NASA CONTRACTOR REPORT

NASA CR-141395

(NASA-CR-141395) APPLICATIONS OF SATELLITE AND MARINE GEODESY TO OPERATIONS IN THE OCEAN ENVIRONMENT (Battelle Columbus Labs., Ohio.) 120 p HC $5.25 CSCL 14B

N75-20682

Unclas
G3/35 14732

APPLICATIONS OF SATELLITE AND MARINE GEODESY TO OPERATIONS IN THE OCEAN ENVIRONMENT

by: D.M. Fubara and A.G. Mourad

Prepared under contract No. NAS6-2006 by:

Battelle

Columbus Laboratories

505 King Avenue

Columbus, Ohio 43201

for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WALLOPS FLIGHT CENTER

WALLOPS ISLAND, VIRGINIA 23337

March 1975

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-141395		

4. Title and Subtitle	5. Report Date
APPLICATIONS OF SATELLITE AND MARINE GEODESY TO OPERATIONS IN THE OCEAN ENVIRONMENT	March 1973
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
D. M. J. Fubara and A. G. Mourad	
	10. Work Unit No.
9. Performing Organization Name and Address	
Battelle Columbus Laboratories 505 King Avenue Columbus, Ohio 43201	11. Contract or Grant No. NAS6-2006
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report
National Aeronautics & Space Administration Wallops Flight Center Wallops Island, Virginia 23337	14. Sponsoring Agency Code

15. Supplementary Notes

In accordance with para. 5.d. of NASA Policy Directive, NPD-2220.4, "Use of the International System of Units (SI) in NASA Publications," a waiver has been granted for this report.

16. Abstract

The overall objective of this study was to assess the requirements for marine and satellite geodesy technology with the emphasis on the development of the case for marine geodesy. This objective was achieved by (1) analysis of various NASA programs and missions for identification of the satellite geodesy technology applicable to marine geodesy, (2) analysis of various national and international marine programs to identify the possible roles of satellite/marine geodesy techniques for meeting the objectives of these programs and other objectives of national interest more effectively, and (3) development of the case for marine geodesy based on the extraction of requirements documented by authoritative technical industrial people, professional geodesists, government agency personnel, and applicable technology reports.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
EREP Skylab GEOS-C Satellite Marine Geodesy	Unclassified - Unlimited STAR Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	119	

*For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This report covers activities preformed by Battelle's Columbus Laboratories (BCL) on behalf of the National Aeronautics and Space Administration, Wallops Station, under Contract No. NAS6-2006, "Services for Oceanography, Geodesy, and Related Areas Task Support". The NASA task monitor was Mr. H. R. Stanley. The Battelle task director was Mr. A. G. Mourad.

ABSTRACT

The overall objective of this study was to assess the requirements for marine and satellite geodesy technology with the emphasis on the development of the case for marine geodesy. This objective was achieved by (1) analysis of various NASA programs and missions for identification of the satellite geodesy technology applicable to marine geodesy, (2) analysis of various national and international marine programs to identify the possible roles of satellite/marine geodesy techniques for meeting the objectives of these programs and other objectives of national interest more effectively, and (3) development of the case for marine geodesy based on the extraction of requirements documented by authoritative technical industrial people, professional geodesists, government agency personnel, and applicable technology reports.

Of the several NASA programs and missions reviewed only EREP/Skylab and GEOS-C are currently approved missions specifically related to marine geodesy and ocean physics applications. The planned Earth and Ocean Physics Application Program (EOPAP) is another important program as a follow up to Skylab and GEOS-C missions, and will require extensive support from marine geodesy. Under the AAFE Program RAD/SCAT System is being developed along with an altimeter which utilizes optimum pulse compression techniques. The RAD/SCAT relates to ocean physics and the altimeter relates both to ocean physics and geodesy.

From the analysis of marine programs and activities, it was found that the emphasis in these programs is on (1) environment (monitoring, prediction and preservation of its quality) and collection of the necessary baseline data, (2) development of ocean resources (for food, energy, minerals, etc.), and (3) development of required technology. Marine mapping and charting activities, which are highly dependent on marine and satellite geodesy technology, are prerequisites for success in most ocean operations. All programs discussed in this report require accurate geographic location. This can best be provided by satellite/marine geodesy techniques. Some programs require accurate knowledge of the geoid, "undisturbed mean sea level", which in the ocean can best be obtained through satellite altimetry in combination with marine geodetic and oceanographic ground truths determined by conventional methods. Other programs have requirements for sea state and wave height information that could be provided also by satellite altimetry and/or a bistatic satellite radar technique under development for NASA. On the other hand, some of NASA's satellite programs such as GEOS-C and Skylab require ground truth data that most of the marine programs can help to provide.

Industry's estimated $2.5 billion expenditures in 1973, for development of ocean resources, exceeds by far all other expenditures for ocean related activities. In contrast, the 1973 funding for a Federal Ocean Program was about $0.7 billion. The off-shore industry trend is toward operations in deeper water. Marine and satellite geodesy techniques are required in the solution of some of the problems involved in exploration and exploitation of ocean resources. A major stumbling block in deep ocean resource development involves resolution of seabed ownership and mineral exploitation rights. Associated with this problem are boundary determination and reidentification which can only be resolved effectively through the use of marine and satellite geodesy technology. Implications of marine legislation and laws of the sea related to ocean bed exploration are described in detail.

The "case" is, therefore, made for marine geodesy from synthesis of the requirements and the dependency on satellite technology in the following major topics (1) environment, (2) ocean resources and transportation, (3) national security and (4) space science and technology and ocean physics applications research.

TABLE OF CONTENTS

APPENDIX A

TABLE OF CONTENTS
(Continued)

Page

APPENDIX B

TABLE OF CONTENTS
(Continued)

APPENDIX C

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

1.0 CONCLUSIONS AND RECOMMENDATIONS

As a preamble to the recommendations that follow, the major findings of this study are first summarized. Section 3, the Case for National Marine Geodesy Program, gives extensive details on the bases of our conclusions supported by over ninety authoritative documents by personnel representing many Government agencies, private industry research organizations and universities. Various marine research programs, energy and resources exploitation activities and legal considerations for marine operations are reviewed with respect to their requirements for satellite/marine geodesy.

The two main outputs of geodesy are (1) geodetic coordinates or positions of points on the continents, the seas and in space; and (2) the geoid (the undisturbed mean sea level equivalent of an equipotential surface in the earth's gravity field) or the earth's gravity field at mean sea level. Determination of these parameters in the oceans specifically is the role of marine geodesy.

1.1 Conclusions

On the basis of this study, the following conclusions can be made:

(1) There are numerous requirements for marine geodesy,

(2) Most of these requirements have not been fulfilled,

(3) There is no publicized, concerted, organized, formal and systematic national effort or policy for a program to "...initiate planning, research, and development for marine geodesy" as advocated by R. Adm. Jones, (former Director of National Ocean Survey of NOAA) since 1966 [92].

(4) There is a need for such a program in marine geodesy. The research necessary to formulate and standardize marine geodesy methodologies, as has been done for "continental" geodesy, has not been initiated. Without this, marine geodesy cannot play its roles effectively. Such roles were summarized by R. Adm. Jones as: "In the immediate future, state, territorial, and international boundaries as well as exploratory property lease limits...must be located. Other oceanographic activities need geodetic positioning at great distances at sea to permit calibration of navigation systems. Structures and operations that are a hazard to navigation must be accurately located and charted."

(5) Other activities in the oceans for which the requirements for marine geodesy were identified include: (a) satellite altimetry applications for computing sea surface slopes in order to model ocean dynamics and deduce current and circulation patterns that affect such areas as weather and its predicition and pollution control; (b) position determination and navigation involved in exploitation of energy and other resources at sea; (2) oceanographic, geophysical and other marine research programs under NOAA, NSF, DoD, etc.; (d) refinement of the gravity field and geodetic groundtruth for satellite altimetry missions and other objectives of the NASA-proposed Earth and Ocean Physics Applications Program (EOPAP).

(6) EREP/Skylab and GEOS-C are, currently, the only approved NASA missions dedicated to earth and ocean physics research required for environmental monitoring, prediction and quality control. The proposed EOPAP is a necessary and logical program for these environmental needs.

(7) The practical applications and the necessity to include the uses of marine geodesy in several marine programs are either not recognized or are being ignored to the detriment of the optimum effectiveness of such marine activities.

(8) Although there is a need for it, the mechanism through which user requirements can be obtained or whereby users can be informed about developed satellite/marine geodesy techniques applicable to their operations does not exist.

(9) Currently, satellite technology is indispensable to effective applications of marine geodesy, especially in the deep oceans. So far, NASA has played the only significant role for supporting research in marine geodesy.

(10) There is lack of intersystems evaluation and calibration of the various systems in use for marine positioning, navigation, etc.

1.2 Recommendations

It is recommended that:

(1) as in the case of the National Geodetic Satellite Program (NGSP), and in view of the high dependency on satellite technology and the successes of previous NASA-supported marine geodesy experiments, NASA should provide leadership in and "...initiate planning, research, and developement for marine geodesy" a long unfulfilled urgent need. The marine geodesy program should include the following objectives:

(a) To provide a mechanism whereby potential industrial and other users can specify requirements for satellite/marine geodesy technology applicable to the solution of problems in the ocean environment, energy and resource development, transportation, national security and space research.

