also computed and compared with the results. The model presently being used is comparing very well with the measured data. When usuable two frequency data are available on an operational pass, the model can be fitted to the two frequency data by least squares and put to good use to estimate the error in the zero set of range differences(18).

The ion concentration in the upper atmosphere depends on the amount of solar radiation. This varies greatly with the times of day, seasons, latitudes, and sun spots. It is greatest at noon and least between midnight and dawn. Likewise, ionospheric refraction errors are least between midnight and dawn and at zero zenith distance of carrier-wave paths. (For this reason, nighttime SECOR observations are generally **appreciably superior** to daytime observations.)

Doppler Effect

A correction is also made for the Doppler effect on the range determination. This effect is small and is corrected for automatically by a Doppler loop that is built into the ground station(29).

Many of the original problems and difficulties involved with SECOR have been eliminated or at least reduced. Calibration is now very good (being ±2 meters). Range residuals are also looking good (±2-4 meters) and systematic bias errors have been eliminated. The range accuracy will improve proportionally if higher satellites are used. The cost of the SECOR equipment will continue to be reduced along with reduction in weight. The system weighing 33,000 pounds originally now weighs only 2,500 pounds due to new equipment design. Hence, transportation costs will be greatly reduced although a SECOR setup may still be too expensive for any one group to consider. The Army Map Service is presently extending the SECOR network with the intention of eventually completing its original plans of a worldwide network. Much of the SECOR work has military implications and is therefore classified.

Conceptual Approaches

Unlike the Doppler method has not been used for positioning at sea, but has been restricted rather to land-based operation. Several approaches to the use of SECOR for determining the positioning of ships at sea have been proposed(85). These approaches employ adaptations of the basic SECOR technique. Two approaches, CODA (COnsolidated DAta) and ODVAR (Orbit Determination and Vehicle Attitude Reference) are considered. An advantage of CODA SECOR over the present system is the fact that the coordinates of the satellite are determined in real time tracking at the master station. The master station would have the only transmitter, and the other ground stations serve essentially as transponders.

A signal originated at a master station (A) is received and transponded at a satellite. The transponded signal is received and transponded again at one of two slave stations (B) and this reply is received and transponded a third time at the satellite. The resulting signal is received back at station A, and a phase comparison of the transmitted and received signals at station A yields a measure of the range ($R_a + R_b$). Likewise, the range ($R_a + R_c$) for a third station (C) can be determined by sequentially receiving and transponding the signal at station C. The satellite's response to station A's transmitted signal is used at station A to obtain a measure of R_a. The data is "consolidated" at station A yielding the ranges R_b and R_c and hence the coordinates of the satellite by "trispheration".

Reid(83) describes two methods for applying the CODA SECOR technique (the three-satellite-position solution and the two-satellite-position solution) to the positioning of a ship. Both methods involve four "ground" stations – the three known stations, A, B, and C, and the unknown station, the ship. The CODA SECOR technique would be used to determine all four ranges from these stations to the satellite at various positions of the satellite. In the three-satellite-position method, three positions of the satellite would be determined, resulting in Figure B-11 which is similar to Figure B-4 except only the master station transmits a signal and all three satellite positions are for the same orbital pass. The nine ranges, R_{a_1}, R_{a_2}, R_{a_3}, R_{b_1}, R_{b_2}, R_{b_3}, R_{c_1}, R_{c_2}, R_{c_3},

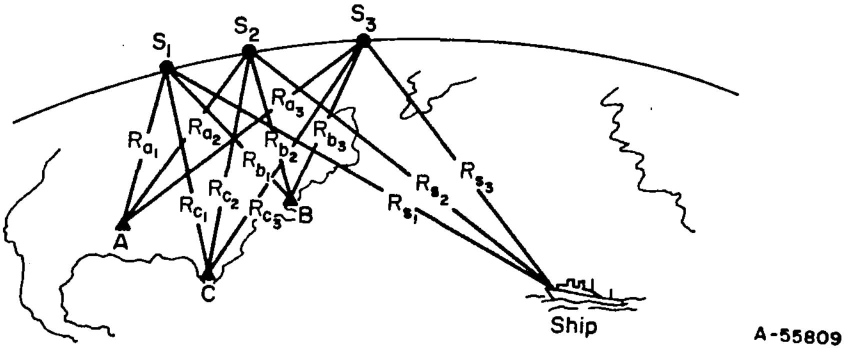

FIGURE B-11. CODA SECOR THREE-SATELLITE-POSITION SOLUTION

determine the satellite positions, S_1, S_2, S_3. These three positions along with the ranges from the ship, R_{s_1}, R_{s_2}, R_{s_3}, determine the ship position by "trispheration". During the time between the determination of S_1, S_2, and S_3, the ship was moving and, hence, the velocity of the ship must be known to a very high degree of accuracy for geodetic work. Present navigation methods do not yield this desired accuracy. The other main source of error, of course, would be that due to the CODA SECOR system itself in positioning a satellite. This is not known at this time although Reid claims "high" accuracy is available. It might be noted again that the three-satellite-position method does not lend itself to the most desirable geometric configuration since all three positions are for the same pass.

In the two-satellite-position method, an estimate of the geocentric radius of the ship is used as the third range in determining the ship position (see Figure B-12). Positions S_1 and S_2 of the satellite are determined as described previously. The velocity of the ship still must be known, and an additional error is introduced due to the assumed geocentric radius. The geometry is somewhat better than that of the previous method, however.

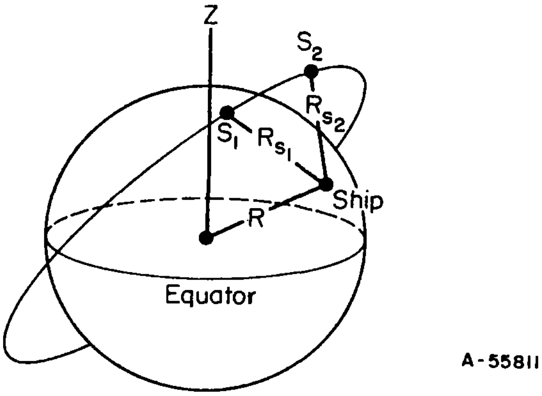

FIGURE B-12. CODA SECOR TWO-SATELLITE-POSITION SOLUTION

If one were interested in first establishing geodetic control at sea, the situation would be slightly different. As with the Doppler system, the problem of determining the ship velocity could be eliminated or at least reduced to the case of being negligible by employing ocean bottom transponders. One of the two (or both) methods described under the Doppler system could be applied; i. e., continuously positioning the ship relative to ocean bottom transponders and thus determining its velocity, or following the same procedure and determining its mean position for the time of observations.

Reid describes a system called SECOR/ODVAR which requires that only one position of the satellite be known and hence, the velocity of the ship is not required.(83) In order to obtain the geocentric coordinates of the ship, however, it is necessary to obtain the geocentric coordinates of the satellite and the three angles which define the orientation of the satellite with respect to the geocentric reference frame. The former can be obtained by the CODA SECOR approach and the latter by Cubic's ODVAR technique which requires phase comparison angle measurements at three antennas located on a set of orthogonal axes on the satellite. According to Reid, however, high accuracy is not possible with SECOR/ODVAR. Therefore, this system will not be discussed any further. The use of ocean bottom transponders to eliminate the velocity problem appears to be a most promising solution for geodetic work.

K. Rinner(85) also outlines an approach to the application of the Secor satellite ranging system to marine geodesy – both for geodetic control and positioning. According to Rinner, "fixed points must be established on the bottom of the sea". The observation point on the surface could then be positioned by the ranges to the markers. Being that range measurements are very little affected by movements of the observation point, trilaterations (of either sea-surface networks or spatial networks) are well suited to determining fixed points in ocean areas. All observations in SECOR trilateration could be reduced to one of the ocean bottom markers referred to as the master station and its coordinates determined by the adjustment. Rinner outlines two possibilities for referring the SECOR ranges from the surface point to the master station on the sea bottom. The first involves establishing two additional eccentric stations on the surface whereas the second involves determining the distances between the sea bottom markers by ultrasonic line crossing and orienting the pyramid determined by these markers and the surface station.

Rinner further presents an argument for using SECOR in navigation in a manner similar to the Doppler navigation system; i. e., the parameters of the satellite orbit would be determined by satellite tracking from known stations and stored in the satellite. Positioning of a ship would consist of observing at least two ranges to the satellite. Ideally, the satellite would transmit its own position when interrogated. The satellite positions, the two ranges, and an estimated geocentric radius of the ship would be used in calculating the ship position.