(b) To identify roles of satellite technology in the physical establishment and reidentification of legal commercial and international boundaries at sea; develop the satellite technology/marine geodesy methodology for these purposes; demonstrate the efficacy and practicability and/or identify necessary modifications of the developed methodology.

(c) To establish experiments for evaluation and calibration, in field operational conditions, of positioning systems (including satellite systems, and the startracker aboard the Apollo Ship Vanguard) in use or useable for marine geodesy. Such systems evaluation should include determination of (i) system precision and accuracy (ii) error sources, mode of propagation and performance criteria, and (iii) determine their suitability for determination of the geoid and geodetic positions at sea in support of oceanography, groundtruth for future satellite altimetry missions, and other needs for marine geodesy required by EIPAP and national needs in the ocean environment.

(d) To establish the fundamental research necessary to develop marine geodesy methodologies for various requirements and operating conditions. This should include specification of methods for finding accurate three-dimensional geodetic coordinates at sea in a defined geodetic datum; establishing control surveys; definition of uniform systems for computations and adjustments with correct statistical involvement for both geodetic controls and geoid determination; and the adaptation of astrogravimetry to marine geodesy.

(2) the logical follow up to this satellite/marine geodesy requirements assessment study is initiation of a project for formal definition of marine geodesy program responsive to the above recommendations.

2.0 TASK REVIEW

2.1 Task Objectives

The overall task objectives were to (1) assess the national requirements for improved marine geodesy; (2) evaluate how, which and to what extent NASA-developed satellite technology and related precision measurement techniques can meet these requirements with respect to national marine programs and activities for national goals such as (a) environmental monitoring, prediction, and quality control; (b) marine exploitation for resources and energy; (c) national security; (d) transportation over the oceans by air and sea; (e) space, earth and ocean physics.

2.2 Research Approach

As a result of the findings from a preceding investigation into the Interactions of Marine Geodesy, Satellite Technology and Ocean Physics [72], the conduct of the research involved:

(1) Reviews and analyses of existing, approved and planned major NASA programs and missions that already relate or could relate to both marine geodesy and oceanographic research which is fundamental to achieving the above enumerated national goals.

(2) Reviews and analyses of existing and planned marine national programs and activities as a means of assessing the applicability and degree of relevancy of satellite/marine geodesy to the goals of the programs and those national goals listed earlier.

(3) Comparative analysis and evaluation of the results of steps (1) and (2), and extraction of documented requirements for improved marine geodesy from several reviewed publications. These were combined to synthesize "the case for marine geodesy" and its dependency on satellite technology.

2.3 National Programs Reviewed

This is a summary of the national programs reviewed and analyzed. Specific details on these programs are contained in Appendix A--Satellite Geodesy Technology, and in Appendix B--National and International Marine Programs and the Roles of Satellite/Marine Geodesy. Appendix C--Present-Day

Accuracy of the Earth's-Gravitational Field--is a review of the results of national and international programs' efforts to accurately define the earth's gravity field. The geoid (the equipotential surface of the earth's gravity field at "undisturbed" mean sea level) or the knowledge of the earth's gravity field at sea level is of fundamental importance to geodesy, oceanography, geophysics and geology, the disciplines on which hang all other environmental considerations outlined under the project objectives.

2.3.1 NASA Satellite Programs and Missions

Existing or approved, and planned NASA satellite programs/missions were reviewed and analyzed for relevancy to and requirements for marine geodesy. The 1972 version of the NASA proposed Earth and Ocean Physics Applications Program (EOPAP) could not be obtained for this study. NASA programs/missions reviewed and discussed in Appendix A included: PAGEOS-1, ATS - Series 1 through M, GEOS-1, -2 and -C, EREP/SKYLAB, GRAVMAG, GEOPAUSE, SEASATS (SATS ALTIMETRY), TDRSS, EOS, SEOS, TIROS-O, GRAVSATS, LAGEOS, ERTS.

The discussions, evaluations and results in Appendix A show

(1) the names of NASA satellite programs/missions

(2) the status of the programs/missions, such as currently operational, or approved but not yet operational or proposed and under evaluation for approval

(3) current and proposed operational schedules

(4) program/mission objectives and applicability to (a) establishment of geodetic controls, (b) mapping and charting, (c) geoid and/or earth gravity field determination, (d) polar motion investigation, (e) geodetic ground truth for satellite altimetry missions, (f) navigation, (g) plate tectonics, (h) sea state monitoring, (i) ocean tide measurement, (j) ocean currents and circulations, water mass transport all of which relate to air-sea interactions that influence weather prediction. Applicability was classified under directly applicable, indirectly applicable not applicable and potentially applicable if further applications research and/or certain suggested slight hardware modifications or additions or increase in mission scope were implemented.

EREP/SKYLAB (1973) and GEOS-C (1974) appear to be the first and currently the only approved missions specifically designed to help in solving earth and ocean physics problems for the benefit of man's environmental needs.

Beyond GEOS-C, there now (1973) appears to be no other approved missions dedicated to solving earth and ocean physics applications problems. However, several missions of this type are under the umbrella of the proposed Earth and Ocean Physics Applications Program (EOPAP). Furthermore, both SKYLAB and GEOS-C missions can only demonstrate hardware and software feasibility or the lack of it because they carry the first generation of unproven spacecraft equipment. It is imperative, therefore, that EOPAP be approved and implemented or the resulting research vacuum could cause irreparable damage to our limited ability for environmental monitoring, prediction, and quality control through geodetic, oceanographic, geophysical and geological research. Section 3 shows the assessed requirements for marine geodesy as the indispensable links in resolving many operational needs in the oceans.

2.3.2 National Marine Programs

Several national and international marine programs or activities were studied to identify the possible role of satellite/marine geodesy techniques for meeting the objectives of these programs and additional objectives of national interest more effectively. These programs include International Decade of Ocean Explorations (IDOE), Azores Fixed Acoustic Range (AFAR), Inter-Seamount Acoustic Range (ISAR), Deep Sea Drilling Project (DSDP), Cooperative Investigation of the Caribbean and Adjacent Regions (CICAR), DoD and NOAA Marine Mapping and Charting, International Field Year for the Great Lakes (IFYGL), Integrated Global Ocean Stations System (IGOSS), Marine Resources Monitoring Assessment and Prediction Program (MARMAP), National Data Buoy Project (NDBP), Geochemical Ocean Sections Study (GEOSECS), Mid-Ocean Dynamic Experiment (MODE), French American Mid-Ocean Undersea Study (FAMOUS), Trans-Atlantic Geotraverse (TAG), Sea Grant, Manned Open Sea Experimentation Station (MOSES), Undersea Long-Range Missile System (ULMS), Long-Term and Expanded Program of Ocean Research (LEPOR), Global Atmospheric Research Program (GARP), GARP Atlantic Tropical Experiment (GATE), Coastal Zones Program, and Arctic Ice Dynamics Joint Experiment (AIDJEX). Marine activities reviewed included those of various industries (offshore oil, gas and minerals, etc.) and marine legislation implications and the Law of the Sea.

Although all these programs and activities listed above were reviewed during this study, only the NDBP, MODE, NORPAX, GARP, GATE, DSDP, AIDJEX, Ocean Resources and Marine Legislation are discussed further here and in detail in Appendix B. The criteria used for this selection were:

(1) Relevancy of marine and satellite geodesy

(2) Availability of descriptive and technical information

(3) Duration to at least 1975 (to allow sufficient lead time for NASA planning and interaction with lead agencies)

(4) Operation in deep water areas rather than in coastal and Great Lakes areas where most geodetic requirements may be satisfied by existing and/or non-satellite systems.

Obviously, marine mapping and charting programs and activities are prerequisites for many ocean operations, and they are highly dependent on marine geodesy and satellite technology. However, mapping and charting activities are not discussed separately, but they are considered in detail in Section 3, The Case for a National Marine Geodesy Program.

All marine programs and activities discussed in this report require accurate geographic location. This can best be provided by satellite/marine geodesy techniques. Some of the programs require accurate knowledge of the geoid "mean sea level" which, in the oceans, can best be obtained through satellite altimetry in combination with geodetic and oceanographic ground truths determined by conventional methods. Others have requirements for sea state and wave height information that could be provided also by satellite altimetry and/or the bistatic satellite radar technique under development for NASA [79]. On the other hand, some of NASA's satellite programs such as GEOS-C and Skylab require ground truth data that most of the marine programs can help to provide.

The importance of the NDBP is underlined by the Industrial Data Users Meeting (IDUM) on the program, attended by representatives from offshore oil and gas industry, marine hard-mineral mining, marine surface transportation, the airlines, fishing industry, commercial meteorology and ship routing firms, coastal engineering and construction organizations, agriculture, the recreation industry, and government agencies. These various national interests extensively use environmental data in planning, designing, scheduling and conducting their operations [3]. Some of the buoys will be moored. Such moored data buoys, being fixed stations in the open ocean, have the potential of serving as valuable

(a) navigational aids to marine and air traffic and

(b) surveying control points for offshore gas, oil and hard-mineral prospecting, bathymetric mapping, physical boundary establishment and reidentification at sea, marine geophysical research, oceanographic research, etc. and

(c) aid to determination of ground truth in support of Skylab, GEOS-C and Apollo-Soyuz and similar future space missions for earth observation. Such moored buoys should carry (1) visual markings and light for day and night visibility, (2) radar targets suitable for use with standard commercial X- and S-band radars, (3) under water sonar beacons for submarine traffic, and (4) radio-beacons for air traffic.