Rinner argues that the advantage of a SECOR system would be the strong geometry of the range networks as compared to results based on range difference as in a Doppler system. "Even if the accuracy of range difference measurements is n-times higher than the corresponding accuracy of range measurements the final results will have only the same accuracy as soon as the range is n-times the length of the difference. In addition, the geometry associated with difference measurements is typically weaker than for ranging systems. Therefore, ranging systems should provide better results when compared with systems using differences of ranges".(85)

The present cost and size of a SECOR set, however, restricts its practical application. Furthermore, none of the preceding methods have been actually attempted and tested whereas the Doppler system is fully operational and its accuracy tested. The accuracy of SECOR on land is still a debatable topic. It would therefore seem logical at this point to experiment with the possible applications of the Doppler navigation satellite system to marine geodesy - leaving the SECOR system for future possible consideration.

RADAR METHODS

In the discussion that follows certain aspects of the C band radar and the USB (Unified S Band System) will be discussed relative to the requirements for a ship positioning system which utilizes satellite position information. If either the C band radar or the USB is used for ship positioning, a ranging technique as described by Calabria(24) would probably be used for the determination of ship position.

Types of Radars

The technical characteristics of the components of the C band radars AN/FPS-16 and AN/FPQ-6 and the USB radar are outlined in Table B-4. The tracking and accuracy characteristics are outlined in Table B-5.

C Band Radar

Each of the Apollo ships will carry a C band radar(61). This radar is the AN/FPS-16 monopulse tracking radar. It was designed specifically for missile tracking. The AN/FPS-16 transmits either a single pulse or a coded pulse. The coded pulse is used for beacon tracking and the single pulse is used for tracking the reflected pulse from a non-beacon equipped target.

In a pulse radar such as this, the return echo signal is generally placed in a range gate. If due to motion of the target, the echo signal is displaced in time from the range gate, an error signal is created in a servo loop which drives a range gate generator in a direction such that the error is returned to zero. Thus the echo signal is continuously gated by the range gate. The range gate system is generally calibrated in range or time.

The raw output data from the AN/FPS-16 is in polar(1) coordinates (slant range – azimuth angle – elevation angle). This is converted into digital form for data processing. The angular information is used for tracking (keep the tracking antenna on the target) but is not useful for determining the position of the target. (This is true for the USB and the AN/FPQ-6, also.) The angular error is too large. It generally exceeds the range error, particularly at long ranges, by a large amount. For example, at 100 miles an angular error of .1 degree results in an angular position error of approximately 30 meters.

NASA is considering using the FPS/16(24) in a ranging mode as a back-up to SINS (Ship Inertial Navigation System) which will provide ship position information for Apollo. An accurate method of recalibrating SINS periodically, independent of weather conditions, is needed and the ship borne FPS/16 tracking the C-band transponder equipped GEOS-II may be considered for this task.

The AN/FPQ-6 and the AN/TPQ-18 appear to be advanced versions of the AN/FPS-16. The An/TPQ-18 is a transportable version of the AN/FPQ-6. The performance of the AN/FPQ-6 is somewhat superior to that of the AN/FPS-16. This is due in part to an improved range tracker, a larger antenna, and a better signal to

TABLE B-4. TECHNICAL CHARACTERISTICS OF RADAR COMPONENTS

		TRANSMITTER		RECEIVER		ANTENNA		
Radar System	Tube Type	Power Output, kw	Frequency	Noise Figure, db	Type Reflector	Gain, db	Beam-width, degrees	Polarization
AN/FPS-16(1)	Magnetron	250 peak	5450-5825	11	12 ft, parabolic	43.5	1.2	Vertical
	Magnetron	1000 peak	5690±25	11	12 ft, parabolic	43.5	1.2	Vertical
AN/FPQ-6(1)	Stable Crystal Oscillator (multiplied)	2500	5400-5900	4	29 ft, Cassegranian	51	0.4	Vertical/Circular
USB	Klystron	1-20 cw	2090-2120	1.7	30 ft, Cassegranian	44	0.85	Linear/Circular
					(42 in. diameter acquisition antenna)	(22)	(10)	

TABLE B-5. TRACKING AND ERROR CHARACTERISTICS OF RADARS

		Coverage	Tracking Rates	Random Error, rms
AN/FPS-16(1)	Range	1,853 km	8,000 yd/sec 2,000 yd/sec^2	6-9 m
	Azimuth	Continuous	800 mil/sec 1.3 radians/sec^2	0.2-0.4 mrad
	Elevation	10° - 190°	450 mil/sec 1.3 radians/sec^2	0.2-0.4 mrad
AN/FPQ-6(1)	Range	59,304 km		±2.7 m
	Azimuth	360°		±0.05 mrad
	Elevation	2° - 182°		±0.05 mrad
USB	Range	800,000 km		±1 m
	Azimuth	Continuous		
	Elevation	2° above horizon		

noise ratio under comparable conditions. No unclassified ship borne versions of the AN/FPQ-6 are known.

Unified S Band System

Each of the five Apollo ships will be instrumented with the USB. The USB will provide tracking, telemetry, command, and communications to the Apollo spacecraft. At lunar distances the USB with 85-foot antennas will be used to provide all tracking and communication with the Apollo spacecraft. The USB with 30-foot antennas will fill gaps in coverage provided by the 85-foot antennas, and it will provide data during the earth-orbital and post-injection phases of the mission. Only the 30-foot antennas will be used with the ship-borne USB.

The USB system utilizes a coherent Doppler and a pseudo-random range system(61). In order to perform the range function, a pseudo-random code is transmitted to the satellite and stored in the tracking system of the USB also. Maintaining coherency, the pseudo-random code is transponded by the satellite. When the transponder signal is received by the USB an autocorrelation function is performed. This essentially determines the round-trip time of the signal between the USB and the satellite.

Both the 85-foot antenna and the 30-foot antenna of the USB have a quadripod-mounted acquisition antenna. The broad beamwidth (10 degrees for the one used in conjunction with the 30-foot antenna) of the acquisition antenna enables the USB to easily acquire the target. Once this is accomplished the USB's 30-foot antenna begins the tracking operation.

Comparison of Radars for Target Positioning

The basic method of target position determination is the ranging technique as described in Reference 24. Since this technique is being considered, the ranging errors of the various radars are compared in Table B-6. It is apparent that the USB is superior to the other systems.

TABLE B-6. COMPARISON OF RADAR RANGE ERRORS(a)

System	AN/FPS-16(1)	AN/FPQ-6(1)	USB(61)
Range Error	±9 m	±2.7 m	±1 m

(a) These values are probably based on ideal conditions.

Accuracy

The only data from actual measurements were for the AN/FPS-16. The position of a GEOS satellite over Miami from two separate orbits was determined with range error of 700 meters, for the worst case. This was an overall error including ship movement, radar error, SINS error, etc. The overall system error for the USB is expected to be ±15 meters(61). Overall error for the AN/FPQ-6 was not available. However, on the basis of Table B-6 the accuracy of the AN/FPQ-6 should be better than that of the FPS-16.

Range errors due to ionospheric propagation are somewhat greater at C band than at S band(13). For example, at C band the error would be approximately .12 meter for a satellite at 150 miles on the horizon whereas at S band it would be 1.2 meters. Range errors due to ionospheric fluctuation would be of the same order of magnitude. In heavy rain, attenuation at S band would be less than the attenuation at C band. In heavy rain (16 mm/hr) the attenuation at C band would be .15 db per mile and at S band it would be .03 db per mile.

The background noise will increase as frequency is increased. If operation is considered in times of high solar activity, a lower frequency should be considered. For example, the background temperature from the atmosphere is 100 Kelvin at S band and it is 110 K at C band for a radar antenna pointed at the horizon.

The C band radars require a separate acquisition radar to "point" them at the target, whereas the USB has an acquisition antenna and can acquire and track the target with no external aid.

It can be seen, considering the available information, that the USB would be superior to the C band system. However, utilization of this equipment requires a satellite with an S band transponder. If such a satellite exists, it is not widely known. The USB provides more accurate range information by virtue of its instrumentation. If it is desired to take advantage of this instrumentation, it would be possible to modify the RF section of one USB. That is, it could be fitted with a C band transmitter and receiver.

OPTICAL METHODS

The optical methods of satellite observation involve photographing the satellite against a stellar background and "reducing" the photographic plates to obtain the direction vector to the satellite. Most of the cameras presently used were originally used in satellite geodesy for "tracking" satellites; i.e., determining the satellite's position in space in some coordinate system at a given time. During the past few years, special mechanical, electronic, and optical equipment has been installed in these camera systems to permit observations from two or more stations for three-dimensional geodetic triangulation which results in the determination of the station coordinates.

There are several advantages to the photographic method of observation. First, the techniques are well understood. Second, the basic equipment is relatively simple, available, and low in cost. Third, the data obtained by optical techniques have proven quite accurate. While the satellite designed specifically for optical observation contains a light source which can be activated electronically for photographic purposes (for example, GEOS-II), large satellites, such as Echo II, with no independent source of illumination, can be photographed at dusk or dawn when reflected sunlight illuminates the vehicle. When used with precision cameras stationed at selected points – known and unknown – information from either operation can be used for determining geodetic positions. In both instances, the position of the satellite is determined from the positions of the stars against which it is photographed.

There are several geometric satellite geodesy programs now underway(4). The first of these is the U. S. World Geometric Satellite Network. Its purpose is to provide a geometric "triangulation" covering most of the world, establishing a unique reference system for the whole earth with its gravity center as zero point, the Z-axis identical with the rotation axis, and the x, y-plane perpendicular to it and coinciding with the equatorial plane. This orthogonal x, y, z-system is necessary to coordinate the spatial positions of the surface points within $1:10^6$ or 1:500,000. Forty-two sites are planned – most of which will be occupied by BC-4 cameras of 30-cm or 45-cm focal length with 100-cm cameras perhaps being used in one or two places. Some of the sites will also be occupied by Transit equipment or SECOR equipment. The extent or manner in which data from these other types of equipment will be used is not known(4).

The data will consist of satellite directions measured in the instantaneous equatorial system. Conventional ground surveys will provide the scale for distances. Results of a preliminary error analysis show that at least four baselines will be needed to scale the net.

Another global program is the National Geodetic Satellite Program (NGSP) directed by NASA. The objectives of this program are to (1) establish a unified Earth reference system and to (2) determine the gravitational field of our planet. This program is a cooperative effort by several U. S. organizations to provide satellites specifically for geodetic purposes. Information from NGSP data is obtained through the Central Bureau for Satellite Geodesy.

In order to accomplish objective (1), eighty-six geodetic control stations must be precisely located by satellite methods. As of the end of 1967, forty-two stations had been occupied. Positions accurate to ±60 feet have been published for twenty of these stations. (The NGSP objective is to locate any two control points within 35 feet of each other using a single set of Earth-centered coordinates.)(73)

Four active satellites and one passive satellite were launched by NASA between October, 1964, and January, 1968, as part of NGSP. They were Explorers XXII and XXVII, GEOS-I, and GEOS-II, and PAGEOS-I. Another GEOS satellite is presently being planned to insure a timely achievement of the geometric objective. Data from four systems are being utilized, two optical (BC-4 and PC-1000 camera) and two electronic (SECOR and Doppler) systems.

There are also a number of projects designed for the establishment of networks much smaller than those already mentioned. These include Reseau Geodesique Europeèn (RGE) covering all of Europe, the Western-European Sub-Commission for Artificial Satellites, the French experiments connecting France and Algeria and Europe and the Azores, and a Japanese project using Tsubokawa camera-detectors(4).

Operational Procedures

Camera Characteristics

There are many different cameras presently being used for satellite observations. Table B-7 outlines only the principal cameras used in the United States. The shutter systems, timing synchronization, timing precision, epoch of observation, and positioning accuracy corresponding to these camera systems are outlined in Table B-8.

Methods of Camera Operation

There are various methods in which, theoretically, the camera at the observing station may be used, with any one camera adapting to only one or perhaps all of the possible modes of operation.

The first mode of operation is the fixed mode; i.e., the camera remains stationary during the star-satellite exposure. As a result, the stars will produce trails on the photographic plate as the Earth rotates and a shutter system must be provided to interrupt or "chop" the stellar trails at known epochs to produce measurable images. If an active satellite is observed, the shutter may then be opened during the satellite flash period and the shutter activated again after the satellite passes in order to "chop" the stellar images. If a passive satellite is observed, the satellite image will also appear as a trail on the plate, "chopped" at known time intervals as are the stellar trails.

A second mode of operation is to drive an equatorially mounted* camera at a sidereal rate. Theoretically, the stars will appear as point images and an active satellite will appear to move through the star field at a rate dependent on the satellite's velocity relative to the star background. A passive satellite moving through the stellar field must be "chopped" to produce point images at known epochs. There are several disadvantages to this method. Any fluctuations in the drive system will produce undesirable image shifts. Also, the physical sizes of the star images will be increased since the exposure time will extend over the entire time the satellite is being photographed. This makes accurate plate measurements difficult since the center of the enlarged star image must be estimated.

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*An equatorially mounted camera allows the camera to turn to the north and south about one axis and to the east and west about another. The axis for the east-west motion of the camera is parallel to the axis of the Earth's rotation, and the other axis, about which the telescope can rotate to north and south, is perpendicular to this axis.

TABLE B-7. PRINCIPAL CAMERAS USED IN THE UNITED STATES

Camera	Focal length, cm	Aperture, cm	Field of view, degrees	Tracking (T)/ Nontracking (NT)	Agency	Remarks
Baker-Nunn	53.5	53.5	35 x 5	Both (Tracks with adjustable angular velocity between 0 to 7000"/sec along any great circle)	SAO-12 Cameras located worldwide U. S. Air Force-3 cameras	Film used to record satellite/stellar exposure Film support a spherical surface Triaxial Mount Special mechanical and electronic equipment has been installed to permit simultaneous observations from two or more stations for geodetic triangulation SAO presently using combination of laser ranging and Baker-Nunn data
K-50 (Modified)	100	25		Both, but used majority of time in NT mode	SAO-3 cameras (presently being deployed to host country)	Internal shutter system Flat photographic plate Developed for temporary use in relocating three Baker-Nunn cameras by simultaneous observations between the old and new sites
BC-4 (ASTRO)	30	11.5	35 x 35	NT	ESSA U. S. Air Force-plates reduced by ACIC U. S. Army	45-cm replacing 30-cm camera New 45 cm lens being optimized for geodetic triangulation Magnitude of star observable: 9-7 Glass plates used Consists essentially of a modified Wild BC-5 aerial camera mounted on the base of a Wild T4 Universal Theodolite ESSA uses only BC-4 for their work in worldwide satellite triangulation net
BC-4 (COSMO)	45	11.5	25 x 35	NT		
PC-1000 (ballistic camera)	100	21	10 x 10	NT	U. S. Air Force Photographic and Charting Service (APCS)-plates reduced by ACIC	Glass plate used Primary observing camera of APCS for tracking active or passive satellites and for stellar triangulation Recently equipped with chopping shutters so can observe both passive and active satellites Data will be used to accomplish control densification in such areas as South America, improve accuracy of space tracking sites and calibrate tracking radars(5)

TABLE B-7. (Continued)

Camera	Focal length, cm	Aperture, cm	Field of view, degrees	Tracking (T)/ Nontracking (NT)	Agency	Remarks
MOTS-24	61	10.2	18 x 23	T (Equatorially or Polar Modes)	NASA	Glass plates used Only active satellites observed for geodetic purposes 12 cameras located at Space Tracking and Data Acquisitioning (STADAN) sites where used for calibration of electronic Minitrack Interferometers 9 additional MOTS and PTH-1000 cameras were used in observing the GEOS-A satellite at selected locations in the Eastern U. S. MOTS data used in orbit determination No geodetic program for these instruments alone is known to have been set up
MOTS-40	101.6	20.3	11 x 14			
PTH-100	101.6	20.3	10 x 10	NT	NASA	Glass plates used New camera system-presently 3 such cameras(43). Only active satellites observed for geodetic purposes Used with MOTS cameras as explained above
K-17	60	17	20 x 20	NT	U. S. Army Map Service	Converted from an aerial mapping and reconnaissance type of satellite tracking Camera system precision is 1".5(4) Used by AMS for calibration of Minitrack systems by photography of a flashing light carried in an airplane To be used for satellite geometrical geodesy