To become useful aids to navigation and surveying, the geodetic coordinates (on an uniform geodetic datum) of each buoy should be known accurately to between 10 meters and 1 km. depending on the type of marine operation involved. Currently, in the open oceans, only satellite and marine geodesy techniques can determine the coordinates of each buoy to the required accuracy referenced to a consistent geodetic datum. The feasibility of 10 meter accuracy in the determination of geodetic positions at sea has been proven [71]. What is needed now is to blend this operational philosophy into NDBP planning and thoroughly investigate how to implement this additional use of the buoys. To monitor the time-varying positions of a moored buoy, ocean-bottom transponders can be used for geodetic-acoustic tracking of the buoy.

For programs such as MODE, NORPAX, GARP and GATE [5,7,14,16,31], there is a need to know relative positions of the hydrophones and the research ships. Accurate geodetic (geographic) locations of these various components and stations comprising the experiment's array should be known so that the results of each experiment can be correlated with results of other oceanographic, meteorologic, geodetic and geophysical experiments in the Atlantic and worldwide. Geodetic-acoustic techniques are necessary for the precise surveying of the hydrophones' relative positions. Satellite geodetic positioning in combination with simultaneous acoustic ranging to the hydrophones from ship(s) is the most effective means of accurate geographic location in the oceans to meet the objective of global correlation of results. Some of the ships and buoys for GATE are required to be stationary and will have to be anchored. The type of anchors used in the past, in the BOMEX program for example, and which failed are expected to be improved upon and used in GATE. As a result of experience from BOMEX, current plans to use anchors prohibits the use of ships more than 1,000 tons. The application of satellite geodesy and marine geodetic-acoustic techniques to locate the ships and monitor their positional time history relative to fixed ocean bottom transponders can relax the current stringent plans related particularly to ship size and anchors.

It will also furnish a backup system if the anchor systems fail as in BOMEX. In fact, the anchor systems could be completely eliminated particularly since the cost of ocean bottom acoustic transponders is competitive with deep ocean anchoring systems. One of the transponders could be a nuclear-powered permanent type (about 20-year life expectancy) so that the exact site of the experiment could be returned to for future confirmation experiments.

GATE will be in operation during the early part of the GEOS-C mission. With a little coordination of efforts with the responsible agencies and institutions, programs such as GATE, and MODE, should furnish useful surface truth data for GEOS-C altimetry data processing and evaluation. On the other hand, satellite technology such as the ITOS satellite series is expected to make key contributions to these programs.

The Deep Sea Drilling Project (DSDP) [4] explores the earth's crust covered by the sea in order to investigate the origin and history of the earth. This must be known to enhance the understanding and further the preservation of our environment.

The DSDP, using the drill ship GLOMAR CHALLENGER, demonstrates the effective use of marine and satellite geodesy techniques. The ship employs dynamic ship positioning techniques for deep drilling. Ocean-bottom transponders are used for relative positioning of the ship and the drill pipe. In addition, a satellite navigation receiver is employed to provide the geocentric location of the drill sites. Results so far obtained have been useful for investigating the hypothesis of continental drift and sea-floor spreading by inference. Marine and satellite geodesy and VLBI techniques can and should be used to experiment in direct measurement of the rate of sea-floor spreading to verify DSDP inferences and current plate tectonics theories. These have bearing on current efforts to predict and eventually prevent earthquakes, tsunamis and similar environmental hazards.

AIDJEX [12,21,61] supported by Canada, Japan, and United States agencies--ONR, ARPA, NASA, NAVOCEANO, NOAA, Army, USCG, USGS, and NSF Office of Polar Programs--is designed to provide the basic understanding of the complete ocean-ice-atmosphere system that affect weather, climate and their predictions. In addition to many oceanographic and meteorological measurements, there will be sea-ice observations involving the determinations of position, azimuth control, sea-ice velocity and acceleration and strain. Determination of these parameters depends on geodetic techniques exclusively, as is further elaborated on in Appendix B where it is shown that the application of satellite-marine geodesy is clearly relevant to the success of AIDJEX. The pertinent techniques are similar to those proven by a NASA supported marine geodesy experiment [71].

Ocean resources and associated industrial activities are discussed in detail in Appendix B. The main purposes were to show (1) the types and quantities and the importance of ocean resources to national needs for food, energy, mineral, security, etc.; (2) the amount of industrial efforts and significant investments involved; (3) the problems associated with exploration and exploitation of these resources; and (4) the requirements for satellite/marine geodesy in the solution of some of these problems to secure maximum operational effectiveness economically and safety-wise. Section 3.2 gives a general assessment of the indispensable requirements for satellite/marine geodesy extracted from documentations of various industrial users.

Legislation for regulating jurisdictions and operational boundary rights are also reviewed in Appendix B. As on land, the actual physical delineation and reidentification of boundaries at sea have to employ geodesy. Throughout the history of man, all efficient and systematic explorations, exploitations developments and use of the continents, and even the moon and other planets are preceded by geodetic operations, mapping, charting, etc. In effect, all the reviewed marine programs and activities reinforce the need to adapt geodesy for similar utilization in the oceans.

3.0 THE CASE FOR A NATIONAL MARINE GEODESY PROGRAM

Several national needs have requirements for marine geodesy, such as:

- Environment-monitoring, prediction, and quality control
- Resources exploitation
- Transportation
- National security
- Space sciences and technology
- Applications to the earth
- Other scientific research.

Analysis of these requirements are made in this report.

Basically, all geodetic activities aim at two fundamental objectives: (1) determination of the three-dimensional coordinates of points on the continents, the oceans or in space in a predefined coordinate system, and (2) determination of the geoid (the equipotential surface in the earth's gravity field coincident with the undisturbed mean sea level) or the earth's gravity field at sea level by gravity measurements.

These two fundamental determinations in the oceans (i.e., the tasks of Marine Geodesy) are indispensable for satisfaction of operational responsibilities of the State Department, NASA, DoD, NOAA, marine and air transportation, off-shore gas, oil and hard mineral industries, and oceanographic research.

3.1 Requirements for Marine Geodesy in Environmental Monitoring and Quality Control

The two main outputs of marine geodesy are indispensable to effective research in oceanography, meteorology, marine geophysics, marine geology, marine biology, waste disposal and pollution control, prevention of accidents at sea, etc. The research and operations of these disciplines constitute the major elements in environmental monitoring and quality control in the oceans which make up about 70 percent of the earth's surface. These two marine geodesy/satellite technology outputs of concern are (1) the absolute geoid (correctly oriented, scaled and earth centered) or the earth gravity field defined at mean sea level, and (2) geographic location or positioning (geodetic coordinates of a point in a known geodetic datum).

3.1.1 The Impact of Marine/Satellite Geodesy on Oceanography and Meteorology

The general circulation of the world's oceans has a strong bearing on the weather and its prediction. Accurate knowledge and modeling of this general circulation is a very important goal in oceanography. The requirements for this goal and its unavoidable dependency on accurate knowledge of the marine geoid which requires marine/satellite geodesy for its determination are emphasized by the following excerpts from the NASA Williamson Study report [1] on the topic of the general circulation:

> "Of fundamental importance to physical oceanography is the measurement of the difference between the topography of the sea surface and the geoid. Given the geopotential of the sea surface and knowing from ship observations the internal distribution of water density, we would then be able to compute the dynamic topography of all isobaric surfaces and the values of the global geostrophic transport of mass and heat by ocean currents at all depths. The great advantage in this approach is that oceanographic calculations of geostrophic mass and heat transports by ocean currents could be made on the basis of facts, avoiding the traditional and invalid assumption (level of no motion) [26, 82, 85] that somewhere deep in the ocean the water is motionless...
>
> "These measurements would be not only of basic scientific interest, but also of practical value. For example, the atmosphere overlies the world ocean and is nourished by oceanic water vapor and heat. Detailed observation of the structure of the oceanic general circulation on a day-by-day basis would surely advance knowledge of the energy exchanges between the ocean and the lower atmosphere [75] and improve capabilities to predict weather by numerical forcasting techniques. For dynamical interpretation of calculations of mass transports, measurements of sea-surface relief would be most valuable if made with reference to the geoid...There is at present no method that permits the potential or gravity at the sea surface to be determined to high spatial resolution from conventional satellite measurements."

[Note: However current plans for satellite altimetry supported by marine geodetic ground truth, etc., can resolve this problem.]

> "Spherical harmonic analysis of the geopotential topography of the sea surface would have to be carried to at least the 360th degree to resolve the topographic changes associated with such important features of the ocean circulation as the Gulf Stream. The optimistic estimates of spherical harmonic resolution from present methods of orbital perturbation analysis suggest that 20th-degree coefficients may be evaluated, but this is too coarse for oceanographic purposes."

Hence more sensitive techniques, such as continuous satellite-to-satellite tracking or marine astrogravimetry and other marine geodesy techniques [40] are needed to obtain the required resolution.