TABLE B-8 CHARACTERISTICS OF PRINCIPAL CAMERAS USED IN THE UNITED STATES

Camera	Shutter system	Timing precision and synchronization(a)	Epoch of observation		Positioning Accuracy
			Active	Passive	
Baker-Nunn	Clam shell capping shutter with exposure time settings from 0.2 to 3.2 seconds begins and terminates exposure. Barrel (timing) shutter rotates 2-1/2 times giving five breaks during a normal exposure at a highly precise angular velocity	Portable clock and VLF Overall accuracy about 1 msec Estimated uncertainty of time given with each observation	Camera station time of instant maximum brilliance of flash Expressed in A. S. time	Station timing system consisting of master clock (set with portable crystal clock and maintained by VLF transmissions) and a slave clock attached to camera Time of master station clock (U.T C.) corrected to A.S.	Estimate and published position error is 4" of arc in right ascension and declination.(43) Absolute coordinates of Baker-Nunn stations given to accuracy of ±15 to 20 meters.
K-50 modified	Chopping shutter	Precision uncertain	Same as above since used with Baker-Nunn		
BC-4	Three internal rotating discs and exterior iris-type shutter used primarily to chop star trails before and after satellite pass	Portable clock and WWV and VLF Uncertainties in the station timing relative to WWV estimated to be less than ±150 microseconds for passive observations	ESSA-time satellite flash was triggered as published by APL UTC epoch of satellite flash converted to UT1 (referred to old conventional longitude of U. S. Naval Obs.) U. S. Air Force-time satellite flash was triggered in U.T.C.	ESSA-Sation camera time reduced to UTC and converted to UT1 Light time correction applied to antedate epoch of station observation to satellite	Triangulation adjustment for a net covering North America yielded typical mean errors of ±4 meters for φ and λ, ±6 meters for elevations, and ±0.7" for a single direction. The worldwide net is expected to yield better results due to recent improvements in equipment and reduction procedures(87).
PC-1000	"Between the lens" internal shutter recently equipped with capping shutter	Crystal station clock and a radio receiver used to determine the clock offset and rate from the time signal Time signals recorded on one channel of magnetic or paper tape and clock recorded on second channel	U.S.A.F.-time satellite flash was triggered in UTC	During plate exposure shutter action recorded on channel previously used for time signal record and thus epoch of shutter action correlated with clock signals(43)	Solutions for station positions based on SECOR, Doppler, and PC-1000 satellite observations each agreed with the results of geodimeter surveys to about 3 meters(5)

TABLE B-8. (Continued)

Camera	Shutter system	Timing precision and synchronization[a]	Epoch of observation		Positioning Accuracy
			Active	Passive	
PC-1000 (continued)		Correlation of recorded signals yields the rate and offset of the station clock(43)			
MOTS-24 MOTS-40	Internal shutter-timing accuracy immaterial since cameras are sidereally driven and observe only active satellites(43). New shutter system being investigated(43).	Accuracy with which time of shutter action related to radio time signals 0.75 seconds(43)	Satellite flash times published by APL(43).	For geodetic purposes only observe active satellites	Presently used mainly for satellite orbit determination along with other systems. Extent to which they will be used for geometrical geodesy not known.
PTH-100	Internal shutter system	Accuracy with which time of shutter action related radio time signals ≈ 25 ms(43)	Brush Timing Recorder records received WWV signals and shutter action. Instant shutter is fully open and begins to close recorded and compared to WWV signal	For geodetic purposes only observe active satellites	Extent to which they will be used for geometrical geodesy not known

(a) Commonly-held opinion that the most accurate time synchronization method is that of carrying stable clocks between standards(4).

A third theoretical method of camera operation is to drive the camera at a predicted satellite rate so that the satellite will appear as a point image. This is not possible in practice, however, since in most cases the satellite rate is not known accurately. The method is also inadequate for active satellites since the flashes will appear superimposed on one another. The only advantage is that faint satellites may be observed for non-geodetic purposes.

The last alternative is a combination of the orbital and stationary techniques. The camera first makes a regular exposure while tracking the satellite. The camera is then fixed and a second stationary exposure is made. This method is subject to the inaccuracies mentioned in connection with the third method, but it is useful in roughly identifying a faint satellite in a cluster of stars(43).

Observational Methods for Positioning

The data obtained from the photographic plates can be used to position the satellite, the observer, or both. Two main observational methods are employed for these ends – simultaneous and orbital. These methods have been discussed relative to SECOR, but the discussion will be recapitulated here in terms of optical methods.

The usual method of determining a station's position is based on simultaneous observations of an artificial satellite by two or more stations. The approach is purely geometric. The satellites are used simply as triangulation points to perform a three-dimensional triangulation in which absolute directions have been observed.

A minimum of two stations is required to fix the position of the satellite in space. If two stations are fixed with respect to a geodetic datum, the third station can be treated as an unknown, and its coordinates established relative to the known sites. As new stations are derived by this process, the triangulation network can be extended laterally into a continental survey; if the target is sufficiently high, it can bridge across the ocean to connect with other major datums.(22)

Simultaneous Observations. The fundamental geometry of the satellite triangulation method is illustrated in Figure B-13. P_1 and P_2 are the known stations and P_3 the unknown. The vector P_1P_2 is thus known and the scale of the net will come from this vector. (The distance between one station and the satellite as obtained by direct range measurement could also be used to scale the net.) All three stations simultaneously observe a satellite at times t_1 and t_2 when the satellite is at S_1 and S_2. (Two different orbits are preferred for better geometry). The observed vectors P_1S_1 and P_2S_1 determine the satellite position S_1 by spatial intersection. The observed vectors P_1S_2 and P_2S_2 likewise determine the satellite position S_2.

These vectors are determined from the photographic plate reduction process*. This process uses the position of reference stars obtained from a star catalogue to determine the apparent right ascension, declination, and direction cosines of the satellite. The satellite positions S_1 and S_2 are then combined with the directions to the satellite from the unknown station to compute the position of the unknown station (by a spatial intersection).

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*This process is discussed later in greater detail.

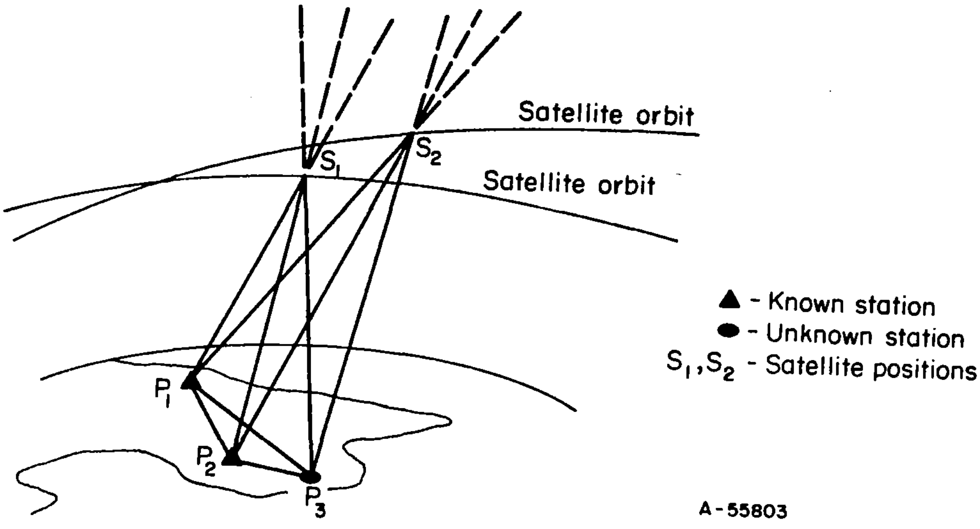

FIGURE B-13. SIMULTANEOUS OBSERVATION METHOD

The coordinates obtained in this way are not geocentric. They are dependent on the position and precision of the known stations from which they were computed and will be given in the coordinates of this reference system. They are subject to the same limitations as the coordinates of points in any geodetic system. It should be remembered, however, that the determined station coordinates are independent of the position of the satellite since this position serves only as an intermediary target. It should also be remembered that only directions and from them angles in the investigated geometric configuration in space can be evaluated from the optical method. The scale must come from an entirely different method(12).

Quasi-Simultaneous Observations. A method of quasi-simultaneous observations is used by the SAO(94). With the Baker-Nunn camera net, simultaneity of observations within one or two milliseconds can be expected when the observers are well trained and the WWV reception is favorable at each of the stations involved. Strict simultaneity is not necessary, however, if the observations are made in sequence and at equal intervals not exceeding a fraction of a minute since it is possible to interpolate the apparent position of the satellite from the series of observations.

In this "quasi-simultaneous" method, the divergence from simultaneity caused by imperfect synchronization is determined "post mortem". From the series of observations made at two stations, an interpolation can be performed to determine either (1) the position at Station B that would correspond to the time the observation was made from Station A, or (2) the position for any selected time in both sets of observations, preferably the time that corresponds to the mid-point of the two times at the two stations. The second method has the advantage of reducing the random errors in the observations since both interpolated values represent a mean value from a set of observed quantities, provided the orbit is smooth.(94)

Orbital Method. It is possible to obtain Earth-centered coordinates directly from optical satellite data with the orbital method of observation. (This method presupposes that the precise spatial position of the satellite can be determined from orbital data.) Photographic satellite observations are introduced at every station over the whole globe, without the restriction of simultaneity with observations at other places. The satellite should be photographed from more than one direction from the ground station to provide good geometric configuration. The directions PS_1, PS_2, etc., (see Figure B-14) are derived from the plate reduction process and the positions of the satellite S_1, S_2, etc., are computed from the orbital data. The position of the station will simply be at the intersection of PS_1, PS_2, etc. This position will be given in geocentric coordinates since the satellite positions are in these coordinates.

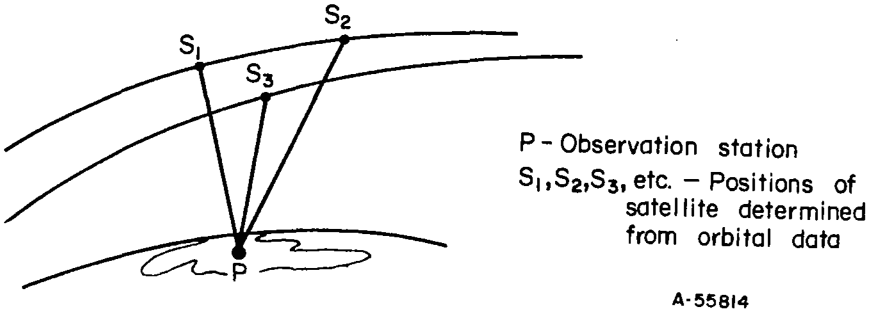

FIGURE B-14. OPTICAL ORBITAL METHOD

When the geodetic coordinates of several stations in a network have been established, a network adjustment is performed using two sets of X, Y, Z coordinates – those of the survey and the geocentric coordinates in which the stations have been determined – to compute weighted mean shifts (ΔX, ΔY, ΔZ) for the remaining stations(22).

Short-Arc Method. The short-arc method is actually a variation of the orbital method. It is used to connect geodetically unknown stations to systems that are so far apart that the satellite cannot be observed simultaneously from all stations (see Figure B-15). The accuracy of the position of the unknown station depends on the accuracy of the six orbital parameters used to position the satellite. At least three positions of the satellite are determined from simultaneous observations at three known stations. These positions are also computed from the orbital elements for the time of the observations. The difference between the sets of coordinates for the satellite yield the shifts, ΔX, ΔY, and ΔZ, from the datum-centered ellipsoid (geodetic coordinates) to an Earth-centered ellipsoid (geocentric coordinates).

The satellite positions at the unknown station are computed also from the orbital elements. They are then "adjusted" by applying the coordinate shifts determined from the known stations. The station coordinates (geodetic) are computed from these adjusted satellite positions, the station being at the intersection of the satellite-to-station vectors. In practice, many such vectors are determined, and a least-squares solution is performed(22).

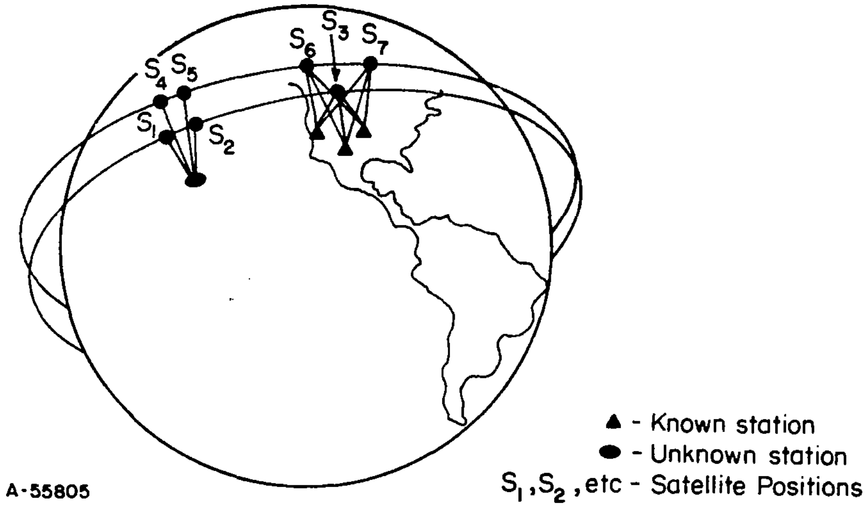

FIGURE B-15. SHORT-ARC METHOD

Plate Reduction Procedures

The methods of optical satellite observations require the utmost precision from the sciences of astrometry, photogrammetry, and geodesy. One of the most intricate operations of the optical method is that of photographic plate reduction whereby the reconstruction of configurations in the object space by means of image space data is accomplished. Various agencies use different plate reduction techniques although they are basically similar. Explanations of the general theory and the Turner or standard coordinate method of plate reduction can be found in Mueller(72), Brown(19), or Podobed(79). Hotter(43) has provided an excellent compilation of the preprocessing techniques of optical satellite observations of the various agencies. The reader is referred to these authors for a detailed treatment of plate reduction procedures. Only a summary will be provided here.

General Method. Basically, reference star images are identified and the corresponding catalogued star positions are updated to the time of observation. Approximate values of the external and internal camera orientation parameters are used to transform the right ascension-declination star coordinates to their corresponding topocentric azimuth-altitude coordinates. These coordinates, along with the corrected measured plate coordinates of the stars, are used in a least-squares solution to determine the camera orientation parameters. Once these are known, the topocentric azimuth-altitude coordinates of an unknown image (the satellite) can be determined from its corrected plate coordinates. (These coordinates are later transformed to right ascension-declination coordinates.)

Turner or Standard Coordinate Method. This method is currently used by the Smithsonian Astrophysical Observatory. For this method, the reference system is a topocentric right ascension-declination system. The plane tangent to the celestial sphere at α_o, δ_o describes the "standard coordinate" system with axes ξ and η. The axis η points toward the projection of the north celestial pole and the axis ξ is perpendicular to η and positive in the direction of increasing right ascension(43, 72, 74). The standard coordinates of an arbitrary stellar image projected on the tangent plane are given by:

$$\xi = \frac{\cot \delta \sin (\alpha - \alpha_o)}{\sin \delta_o + \cos \delta_o \cot \delta \cos (\alpha - \alpha_o)} \tag{18a}$$

$$\eta = \frac{\cos \delta_o - \cot \delta \sin \delta_o \cos (\alpha - \alpha_o)}{\sin \delta_o + \cot \delta \cos \delta_o \cos (\alpha - \alpha_o)} \quad . \tag{18b}$$

The tangent plane coordinate system can be transformed to a camera plate coordinate system (parallel to it) by the following linear transformation equation:

$$\bar{x} - \bar{x}_p = a_1 \xi + b_1 \eta + c_1 \tag{19a}$$

$$\bar{y} - \bar{y}_p = a_2 \xi + b_2 \eta + c_2 \tag{19b}$$

where

$\bar{x}$, $\bar{y}$ = the measured plate values

$\bar{x}_p$, $\bar{y}_p$ = the coordinates of the principal point

a_i, b_i, c_i = the linear plate constants .

The plate constants are determined from the reference stars. The origin (α_o, δ_o) of the reference plane is determined by one of several methods. The geometric center of the plate defined by the fiducial marks, the geometrical center of the reference stars, or the coordinates of a star in the area of the geometrical center may be used. The standard coordinates of a reference star are computed from Equations (18a) and (18b) using the values α_o and δ_o. Next the known star images ($\bar{x}_i$, $\bar{y}_i$), and the unknown satellite images ($\bar{x}_s$, $\bar{y}_s$) are measured. Three stars will give a unique solution of the plate constants in equations (19a) and (19b). More than the minimum number of stars are used in practice, however, and a least-squares solution is performed. Once the plate constants have been determined, the standard coordinates of the unknown satellite images can be determined.