> "...However, further investigation should be made of surface techniques to determine variations in geoid height: i.e., the deflection of the vertical (the slope of the geoid, and hence the horizontal derivative of potential $\partial V/\partial s$, referred to the fixed stars). The accuracy desired is $\pm 0\overset{''}{.}5$ for an averaging distance of 15 km...
>
> "A difference of the slope inferred from the altimetry from that derived from the deflections of the vertical would indicate a slope of the sea surface with respect to the geoid, i.e., the presence of a current. The observed slope would be very close to the slope of an isobaric surface (1 atm) and, with 0.1-m resolution in the altimetric data, yield a measurement of the dynamic slope accurate to 0.1 dynamic meter. Such resolution in the dynamic topography of an isobaric surface would permit the internal field of pressure and currents at all other depths in the ocean to be computed with an error of only 20 percent or so wherever measurements have been made of the vertical specific-volume gradient in the underlying water column."

These same requirements for the marine geoid or a definition of the earth's gravity field at sea level by marine geodesy in support of physical oceanography and consequently numerical weather prediction are amplified by Kaula [54, 55]:

> "The ocean physics panel considered the use of altimeters to determine variations in the sea level surface; precise positioning and tracking of ships and buoys; and ocean transport and diffusion.
>
> "The great difficulty in solving the general circulation problem in oceanography is the lack of an adequate pressure boundary condition. The mean sea level differs from the geoid because of variations in temperature and salinity, which are adequately known, and barometric pressure and wind stress, which are not. Consequently integrations to determine the circulation have had to make the unsatisfactory assumption that at some level there was no motion. Repeated measurements of the sea surface would enable elimination of this assumption, provided they were to an accuracy of ± 10 cm. Furthermore, to distinguish the geoid from the sea level, there must be some measure of the variations in gravity. This circumstance will require some smoothing of the boundary condition, but in any case the altimetry would contribute greatly to the solution of the ocean circulation problem, and thus to the problems of diffusion, heat transport, air-sea interaction, etc...For ship-borne gravimetry it is desirable to measure vessel location to ± 100 m and velocity to ± 5 cm/sec. A

satellite navigation system together with a network of geodetic control points on the sea floor would contribute greatly to the attainment of these accuracies."

Kaula advanced the following rationale to support the above statements:

"The...above would be of some benefit in the support they render to navigation, orbit-determination, geodetic survey, etc. However, their main practical value arises from their scientific value. It seems inescapable that our fundamental understanding of the natural environment must be radically improved if exploitation of the environment is to continue at the same pace, without deterioration of its quality, on into the next century...Better insight into such things as air-sea interaction...is also needed to improve protection against the environment. Space and astronomic techniques" (as employed in marine geodesy) "can make a contribution to this improved understanding of the terrestrial environment, in particular the:

- driving forces and response mechanisms of the long term dynamics of the solid earth;
- causes and consequences of the ocean circulation;...
- contribution of ocean currents and heat transport to the global heat balance;...
- energy dissipation in the oceans..."

In support of the systems and techniques to implement this required research into the application of marine geodesy and satellite technology to oceanography and meteorology for environmental prediction and protection, Kaula further stated:

"The above described systems would logically be supplemented by:

- navigation systems accurate to ± 5 cm/sec. (i.e., 0.1 knot) for ships;...
- position measurement of ± 2 km accuracy over 5 day intervals for buoys;
- surface geodetic surveys...
- Theoretical research, including large scale computer use."

To implement all these, the employment of marine geodesy is inescapable. For instance, it is not enough to design and build a marine navigation system and assign it the above specified accuracy. The instrument must be tested in various real operational conditions to establish its accuracy. This would establish present accuracies achievable and guide future systems' developments. Marine geodetic controls already mentioned above by Kaula and discussed in [41, 42, 67, 68, 69, 70, 71] are indispensable requirements for testing and calibrating navigation systems in actual operational conditions. This would eliminate the undesirable situation described by Jury [53] as:

> "Definition of system accuracy and performance are as varied as the product of the number of systems used and the number of using agencies."

Jury went on to suggest among other things that:

> "Controlled tests should be conducted against an adequate standard to determine the accuracy and performance of navigation systems prior to commitment for operational missions... A national committee is needed to establish test procedures and accuracy definitions...and select...test facilities suitable...for general oceanographic and...programs."

There are more documentations such as [46, 72, 84, 88, 89], linking physical oceanographic research and its contributions to weather prediction and other environmental goals with the determination of the marine geoid, and marine geodetic controls which depend on the application of marine geodesy and satellite technology. A flowchart of this interaction and the benefits to certain national goals is depicted in Figure 3-1.

Certain environmental requirements for the geoid have been established. For the determination of the geoid at sea both by classical methods and satellite altimetry marine geodetic controls are required [43, 67, 72]. Marine geodetic controls are needed for the geometric computation of quasi-stationary departures of the sea surface topography from the geoid, using satellite altimetry data. In Section 2, various ongoing and planned national marine programs such as AIDJEX, NDBP, NORPAX, GARP, GATE, MODE, GEOSECS, etc., have been discussed. The common objectives of all these NOAA, and/or NSF managed programs is to improve the description, prediction, monitoring, research, and management of the atmospheric and marine environments of the living/non-living resources of the sea through the acquisition of data at sea, [6, 24]. The need for geodetic controls for optimum effectiveness of these environmental programs have been established along with the program descriptions. In the deep oceans, satellite geodesy is the key to the establishment of the required marine geodetic controls.

3.1.2 The Need for Marine/Satellite Geodesy in Waste Disposal, Pollution and Seabed Hazard Prevention

In the use of the ocean for waste disposal, various questions remain unanswered. Such questions include:

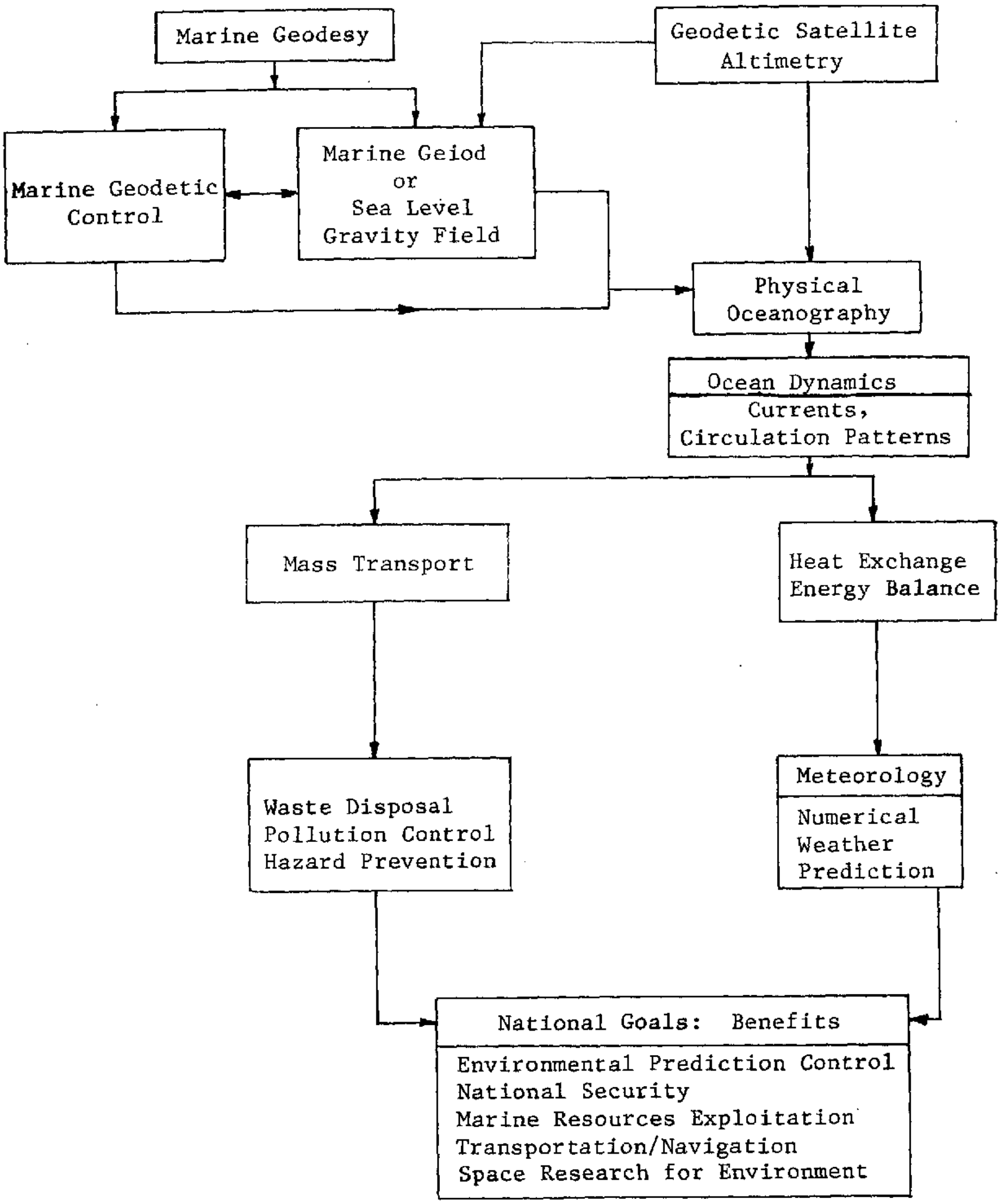


FIGURE 3-1. INTERACTION OF MARINE GEODESY WITH PHYSICAL OCEANOGRAPHIC RESEARCH AND NATIONAL GOALS

(1) Where was the waste dumped?