The direction to the unknown satellite image (α_s, δ_s) is then found from Equations (18a and 18b),

$$\tan (\alpha_o - \alpha_o) = \xi_s / \cos \delta_o - \eta_s \sin \delta_o \tag{20a}$$

$$\tan \delta_s = \frac{(\sin \delta_o + \eta_s \cos \delta_o) \cos (\alpha_s - \alpha_o)}{\cos \delta_o - \eta_s \sin \delta_o} \quad . \tag{20b}$$

This method is a great deal less complicated than the general method of solution, but it has its limitations as outlined by Hotter(43) due to the following factors:

(1) The projection equation used to find the standard coordinates is an approximation valid only for limited area around the (α_o, δ_o) origin.

(2) The equations are based on the assumption that the tangent plane (ξ, η) is parallel to the camera plate ($\bar{x}$, $\bar{y}$). Hence, only narrow fields of view should be used. (The field of view of the Baker-Nunn camera for which this method is used is 35° x 5°)

(3) The measured coordinates $\bar{x}$, $\bar{y}$ are assumed to be unaffected by lens distortions.

Output Data of Plate Reduction. The output data of the plate reduction process is the direction to the satellite usually stated in terms of right-ascension and declination. This is preferred since if the satellite's position is given in azimuth-altitude, additional information would have to be provided before further investigation would be possible.

Also, the observed satellite position must be corrected for aberration (due to relative velocity between observer and satellite), parallactic refraction (due to fact that the satellite is a finite distance from the observer), shimmer, and, in the case of passive satellites, the fact that the observed center does not correspond to the geometric center. The output data as given may or may not be corrected for these phenomena. Furthermore, the right ascension-declination of the satellite may be referred to different reference systems with the epoch of observation defined differently. For example, the ESSA gave the final coordinates of the GEOS-I satellite in the right ascension-declination system representing the "apparent topocentric" position (i.e., the observed position corrected for astronomic refraction and diurnal aberration) at the epoch of observation. In order to obtain the true topocentric position, corrections would have to be made for diurnal aberration and parallactic refraction. (No correction is necessary for parallactic aberration since the epoch of observation was taken as the time the flash was triggered by the satellite.) The data ouput of the SAO, on the other hand, gave the satellite coordinates in terms of the geocentric (i.e., not corrected for diurnal aberration) right ascension and declination referred to the epoch of observation and to the mean equator and equinox of 1950.0. Corrections for parallactic refraction and diurnal aberration were not made. The epoch of observation in the A.S. (Atomic Standard) time system used refers to the time of maximum light intensity rather than to the time the flash was triggered.(43)

Accuracy

Spatial triangulation of the type discussed requires suitable location of camera stations relative to satellite passes. Since many of the camera stations were located for tracking satellites rather than for providing information on station locations, simultaneous observations from more than two stations is not always possible. This has been particularly true of the Baker-Nunn camera system in which the long distances between the stations (these range from 2000 to 7000 km) and the satellites more often observed do not permit a complete three-dimensional triangulation scheme. Methods have been developed, however, for using the information obtained when only two stations are involved in simultaneous observations to determine the direction in an absolute reference system of the line connecting the two stations(94).

Work along this line was performed by Mancini and Gambino.(12) Observations of the active satellite Anna-1B were carried out by the precise PC-1000 camera from stations in the southern part of the United States. The resulting accuracy was rather high since no time error was involved. The station-to-station direction was concluded to involve a mean error of about ±0."7 and its horizontal component proved to be precise within ±0."5, this being the error of the azimuth(12).

Direction determination between stations was also performed by Milbert (for the net of stations Bucharest, Nikolajeu, Poznan, and Riga) and by Arnold et al. (for the direction between Potsdam and Bucharest). The various experiments in direction-vector determinations indicate that there is a good chance of reaching the required precision of $1:10^6$ in the near future(12).

It is obvious that in the simultaneous method of observation (as well as the orbital), timing is all important. An accuracy of one millisecond is required in observation of satellites for geodetic purposes. If it is assumed that the apparent angular speed of a satellite (of altitude 1,000 km) when near the zenith of an observing station is approximately 1500" per second, an error of 1 millisecond in timing causes an error of 1."5 in the position of the satellite which causes an error of 8 meters in the position of the station(64).

If an active satellite is observed, the times of the flashes from the satellite are known. The satellite flash times for the GEOS-I were monitored and controlled by the Applied Physics Laboratory of the Johns Hopkins University. The APL published bulletins to correct the flash time (governed by the satellite clock) to WWV (U.T.C.).

If a passive satellite is observed, timing is extremely critical. If the camera is siderally driven and the satellite image is "chopped", the epochs of satellite observation will be determined by the shutter action. If the camera is fixed, the epoch of star and satellite observations (i.e. the time the satellite is exposed at the camera-station time) is determined by the shutter action.

The shutter chopping the satellite trail must be of the highest standard in order to yield a time-recording precision of about ± 1 msec without systematical influences and without camera vibrations caused by the shutter action. Rotating sector shutters or similar units have proven to be the most successful equipment for this, whereas louvre shutters seem to give rise to too intense vibrations(12).

Table B-7 outlines the timing precision and positioning accuracy obtainable with the various camera systems.

Experiments at Sea

Thus far, all optical systems discussed have involved use of land-based cameras. Limited experiments, however, have been performed on ships, and the results obtained show promise for geodetic application of optical methods to the establishment of marine control points. Of particular interest is the experimental work of Jury at the Air Force

Eastern Test Range with Photogrammetric Ocean Survey Equipment (POSE). The details of this work may be found in several published reports(47-50).

The POSE system consists of a gyrostabilized, stellar-oriented camera with associated timing equipment mounted aboard a ship. The ship station was used as an unknown station, but its relative position to either underwater acoustic beacons(49) or land-based theodolites and cinetheodolites(50, 47) was known. Using simultaneous observations of a satellite from the shipboard camera and several land-based camera stations, the geographic position of the ship was determined by triangulation.

The mathematics involved are essentially an extension of the land-based camera situation, accounting for the relation of the camera to a stable platform mounted on the ship. In the report by Jury(48), X, Y, Z represents a topocentric, azimuth-altitude coordinate system defined at the mean water surface where the Z-axis corresponds to the observer's zenith, the Y axis to his North, and the X-axis is perpendicular to the Y, Z-plane (i. e., points East). The X, Y, Z coordinates of the ship at time t_i are computed from its U, V, W coordinates by a coordinate transformation where the U, V, W axes represent the inertial equatorial coordinate system. The U and W axes lie in the meridianal plane of the gyro-camera G_o at time t_o. (G_o is the intersection of the axes of the gyro-stabilized platform.) The coordinates of the gyro-camera G_i at time t_i are derived by performing a coordinate transformation accounting for the effects of ship translation and earth rotation. A transformation is then made from topocentric coordinates to stable platform coordinates accounting for ship roll, pitch, and azimuth rotations about the metacenter and resulting in new coordinates of G. The transformation matrices are given by Jury(50).

The star direction cosines are derived relative to the topocentric and stable platform coordinate system. The target (satellite, airborne strobe light, etc.) position and the camera position are likewise derived relative to the stable platform. This allows for the determination of the direction to the satellite from the photographic plate coordinates of the satellite.

Since the actual experimental tests are explained in detail in the references previously cited, only a summary will be provided here.

For the preliminary experiment, a Wild BC-4, 21-cm focal length, F 4.2 camera was mounted on a platform permitting stabilization in roll and pitch. The gyro-stabilized camera and five land-based stellar-oriented cameras observed an airborne strobe light against a stellar background. Cinetheodolite observations were also made of a light source on the mast of the ship to locate the ship, and hence the gyro-camera, accurately. The position of the gyro-camera, determined in this way, served as the standard for comparing the results of the gyro-camera position computed from the airborne-strobe-light observations.

In the second series of tests, a BC 600-mm-focal-length, stellar-oriented camera was mounted on a platform with three-axis stabilization. The platform could be separately torqued in roll, pitch, or azimuth to enforce drift such that the optical axis of the camera could sweep through a given angle per unit of time. This caused the stellar energy to sweep across the photographic plate at a uniform rate and reduced the problem of a stellar (or satellite) trail overlapping itself.