(2) What are the ocean bottom topography and depth of water?

(3) How do the bottom topography and geologic structures influence disposed waste and the effects of the waste?

(4) Will the location of the waste vary with time and if so, where and when will the waste affect the environment?

(5) Does the waste degrade?--At what rate and with what effect on the environment?--If waste does not disintegrate will it be a potential hazard to deep submersibles, mineral exploitation, cable and pipeline laying and other marine activities?

The answer to "where" can be provided only by accurate positioning information in a known geodetic datum and derived from navigation and/or location determination equipment. Elsewhere, in various parts of this report it has been shown that: (a) existing navigation and positioning systems have not been evaluated and calibrated in real operational conditions for reliable assessment of systems accuracy. All accuracy statements are theoretical estimates that vary with the users and geographic locations; (b) intersystems comparisons in theory and actual operations are nonexistent. In fact, different systems give different values for the latitude and longitude of the same location and very often such differences are significant to the validity, safety or effectiveness of the marine operations [80] For example, such systems differences could lead to inadvertently dumping two dangerous wastes (e.g., weapons) in the same location or conducting another marine operation over a previously dumped hazardous waste. Because, through the use of different uncompared navigation or positioning systems, two operations were in fact over the same location when the positioning systems indicated the contrary, several ships have been wrecked by running into previous ship wrecks in the English channel and elsewhere; (c) application of marine geodesy and satellite technology is currently the only valid means for the navigation and positioning systems evaluation, calibration and intersystems comparisons discussed above [53, 64].

Emphasizing the above need to know "where" is the following excerpt from a paper [28] by the staff of the U. S. Naval Oceanographic office, National Academy of Sciences, Woods Hole Oceanographic Institution on:

> "Hazards of the Deep...Threat to all ocean bottom activity. Although the following discussion is restricted to the threat to research submersibles...it should be obvious that the threat applies equally to all activity on or near the ocean

floor. Therefore, those involved in such efforts as Sealab, offshore oil well drilling, salvage, etc., would be well advised to take this threat into consideration in the planning and execution of their programs and operations...adequate data do not exist to support precise statements regarding the geographic distribution...on or in the ocean floor."

Accurate and detailed bathymetric maps and geologic surveys are, in principle, the answer to the need to know ocean bottom topography and geologic structures at "waste disposal" sites. Usually, this information is obtained from previous surveys. But as pointed out in [59]:

"...we are confrnted with the problem of how accurate the position of the survey ship was at the time it obtained the original survey data."

Of course, one answer is to conduct, in situ, all the necessary surveys, having first emplaced two or three geoditically located ocean bottom markers, using marine/satellite geodesy techniques.

Mobility of disposed waste in the oceans depends on the presence and magnitude of currents, density of the waste material and its ability to disintegrate physically and chemically. Our present knowledge of ocean circulation and ocean current patterns or mass transport of the ocean is inadequate to realistically predict the mobility and diffusion of disposed waste. Drastic improvement of such knowledge is required if the oceans are to be used for waste disposal without damage to the environment or hazard to man's operations in the oceans. In respect of improving our knowledge of ocean dynamics, the roles of marine geodesy and satellite technology have been discussed in Section 2.1. Several national marine programs such as NDBP, MODE, GARP, GATE, NORPAX, Skylab, and GEOS-C, are designed to aid in improved knowledge of ocean dynamics. These programs and relevant roles of marine geodesy have been discussed elsewhere in this report.

The need for improved knowledge of ocean dynamics, particularly ocean transport and diffusion, which are important factors in waste disposal, pollution control and seabed hazard prevention is amplified by the NASA report on the Williamstown Study [1].

"The elucidation of the general circulation is a fundamental problem in physical oceanography. Interest in the results ranges from simple scientific curiosity to very practical and topical concerns such as the spread of nutrients or of pollutants that have been released in the deep sea deliberately or by accident. After a century of study, oceanographers are still unable to answer such questions as: How long will any leakage of supposedly sealed reactor waste take to reach the surface from a deep dumping ground? or where will any leakage first make its appearance at the surface? When dealing with the surface circulation, which has been by far the most fully explored, oceanographers are hard put to predict the motion of a Santa Barbara oil slick, to name another practical example. Some of the most important questions asked of oceanographers concern the distribution and transport of substances in the ocean. The answers to these questions have as their starting point statements about mixing and flow in the sea. Such questions must be answered if disasters are to be avoided in the exploitation of the oceans. Oceanographers may answer these questions only if they can understand the motion of the water of the sea."

All the discussions on environmental monitoring and quality control center on oceanography. That oceanography alone cannot meet these environmental objectives without marine geodesy is emphasized in [1] as follows:

"A long-standing problem in deep-sea oceanography is that of adequate horizontal positioning. Many quite proper scientific questions are simply not asked because off-shore navigaton, even by TRANSIT satellite, is not accurate enough. Continuous vehicle location of ±100 m or better and a determination of 5-min average vehicle velocity to ±5 cm/sec or better can be achieved by radio navigation within 100 miles of land, but off-shore navigation is only one-tenth as accurate at best. Removal of this limitation would produce a quantum jump in open ocean research and survey opportunities.

"There are basically two types of measurement requirements:

1. Positioning of fixed points on the ocean floor where several repeated measurements can be made; and
2. Positioning while the vehicle is underway so that only a single measurement can be made at one place.

"It is desirable that the accuracy achieved with type-1 measurements be an order of magnitude higher than with type-2 to permit precise station-keeping and to provide reference points for survey operations. Marine geodetic reference points are needed to serve as sites in the open sea and for navigation and mapping control for the calibration of positioning and surveying systems. It has been shown that such reference points can be marked by an acoustic transponder array on the sea floor [66] and [42, 69, 71]."

In spite of all this documented evidence and the above excerpt, oceanographic research programs and other marine activities continue to be planned and executed without any formal inclusion of the roles of marine geodesy. Such programs include NDBP, MODE, GARP, GATE, NORPAX and other

IDOE activities. Underlying all this is the absence of a national program in marine geodesy to provide increased national consciousness of and promote research to identify and formalize methodologies and operational specifications in "marine geodesy" as has been done for "continental geodesy".

3.1.3 The Significance of Marine/Satellite Geodesy to the Environmental Needs for Marine Geophysics and Geology

Effective monitoring, prediction, preservation and exploitation of the environment requires more than the current piecemeal activities in marine geophysics and geology, and the inclusion of marine geodesy in these activities. Efficient synthesis of marine geophysical and geological data to deduce globally meaningful models of the environment demands reliable knowledge of locations of the acquired data. The need to know "...how accurate the position of the survey data" [59] exists. There is also the need to use geodetically located markers to (a) demarcate the boundary of the survey area and (b) continuously track the survey ship to obtain consistently accurate ship locations throughout the survey duration. Such marine geodetic controls further permit a return to the same site to repeat data acquisition either for confirmation or for investigations such as sea floor spreading that require repeated measurements on site.

With respect to this role of marine geodesy, the statement from [1] that

> "A long-standing problem in deep-sea oceanography is that of adequate horizontal positioning...fixed points on the ocean floor where repeated measurements can be made...to permit precise station-keeping and to provide reference points for survey operations"

applies equally if not more stringently to marine geophysical and geologic operations.

Instruments required in these geophysical and geological data acquisition need not only calibrations but also the correlation and elimination of systematic errors in acquired data through the use of "base stations". The needs for and methods of utilization of such base stations were elucidated by Kivioja [56] in "Significance of Open-Ocean Gravity Base Stations and Calibration Lines" which ended with the conclusion that:

> "All the fields of study that have been mentioned and possibly some others, will benefit from the gravity surveys on oceans. The framework for a successful execution of a gravity survey

> is provided by a network of gravity base stations. Good gravity anomalies can only be obtained by using good gravity base stations."

The use of satellite altimetry to compliment or even partially eliminate conventional marine gravity anomalies measurements is under investigation. In either case, the use of marine base stations or marine geodetic control points remains indispensable.

Further elaboration of these issues in [1] states that:

> "Gravity measurements on a worldwide basis are needed to further understanding of the earth's figure and mass distribution. The largest errors in gravity measurements at sea, whether the measurements were obtained from shipboard or in airborne systems, are caused by navigational uncertainties. It is necessary that the E-W component of velocity of the surveying vehicle be known to 1.0 knot (5 cm/sec) to reduce observed gravity to rest with an accuracy of 1 mgal...Marine geodetic reference points are needed to serve as sites in the open sea for navigation and mapping control and for the calibration of positioning and surveying systems. It is desirable that these reference points be located in an ocean-wide geodetic coordinate system and that standards of gravity be known at each station to ±0.1 mgal, magnetic dip to ±1', magnetic intensity to ±1 gamma, and water depth to ±0.5 m (referred to mean sea level). It has been shown that such reference points can be marked by an acoustic transponder array on the sea floor [66]...It is intended that these marine reference points be moved about to meet existing research and survey requirements. Apollo tracking ships appear to be suitable vehicles for locating these stations to the required accuracy. But the full capability of these ships can be achieved only when a satellite is equipped with either a C-band or S-band radar transponder and a doppler system..."

(as in the GEOS-C mission planned to begin in mid 1974. Experiments with GEOS-II in the Bahamas and Puerto Rican trench [42, 69, 81] have demonstrated feasibility of such a capability and confirms the continuation of the above excerpt.)

> "The propsed open-ocean reference points would be valuable in this connection for navigational control. Electromagnetic or acoustic positioning relative to these stations could fill in the gaps between satellite fixes and would thus provide a much needed improvement in the measurement of ship velocity for the reduction of gravity observations to rest."

All these requirements point to the need for more concerted effort and systematic research in marine geodesy. This can only be realized by the establishment of a well organized national marine geodesy program.

3.2 Requirements for Marine Geodesy in Resources and Energy From the Oceans, and Transportation

Determinations of geodetic controls and the geoid at sea (the two main tasks of marine geodesy) are requirements for efficient transportation and effective but non-destructive exploitation of the oceans for living and non-living resources and energy. Basically, the geodetic controls are needed for (1) mapping and charting; (2) lease, territorial or operational site boundary delineation and reidentification; (3) navigation--time-varying position determination, navigation systems calibration, standardization and intersystems comparison which help in prevention of hazards due to navigation or positioning errors; (4) reconnaissance surveys and operational relocation. The geoid is needed as shown in Section 3.1 for oceanographic research related to weather forecasts, pollution which affects marine living resources, and other environmental monitoring and quality control required for marine activities related to resources, energy and transportation.

In support of the above promulgation and as a basis for further elucidation, excerpts from some industrial user documentations will be quoted. Basic user requirements for satellite/marine geodesy by the hard mineral industry is not much different from those of the oil/gas industry. Therefore, the oil/gas industry will be used mostly as the example.

The following are comments by Sheriff [80] of Chevron Oil Company on "The Requirements and Problems of Navigation for Geophysical Exploration", presented at the 1973 Symposium on Offshore Positioning for Petroleum Exploration and Production:

> "Marine geophysical work is expected to continue at roughly the level of $125 million per year. Most of this work is seismic, some gravity; both require accurate positioning on a continuous basis...Geophysical surveying from ships constitutes an almost universal step in the petroleum exploration of offshore areas... The seismic specifications (25 feet CEP) are given in terms of repeatability rather than accuracy because usually the important aspect involves having different points bear the right relation with respect to each other and being able to relocate the same spot, rather than knowing locations in terms of geodetic or statuatory coordinates. The latter sometimes are also important and impose additional requirements. For example, a location may be repeatable in each of two different systems without the two systems agreeing on the coordinates of the point and neither may give geodetic or legal coordinates."

Because repeatability alone can lead to disastrous mistakes such as operating outside one's lease boundary, he then recommended:

> "...Tie off the navigation system into local geodetic control. At least two points need to be tied in to provide this relationship and these should preferably be at opposite sides of the survey area. These might be done by static satellite observations involving 10 or so fixes while tied up at known location."

On the same topic, Clewell [29] stated:

> "One of the primary items of interest was repeatability; the ability to go back to the same point again and find the same object or position on the bottom, which often may not have any close correlation with the true geodetic position indicated by the system. However, it is necessary to relate this repeatability data, in whatever form it may be and with whatever accuracy, to some geodetic point when the information is collated ashore."

These recommendations require satellite/marine geodesy for which there is no organized program of research to establish pertinent methodologies in spite of several experiments [63,70,71] that have demonstrated feasibility.

The need for (1) reliability in marine positioning and (2) adequate intersystems evaluation and calibration for standardization of navigation systems in real operational conditions, and the roles of satellite/marine geodesy are discussed in Section 3.3. How this need affects the marine oil/gas industry is emphasized by the following from Sheriff [80]:

> "At the Second Symposium on Marine Geodesy in New Orleans, Jones and Sheriff [52] pointed out that despite the money involved in marine petroleum work, it did not follow that the very best positioning technology would be used. 'Hard economic judgments balancing positioning costs against the probable and possible costs consequent to less precise positioning' have to be made. This, of course, remains true. But have our judgments been good?
>
> "Consider the following, all of whic happened recently:
>
> (1) Intersecting seismic lines show differences in water depth of several hundred feet. The survey was run with an integrated satellite-gyrocompass-doppler-sonar system using real-time filtering. Water depth was highly variable so that the doppler-sonar frequently switched between bottom-track and water-reverberation modes.
>
> (2) Common geological features in seismic data are displaced by a mile. The survey was run with Loran-C in the hyperbolic mode. Ironically, a back-up navigation system

on the ship indicated a discrepancy at the time but was not believed.

(3) Aircraft flying lane count to a survey ship using a CW phase-comparison radio system show discrepancies on a quarter of the flight.

(4) A Shoran transponder is located on the wrong island.

(5) A navigation system fails and the back-up system on board is discovered to be non-operational...

(6) A shotpoint map prepared in post-mission analysis indicates that ship speeds at times reached 70 knots. Three features are evident:

(1) The situations which restrict navigation systems are not considered adequately when surveys are being planned and, hence, inappropriate systems are chosen.

(2) Operations are carried on wider conditions which exceed the limitations for accurate location determinations.

(3) The accuracy figures quoted for navigation systems do not represent operational conditions.

I do not cite the above failures as typical; in these surveys we know that errors occurred. A "typical" survey is more than apt to be one for which the accuracy actually realized is never determined. While inconsistencies in the geophysical or other data may point to a location bust, lack of obvious inconsistency cannot certify that locations are correct. Without an independent means of verifying location, one cannot determine that a measurement is accurate."

To remedy these problems, Sheriff's recommendations included:

"...(1) Tie the navigation system into local geodetic control...

(2) Specification as to what constitutes acceptable performance, such as the range of acceptable angles at closest approach for a satellite, the minimum number of doppler counts for a fix, the maximum correction between a dead-reckoned position and a satellite fix, how to accommodate corrections under various conditions, etc.

(3) Definition as to which system provides the primary navigation under given circumstances.

(4) Operational specifications such as the minimum number of independent location determinations along any given line or within any given period of time, for example, requirements for satellite fixes near the beginning and end of a line, the conditions which require circling and rerunning portions of a line, etc."

The satellite/marine geodesy research for effective implementation of such recommendations is awaiting a systematic and organized national program in marine geodesy.

On the general mapping and charting needs for "Subsea Mineral Resources and Problems Related to Their Development", McKelvey [62] stated:

> "Basic documents, especially regional topographic and geologic maps, lay the groundwork for identifying areas favorable for the occurrence of various minerals and for an appraisal of their potential resources.
>
> "Three kinds of maps are needed:
>
> (1) Accurate topographic or bathymetric base maps that show bottom depth and shape of features by contours and are used as base maps for geologic and other studies.
>
> (2) Surficial or bottom-sediment maps that show the kinds, distribution and thickness of the sediments that lie at the surface of the sea bottom.
>
> (3) Geological maps of the bedrock beneath the sea bottom that show the distribution, thickness, and structural relations of rock units underlying the sea floor and that make possible three-dimensional analysis of potential oil- and mineral-bearing structures."

McKelvey cites the development of an acoustic pinger as a fundamental need for mineral evaluation and mining.

> "...new device is a radioisotope-powered acoustic pinger that has a 5-year life, usable in water as deep as 6,000 feet, and will precisely mark undersea locations, a fundamental need in both mineral evaluation and mining."

The feasibility of using ocean bottom acoustic transponders and satellites or other surface positioning systems for tracking a ship to permit accurate mapping and charting tied to a known geodetic coordinate system has been demonstrated in several marine geodetic experiments. What is needed now is a formal establishment of methodologies, performance criteria and operational specifications through marine geodetic research.

Formal inception of marine geodesy can be credited to the First Marine Geodesy Symposium of 1966. In his paper "Marine Geodetic Problems of Industry and Commerce," [27] Burg, then Vice President of Geophysical Services, Inc. of Texas Instruments, Inc., stated: "Industry and commerce have many uses for marine geodesy...a rather broad subject..." He described the general uses of marine geodesy to cover

"...national defense, development of marine resources, navigation, safety and economy of sea-going activities, support for scientific investigation of marine phenomena."

He further stated:

"Development of marine resources, through the exploration, development, and exploitation phases, is dependent upon position-fixing.

"Navigation, above and beneath, as well as upon the sea, was the first use of geodesy. However, with expansion of commerce and development of marine resources by industry, navigation becomes more of a science and less of an art.

"The installation of resource development platforms and accompanying increase in sea traffic places a new requirement upon geodesy. The safety and economy of these ocean environment activities becomes an important concern, related to navigation and position-fixing.

"The scientific investigation of marine phenomena becomes more meaningful if the locations of the measurements are accurately known.