Simultaneous observations of a satellite were made with the shipboard camera and several land-based cameras. The procedure is one of satellite triangulation as explained previously. In this case, however, the unknown station was the camera aboard the ship. Throughout the tests, the active satellite GEOS-I and the passive satellites PAGEOS, Echo I and Echo II were observed. As in the preliminary tests with the aircraft, time variant positions of the ship were also determined by land-based cinetheodolite and survey theodolite observations of a light source on the mast of the ship located 4 to 5 nautical miles off shore from Cape Kennedy. (This technique is claimed to provide positioning accurately to better than 5 feet.) These positions served as a standard for the POSE-determined positions.

The results of the experimental tests showed the combined weighted mean to differ from the true position by 29 feet in latitude and 6 feet in longitude (geodetic coordinates). The differences in the latitude and longitude determinations were attributed to inaccuracy in timing and to the satellite trajectories which were almost all in a north-south direction. Claims were made that ship positioning with respect to the fixed-camera datum could be achieved almost anywhere in the world to a geodetic accuracy of 30 to 60 feet with the prototype POSE system. Also, ocean-bottom beacons at depths of several thousand feet could be positioned with POSE and an acoustic system to accuracies varying from 45 to 70 feet. (No use was actually made of an ocean-bottom acoustic beacon system during these tests, so this is a theoretical conclusion based on known data.)

LASER METHOD

The laser is unique in that it can be utilized for satellite observations as an optical and/or electromagnetic system. Hence, the laser is capable of yielding both the angular and the range measurements necessary to determine the full vector of the spatial position of the satellite relative to the tracking station - a feature which makes it most attractive for geodetic work. Its versatility is further evidenced by the fact that the laser can be applied to all three techniques of utilizing electromagnetic waves for measuring distance; i.e., measuring the transit time of pulses, measuring the phase comparison of a modulated wave, and observing interference fringes.

The electromagnetic energy emitted by the laser is especially useful because it is monochromatic, spatially coherent, and highly concentrated. Thus far it has been used in satellite geodesy for determining ranges by measuring the transit time and for determining satellite azimuth and elevation by photographing the laser-illuminated satellite against a stellar background. The advantages of the laser for these purposes seem to be many:(56)

(1) The satellites required are essentially passive once they have been equipped with retroreflectors.*

(2) Unlike other optical methods, daylight tracking may prove possible when predicted angular positions for pointing the laser are determined - although the signal-noise ratio may be high.

(3) The large pulse power permits range measurements at much longer distances (megameters) than possible with UHF or micro-wave ranging systems.

(4) Pulses whose lengths are only tens of nanoseconds can be produced when the laser is operating in the Q-switched mode, thus eliminating the complication of the correlation techniques in the receiver when UHF or micro-wave ranging systems are used.

(5) Ionospheric propagation effects present in UHF or microwave ranging are avoided with the ruby laser since it transmits in the visible wavelength region. Also, the tropospheric correction is simpler since atmospheric water vapor does not affect propagation.

One disadvantage of the laser when compared to radio ranging is the fact that the laser receivers are less sensitive. Also, since visual tracking of the satellite is presently used, the laser is not an all-weather system.

Although it may be possible to obtain a signal return from a larger satellite such as Echo II - not equipped with retroreflectors and thus acting as a specularly reflecting sphere - the retroreflector greatly simplifies the task. The first retroreflector equipped satellite (Explorer-XXII) was launched in October, 1964. Photoelectric returns were reported shortly afterward by Plotkin et al. of NASA, Snyder et al. of GE, and

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*For range measurements it presently appears as though this will be necessary.(56) Illuminating the satellite with the laser for photographic purposes, however, may prove possible with balloon satellites such as Echo II.

Bivas and Blamont of Service d' Aéronomie, Centre de la Recherche Scientifique. A laser photograph of a satellite was obtained by Iliff of the Air Force Cambridge Research Laboratories (AFCRL) in January, 1965. The SAO obtained both photographic and photoelectric data simultaneously in June, 1965.(56) Table B-9 outlines the major characteristics of those satellites presently equipped with retroreflectors.

TABLE B-9. SATELLITES EQUIPPED WITH RETROREFLECTORS

Satellite	Apogee, km	Perigee, km	Inclination, degrees	Period, min.
Explorer XXII	1075	895	80	105
Explorer XXVII	1315	945	41	108
GEOS-I	2270	1120	59	120
GEOS-II	1580	1095	106	112
Diademe I	1340	565	40	104
Diademe II	1880	590	39	110

Types of Lasers

Several types of lasers are commercially manufactured today - gas, solid, and semi-conductor lasers being the most common. These are named according to the active medium which provides amplification of the wave. Solid-state lasers, especially the ruby and neodymium-doped glass lasers, have shown the most promise for geodetic work. They generate great bursts of energy in short pulses and although the gas laser has produced minimum beam divergence, values in the order of 10^{-4} to 10^{-5} radian can be obtained from rubies through the use of auxiliary optics.(37)

The ruby laser produces an intense monochromatic red light with a wavelength of 6943 Å. This light is especially suited to satellite tracking since photographic film and photoemissive devices are more sensitive to it than to light in the infrared region. Several agencies have used this laser for satellite work since the launching of Explorer XXII. When used for range measurements, the laser is "Q-switched"; i.e., one of the fixed reflecting surfaces is replaced by a device (Q-switch) consisting of a rapidly revolving mirror that restricts the laser action to the instant when the revolving mirror is exactly parallel to the opposite reflecting surface.

Components of Laser System

A laser ranging system consists of a retroreflector-equipped satellite, a laser transmitter, a precise tracking pedestal for pointing the laser transmitter; a receiver-detector system, and a ranging and data-control system. In the case of angular measurements, a camera system for photographing the illuminated satellite is, of course, necessary also.

A retroreflector directs the reflected laser beam so that its power is sufficient for detection. For example, the beam return for a satellite such as Explorer XXII is

3.6×10^7 times more powerful than that from a specularly reflecting sphere 1 square meter in cross section.(56) The returns from all satellites will exhibit velocity aberration, but retroreflectors, by design, spread the returning beam by a compensating amount(60). The diverging cone of the reflected beam is determined by the diffraction limit, orthogonality of the surfaces, surface flatness, or a combination of these(98). The individual cube corner prisms of the reflector are composed of radiation-resistant fused silica with silvered reflecting surfaces.

The laser transmitters used by the various organizations and agencies for satellite geodesy have all been ruby lasers. An auxiliary lens system can be used to reduce the beam to the desired width. When visual tracking is used, a laser beamwidth of 1-1.2 milliradians appears to satisfactorily allow for tracking errors(16, 46, 58). At a distance of 1 megameter, the diameter of this beam will be 1 kilometer(57). The energy of the pulse (in the Q-switch mode) ranges from 0.5-1.2 joules. When preset tracking is used, the laser transmitter is used in the long normal pulse mode since maximum pulse intensity is desired.

The laser transmitter itself is mounted on a device such as a naval gun mount or modified Nike-Ajax radar pedestal for tracking purposes. The possible two modes of tracking are that of visual tracking where the observer actually controls the instrument, or "preset" tracking where command inputs on a drive tape control the procedure. Preset tracking usually means that a wider beamwidth must be emitted in order to allow for uncertainties in the satellite position, and hence a weaker signal return can be expected. This method has an advantage, however, in that it can be used when weather conditions aren't favorable for visual tracking. The SAO, which is presently operating two laser stations designed for visual tracking and one for preset tracking, can vary the beamwidth from 2-20 minutes of arc to compensate for positioning errors in the preset mode of operation(57).

Operational Procedures

The GSFC digitally controls its tracking procedure according to both predicted satellite orbit positions and visual corrections. The antenna position programmer compares the actual angular position of the tracking pedestal to the angular position command inputs on the drive tape and generates appropriate servo-error signals to the drive pedestal to correct its position. Manual positioning is also possible(46). The tracking accuracy of this system with respect to the actual satellite position has been found to be in the order of 0.1 degree. This was determined by observing the bias necessary to keep the satellite visually aligned with the laser transmitter optical axis.

The receiver consists basically of a telescope and photomultiplier. Typical telescopes in use have apertures of 16 and 20 inches. The output of the photomultiplier is used to terminate the range measurement. The receiver may be mounted with the laser transmitter and tracking telescope or it may be located several tens of meters away to compensate for velocity aberration.