"If we analyze each of these general applications of marine geodesy, we recognize a common basic requirement. This is position-fixing. This can be static or dynamic or both static and dynamic. Every oceanic activity has a static position-fixing requirement--of knowing precisely where on the face of the earth the activity is located. Most activities have a dynamic position-fixing requirement--of knowing precisely the location of one point of activity relative to adjacent points. This is an especially critical requirement in the case of exploration for resources and collection of scientific data...we can be sure that the Science of Marine Geodesy will be a key contributor in this oceanic resource development. We know the geodetic requirements, the motivations are there, and we must provide the capabilities."

To provide the required capabilities demands a national commitment to a program of organized research in marine geodesy and the associated satellite and electronic technologies.

On the issue of navigation and positioning requirements, Captain Putzke [76] summarized the following:

"The Coast Guard's analysis of user needs for the maritime navigation community, is to a large extent based upon the results of a requirements survey. This survey, conducted by an independent contractor, assessed the user needs in three different environments, namely the high seas, the coastal/confluence zone and the harbor and estuary or terminal environment...

"The overall objective of the study was to identify and describe the total spectrum of the marine operations requiring a position fixing service to perform its assigned mission. The study was directed toward an "on site" position fixing capability which is distinctly different from the point-to-point navigational capability. In other words, who are the users and what are the requirements for "on site" marine positioning?

"The survey was conducted through a combination questionnaire and interview technique, with a response level of 62%, most of which was productive. With the exception of governmental vessel operators having classified military requirement, the field of existing users was well covered in the United States.

"The categories of special purpose users are:

- Government
- Institutional
- Industrial.

"The categories were subdivided into operational areas (missions) consisting of:

- Oceanography
- Geophysics
- Hydrology
- Marine Biology
- Oil exploration
- Cable and pipeline surveying and construction
- Dredging
- Salvage (search and recovery).

"Current requirements most important consideration...is in the level of accuracy of position. The majority of those surveyed indicated that this requirement is in the 0 to 50 foot range. Analysis and interpretation of interviews and response to the questionnaire reveal the following conclusions.

Dredging	- 5 to 6 feet
Pipe laying	- 1 to 10 feet
Cable laying	- 1 to 10 feet near shore 1000 feet thereafter
Salvage	- 30 feet
Oil exploration	- 50 feet
Hydrography	- 10 to 100 feet near shore 500 to 1000 feet beyond 100 mile
Geophysics	- 50 to 100 feet
Oceanography	- 500 feet
Marine Biology	- 500 to 1000 feet."

A Government/OSTAC Workshop on marine mapping, charting and geodesy organized by National Security Industrial Association [29] reported similar findings for requirements.

"The consensus of workshop members were as follows: The accuracy requirements for dredging--five to six feet; for pipe and cable laying--less than ten feet; for salvage operations--thirty feet; for operations in the field of hydrography--ten to one hundred feet in areas near shore--in areas over one hundred miles from shore--six hundred foot accuracy is needed; for geophysics--a range of fifty to six hundred feet (but this is primarily a relative accuracy requirement); for oceanography--an absolute reference accuracy is required of five hundred feet--however, a thirty-five to three hundred foot relative accuracy is required; for marine biology--fifty to one thousand feet depending on the specifications of the operation; for oil and gas exploration--in the area from the coast to twenty miles from shore--fifty foot accuracy--and in the area from twenty miles to three hundred miles offshore--fifty to one hundred foot accuracy is needed...

"On the accuracy requirement for submersibles, in the near short and offshore environment, one-tenth of a nautical mile was considered as the present requirement by the workshop participants. There is a need for charting and mapping based on a common geodetic reference. There is a current need for a simple conversion system.

"It was pointed out that accuracy, in terms of presently available systems, is not constant throughout the coverage area of that system; there is a dilution of the accuracy with distance from the station reference. It was determined that there was a need to know what degree of confidence may be placed in the system accuracy at various points within the coverage area.

"Instrument reliability, standards and calibration are continuing problems in most measurement areas and need additional support and emphasis.

"One of the primary problems identified was that the various charting and mapping operations that go on today are not based on a common geodetic reference. The need for such a common geodetic reference was expressed by most members of the group.

"...There is a need for some mechanism through which the needs of user groups can be presented to the government, and that these needs must be presented in specific terms. In the past, needs have often been defined in terms of 'the best we can get'. This type of requirement is of little use as a long-range planning factor."

A well organized national seminar for user requirements is suggested for this needed mechanism.

These statements for requirements which only satellite/marine geodesy can be used to conclusively satisfy as explained in Section 3.3, are further amplified by Cohen [30]:

"Most individuals who conduct work of any kind...would attest to the importance of position determination...there are and will be requirements for position determination of greater accuracy.

"There is ready agreement that a requirement exists for accurate terrain maps. By requirement is meant the need for the map--or bathymetric chart--as a tool to aid in the performance of certain work in the oceans. By the term accurate is meant a reasonable current portrayal of bottom terrain at some suitable working scale. There is no difficulty in establishing recognition that proper bathymetric charts are requisites to effective accomplishment of many end goals in the oceans, and it is probably correct to state that certain things could not be done in the absence of such charts.

"The group of tasks that follow next all necessitate standards allowing for very accurate position, ±20-50 meters. These tasks have a certain commonality: there is direct relation between validity of measurement and position. It is fair to predict that submersibles will be potent tools for implantation of gear, rescue and salvage, mining, deep drilling studies, retrieval of treasure and man-in-the-sea programs. The chart product for the latter category will invariably be of large scale, perhaps 1:5,000 or even larger, have a close contour interval (2-5 meters) and will necessitate extremely detailed bottom surveys.

"Cable-laying ships frequently conduct on-site surveys and chart compilation prior to the lay. The accuracies are manifold due to the nature of the operation, with depth parameters of importance in the sound channel and because the array of cable must be in predetermined azimuth. The shortest distance to shore, terrain considerations notwithstanding, is of importance because of the expense of cable. Precise position in real time is paramount in this kind of operation.

"Pollution studies and waste disposal are, of course, directly interrelated. Here, again, the author falls back upon leaving it to those more expert than he as to accuracies required. In certain cases, such as disposal of radiation-type waste in deeper ocean areas, exact position would appear to be critical.

"In conclusion, even if the data above are valid and receive general agreement, the biggest job still lies ahead. This is to translate the accuracy standards desired to specific programs of surveys and chart production. And this may be the most difficult task of all."

On the issue of physical determination and reidentification of boundaries at sea, R. Admiral Nygren made the following comments [73]:

"We are talking about marine law and marine boundaries, and there is a great sensitivity on the part of various jurisdictions to express any kind of policy or to make any kind of controversial statements in this area at this time. As we look at the problem of boundary determination, we find a shake out into at least four general groupings. There are some technical problems; Admiral Jones will discuss some of these in his paper. There are some legal problems. There are some problems which, for want of a better name, might be called policy questions, and Dr. Alexander will touch on some of these. Some of the most important problems of boundary determinations are political. Nobody wants to touch these with a ten-foot pole, apparently, because boundaries really are limits which define various jurisdictions. No matter how you slice it, they are areas over which somebody exercises effective control of some kind or another. And this control in the off-shore area, particularly, includes the ownership or the right to manage resources or wealth. And, resources have been and are the source of strife all over the world.

"Conflicts have arisen between states, between the states and federal government, between federal government and international agencies, and between countries. I would call to your attention the example of the Intergovernmental Oceanographic Commission, which now includes 66 countries. Many--perhaps most of them--have no capability in oceanography whatsoever, but have a great interest in the 'limitless riches of the ocean', and they are in that organization either to get their share, or to be sure that nobody else gets their share. So, I think it is safe to say that this problem of the limit of national jurisdiction is going to continue in various international forums for a long time to come. There is really no reason why we should expect that the historic controversies over land boundaries will not be carried over into the oceans. They already are being carried over into the oceans. So, in my opinion, the future really doesn't hold much hope for peaceful solutions to many of these things. The pattern has never been peaceful. If we succeed in this, it will be truly remarkable.

"Now these boundaries between various jurisdictions must be accepted, must be recognized, must be definable, and they must be recoverable. And whether these boundaries are extended from shore or from shoreline features to various distances off shore, whether they are defined by underwater features themselves, such as isobaths or sea mounts, or whether they are defined by mathematical lines, such as meridians and parallels, they must be properly positioned, and this is where the job for the geodesist comes in. I do not believe he is always going to enjoy his role in this part of the field."

Rear Admiral Jones' discussion [51] included:

"Accelerated development and growth of the use of the sea are indicative of expanded exploitation for the benefit of commerce, industry, recreation, and settlement. Some day aquaculture may well rival and surpass agriculture in importance as the population growth forces increased dependence upon the marine environment for survival.

"Increased national effort must be made if our technology is to be used effectively in making intelligent use of our oceanic resources. One of the basic problems now being encountered is the determination of the extent of offshore waters over which a maritime nation has sovereignty. Ownership of rights to the ocean floor, state-federal jurisdiction, the extent of fishing rights, and other factors are pressing problems.

"The Geneva Conventions, adopted in 1958 and ratified by the United States in 1964, clarify some of the legal questions involved, but many remain unresolved. The federal-state contention over lands and minerals in the complex coastal areas is far from settled. The era of submarine law is here, and with it is a dire need for determining precise jurisdictional boundaries."