When the satellite reflector image is photographed, the photographic plate serves as a receiver also. The AFCRL used their PC-1000 stellar camera with a focal length of 1016 mm, an aperture of 200 mm, and a field of 10° x 10° to photograph Explorer XXII when illuminated by the laser.

The ranging and data-control systems refer to all those peripheral devices controlling the operation of the transmitter and receiver, the timing of the signal, and the recording of data.

Measurement of Transit Time of Signal

The station clock is used to control the operation of the laser transmitter and to measure the instant at which it is fired. There is, of course, a time delay between the "on-pulse" or firing signal and the actual firing time. Presently used station clocks time the transmission of the laser pulse to within 100 μsec. Also, a 1-MHz signal is started by the laser emission and used by an electronic time-interval counter to measure the transmission time of the laser pulse to the satellite and back. A resolution of ±10 nanoseconds which correspond to ±1.5 meters is obtainable with this device(16, 46, 60).

The range is determined by multiplying one-half the measured time interval by the velocity of light in a vacuum and making several corrections. Besides the time delay between the energizing of the laser and the emission of radiation, there are time delays introduced in the system's amplifiers and transmission lines. Also, a correction should be made for the effects of atmospheric refraction. When the laser transmitter and receiver are not collocated, a further correction is applied to account for this.

Range Equation

The range equation used by SAO for comparison purposes is:

$$S = \frac{1}{R^4} \cdot \frac{A_s A_r}{\Omega_1 \Omega_s} \cdot T^2 . E . \frac{10^{19}}{2.86} \cdot \frac{\text{photons}}{J} \quad ,$$

where

S = received signal in photons
R = range of the satellite
A_S = effective area of satellite's retroreflector
A_R = effective area of receiver's light collector
Ω_T = solid angle of transmitted beam
Ω_s = solid angle of beam reflected from satellite
T = atmospheric extinction
E = transmitted energy of laser.

Experimental test results have shown returned signal strengths to be up to 20 db below the calculated value(59).

Angular Measurements

The azimuth and elevation angles of the tracking pedestal can be recorded along with the time of laser emission to provide some indication of the direction to the satellite. For more precise values, however, experiments to photograph a satellite when illuminated by a laser beam were conducted. The laser can be used to illuminate the satellite when it is in the Earth's shadow and not visible by reflected sunlight. In this case, maximum energy rather than minimum pulse length is desired. Since the satellite cannot be tracked visually, a beamwidth greater than 1 milliradian is also necessary to compensate for satellite positioning errors. The AFCRL as mentioned earlier, used a PC-1000 camera to photograph the satellite reflector image. The laser was operated in the normal long pulse mode of 2.7 msec duration, and the beamwidth was reduced only to 15 arc minutes. The camera shutter was opened just before the shot and remained open until after the laser was fired. Two precalibrations and two post calibrations were made for angular information. Although an actual position based on plate reduction was not attempted because of the lack of adequate star calibrations, this preliminary work demonstrated the feasibility of the concept(98). The SAO also conducted an experiment which did not yield any useful data on satellite location but also demonstrated the feasibility of photography with a laser(56).

Geodetic Positions

There are two possible methods for utilizing laser data: a purely geometric method and a semi-dynamic method(16). In the former, if a series of ranges are obtained for known satellite positions, a spatial intersection such as that performed with SECOR measurements would yield the coordinates of an unknown station.

Another possibility is to combine range measurements with azimuth and elevation measurements obtained by simultaneously photographing the satellite. With this procedure, the satellite's position or the observer's position (if the satellite position as predicted from its orbital parameters is used) can be determined.

Still another and more complicated possibility would be to make simultaneous observations (range and/or angular measurements) from three known and one unknown station to position the satellite and then the unknown station as is done with SECOR or with optical methods.

A semi-dynamic method could be used when the means for a purely geometric method are not available or inadequate precision is estimated. In this case, the orbit parameters intervene, at least as auxiliary unknowns, and a program of differential corrections used. This approach is discussed at some length in Reference 16.

Accuracy

The accuracy of the laser ranging system depends on the accuracy of the time-interval counter, the duration of the pulse, the determination of the time delays in the system's components, the accuracy of the atmospheric correction, the uncertainty in the epoch of observation based on the worldwide synchronization of clocks, and the accuracy of the value for the velocity of light in a vacuum. Commercially available time-interval counters currently have an accuracy of 1 nanosecond (15 centimeters). Pulse durations, however, for the presently used Q-switched ruby lasers are about 10 nanoseconds (or 1.5 meters). This range error can be made less than 1 meter if the return signal is sufficiently strong to define the pulse's leading edge or if pulses with durations of less than 10 nanoseconds can be generated.*

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*In Reference 46 it is reported that pulses whose durations are considerably less than 1 nanosecond have been generated.

Calibration of the laser system against a known target for time delays has yielded an accuracy of ≈ 1 meter. Whether this will improve with an improved system is difficult to predict. Atmospheric corrections based on temperature and pressure readings at the time of the pass and formulas from the National Bureau of Standards should be accurate to 0.4 nanosecond (or 0.06 meter)(58).

The worldwide sychronization of clocks is presently maintained at approximately 100 μsec. This would have to be improved to within 10 μsec for decimeter accuracy. The velocity of light, on the other hand, is known to only 1 part in 10^6.

The preceding gives an indication of the theoretical accuracy of a laser ranging system. It might be interesting to note some of the conclusions based on experimental work performed since the launching of Explorer XXII.

The SAO has reported partial results* of its initial experiment conducted from June, 1965, to July, 1967, at Organ Pass, New Mexico. (The SAO collocated a laser ranging system with its Baker-Nunn camera so that range measurements could be performed along with optical observations of the sunlit satellite.) The measured ranges were compared with those derived from field-reduced orbits; hence, the results will be more meaningful when precisely reduced orbits are obtained. Also, the collected data were used to compare the recorded return signal strength with that predicted by the range equation. This latter procedure indicated a maximum discrepancy of approximately 20 decibels for a satellite range of 1.5 megameters and elevation range of 60° to 69°

The deviations of the measured ranges from the field reduced orbits varied between the extreme values of -200 to +620 meters. All of the observations were for GEOS-I, and Explorer XXVII. According to Reference 59, these initial experiments show only that there are no apparent large discrepancies between the laser measurements and the Baker-Nunn measurements.

The GSFC has collected laser ranging data for three U.S. and two French satellites. Explorer XXVII data obtained by laser ranging at Goddard Space Flight Center and GEOS-I data obtained at Rosmon, North Carolina have been analyzed. Since a more accurate reference system was not available for comparison, an internal analysis of the data was performed(67). The data, consisting of range-only measurements from a single observing station, were reduced using a minimum-variance differential-correction program. Results indicated that the examined data exhibited no statistically significant nonrandomness. The root mean square of the range residuals in most cases was less than two meters, and the residual histograms displayed a slight asymmetry toward the long-range side.

Navy TRANET Doppler data obtained on one of the GEOS-I passes was also utilized in a Doppler-only solution and in a combined laser-Doppler solution. The average rms range value of 1.6 meters did not change between the laser-only solution and the laser-Doppler solution whereas the rms range-rate value changed from 0.03 m/sec in the Doppler-only solution to 0.04 m/sec in the laser-Doppler solution. No significant systematic trends appeared in the laser results when compared with results obtained with the Doppler system(67).

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*Results here refer only to those tests conducted from December, 1965, to February, 1966(59), although a report(11) of earlier work is also available.

An intercomparison of Goddard Range and Range Rate (GRARR) and Goddard laser data obtained by side-by-side tracking of the two systems at Rosman, North Carolina, between July, 1966, and November, 1966, was performed to aid in the evaluation of the GRARR system and to determine the effectiveness of the laser as a calibration instrument for electronic tracking systems. The results indicated that laser orbits could be used to detect systematic errors in both the range and range rate to about 2 m and 1 cm/sec respectively. A summary of the laser data showed an average range rms of 1.8 meters(14).

International efforts are presently underway for establishing a worldwide laser network. The SAO presently has three laser systems installed at Baker-Nunn sites in Arizona, Hawaii, and Greece. Plans are to add to this each year until all Baker-Nunn sites have a laser system. The French National Space Agency has two laser tracking stations, - one near Merseilles and one in Spain near a Baker-Nunn site. Likewise, the Greeks have installed a laser system at an SAO station near Athens. It is possible that the Australians will have a station in operation during the summer of 1968. Also, NASA's Goddard Space Flight Center has joined in these efforts(7).

APPENDIX C

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