He further stated that for:

"Boundary demarcation, or the laying out of a boundary on the ground and with an appropriately detailed pictorial representation...the field work involved encompasses ground control; projection of the boundary line; mapping the boundary strip; and placement of survey monuments. Problems usually encountered in demarcating a dry land boundary are consideraly more complicated in the demarcation of a submerged land boundary...Mean sea level takes on a new significance when we deal in the offshore area. Mean sea level '(the geoid)' is defined by geodesists as the equipotential surface which the oceans would assume if the only forces acting upon them were the earth's gravitational forces and the centrifugal forces set up by the earth's rotation. There are other forces, however, with which we must deal, such as the tidal forces of the sun and the moon, and the meteorological forces such as wind, atmospheric pressure, and others which vary from time to time and place to place.

"These forces produce an ever changing surface of the sea which is difficult to relate to the ideal equipotential surface of the geodesists' mean sea level. It is true that the differences between the outer surface of the sea and the equipotential surface are of a rather small order; perhaps only a few meters at most. Still some oceanographers are interested in what they call the slope of the sea and its position above or

> below the equipotential surface at any given time at a given place."

On the continents, these problems are resolved by appropriate geodetic methodologies developed through concerted and well organized national research and international cooperation. At sea, these problems must and can be solved by marine geodesy. However, formal development of the appropriate methodologies is awaiting the creation of an organized and systematic national research program in marine geodesy.

Air and sea transportation depend on navigation and hazard prevention in navigation is of utmost importance. Flawless knowledge of position of transportation vessels relative to one another, relative to hazards (such as sunken vessels or exploration constructions or natural features), and relative to the ports of start and destination or other transportation facilities enroute, all hinge on well evaluated and calibrated positioning and navigation systems. The navigation requirements for marine geodesy are discussed later. As mentioned earlier, the incorporation of marine geodesy into the National Data Buoy Program (NDBP) would greatly help in providing aid to air and sea transportation over the oceans and the continental shelf by giving the vessels highly reliable positioning information.

This assessment of requirements for marine geodesy can be summarized by Rear Admiral Jones' comments [92] that:

> "The increasing recognition of the vast resource potential of the Continental Shelf and ocean regions has hastened the emergence of a relatively new discipline in geophysical sciences: the marine geodesy. Just as classical geodesy is needed on land to increase knowledge of the size and shape of the earth, to establish precise horizontal and vertical control for mapping and cadastral surveying, and to provide essential related gravimetric and astronomic data, so marine geodesy is opportune throughout the remaining three-fourths of the earth's surface--the oceanic areas. It is apropos that the geodetic community should take the responsibility and leadership to investigate the problems, determine the requirements, and outline a program of marine geodesy.
>
> "The plans and programs of the Coast and Geodetic Survey envision the immediate requirements for marine geodesy to be horizontal control and gravity determinations; needed for exploration and development of oceanic resources of the Continental Shelf regions. Obviously,

the basic geodetic networks over the entire Continental Shelf cannot be established in just a few years and with limited resources. However, activities must be initiated now to respond to the need for marine geodesy and to assure that these activities will serve the same functions that the present geodetic systems serve on the continental and island land masses. These functions include:

(1) Maintain a specified standard of accuracy over large areas and long distances

(2) Assure coordination between activities accomplished at different periods of time and at adjacent locations

(3) Provide means to reestablish boundaries.

"Geodetic surveys have been extended short distances into the marine environment to satisfy the immediate needs of the petroleum industry by using classical land techniques to locate offshore platforms and exploratory lease limits. Oceanographic activities have included gravity determinations at sea, both by surface vessels and by submersibles. Ocean-bottom gravity meters are also being employed. To date, actual marine geodetic activity has only been a 'drop in the ocean'.

"In the immediate future, state, territorial, and international boundaries, as well as exploratory property lease limits on the Continental Shelf, must be located. Other oceanographic activities need geodetic positioning at great distances at sea to permit calibration of navigation systems. Structures and operations that are a hazard to navigation must be accurately located and charted. There is, therefore, an urgent need to initiate planning research, and development for marine geodesy."

This statement of need is more true today than it has ever been. The necessary program to accomplish Rear Admiral Jones' suggestion for "...initiate planning, research, and development for marine geodesy" is yet to be instituted.

3.3 National Security Requirement for Marine Geodesy

The various activities which require marine geodesy directly or indirectly, and which are important for national security include (1) surveying and mapping, (2) navigation, which involves knowing one's geographic coordinates at any given time, (3) calibration of missile systems and navigation equipment, (4) guidance of missile systems, (5) accurate gravity field model for computation of satellite orbits and missile trajectories, (6) waste and weapon disposal at sea, (7) search and rescue, (8) meteorological forecasts, and (9) boundary determination.

As a preamble to specific discussions of the above needs, the following are excerpts from "Requirements and Views of DoD in Marine Geodesy" by Capt. M. Macomber [59].

> "The agencies (in DoD) find that their activities require a diverse input of geodetic information, some of which is readily available, but some of which must be measured for the particular project being undertaken... We will require a knowledge of gravity to guarantee the proper orientation of the major geodetic systems correctly in a world datum... The knowledge of gravity that is required for the datum orientation cannot be limited to land areas, but must extend to the ocean areas of the world surrounding each major geodetic datum.
>
> "So far we have considered geodetic requirements in land areas which require a knowledge of gravity in the marine environment. Let us now consider a problem more intimately connected with the oceans. In keeping with the nation's greater international awareness, the need has developed to maintain knowledge of the location of major fleet units on a continuing basis in the same coordinate system used for the land areas.... We are satisfied with high quality navigational control, but this in turn requires information of geodetic accuracy either on or contiguous to the ocean areas. Unfortunately, I am unable to address the positional accuracies required, but there are many considerations that may be discussed at this time.
>
> "The most popular positioning systems in use today for navigational purposes are the long-range electronic systems....If we consider the installation of stations in a major datum that can be converted to a world geodetic system, and if we assume that trivia such as errors in the propagation velocity are nonexistent, then we can expect relatively high accuracy in the determination of positions at sea; however, we must keep in mind that these systems have hyperbolic lines of position, and that the expansion of the lanes as we depart from the baselines has an adverse

effect on the resolution of the system. We must also keep in mind the angle of intersection of the two lines of position and use the system only in those areas where the position can be determined with reasonable validity. As the area in which the vessel is operating changes, it is necessary to change the location of the shore navigation stations used, or to accept some degradation in the positioning information. As we go farther out into the ocean, the problem becomes more acute. When we reach an operating area where it is necessary to select three islands for transmitting sites, we are severely limited in the configuration of the net. To further complicate the problem, those islands which are strategically placed for a given navigation net may not be diplomatically accessible for the construction and operation of navigational aids, so it becomes necessary either to use poorly placed transmitter sites or to move operating areas to locations where coverage by the long-range systems is sufficiently accurate.

"Because of these limitations on the long-range electronic systems, especially when coupled with other problems such as uncertainties in the velocity of propagation, jamming possibilities, poor reception characteristics under many atmospheric conditions and a myriad of other features, other systems have been developed or are currently under development which are considered to be more universally acceptable.

"The second system to be considered will be bottom contour navigation. The U.S. Navy has been quite successful in recovering positions at sea by matching fathograms taken over bathymetric features with the results obtained by a survey vessel whose position was accurately known. Although the recovery of position is considered good, we are confronted with the problem of how accurate the position of the survey ship was at the time it obtained the original survey data. This then breaks down, in most instances, to the problem considered before with the use of the long-range electronic systems, but with the added degradation caused by the additional sounding operations involved....

"Navigation by geophysical phenomena has often been mentioned as a prospective device, with either lines of magnetic intensity or lines of the force of gravity being used. Both of these systems....suffer from the same problems as the bottom contour navigation, plus the additional difficulty that resolution is not so good, under the present state of the art, as in the case of bottom contour navigation.

"Navigation by satellite has become possible operationally ...The requirement for the gravitational field...that could be deduced from our present knowledge of gravity..." can not yet be adequately satisfied as shown by Decker [32].

"An extremely accurate description of the gravitational field at the altitude of the satellites is required. It is indeed fortunate that this field could be derived to sufficient accuracy at that altitude from satellite tracking data and did not need to be determined from terrestrial measurements. It is regrettable that we are unable to describe the same gravitational field at zero elevation to the same accuracy. Although this system provides measurement precision of geodetic quality, and has satisfied many of our geodetic positioning requirements, it must be borne in mind that the navigational data derived are not continuous, so some means must be available to bridge between fixes. The dynamics of the satellite system causes fixes in low latitudes to be about 2 hours apart.

"This quite naturally leads us to the inertial system, which is the last system to be considered. The mechanical basis of the systems are such that the navigators attempt to track the local vertical rather than the geodetic position. If there were no factors such as gyro drift to degrade the position keeping qualities of these instruments, they would do an outstanding job of indicating the astronomic position of the navigating unit; however, since there are errors which creep into the system, it is necessary to reset the navigator periodically. The combination of navigational satellite and inertial navigator should approach an ideal system. Unfortunately, when the inertial navigator is reset to the true position, the component of the gravity vector perpendicular to the ellipsoidal normal causes an apparent horizontal acceleration. This results in an oscillation of the navigated position about the astronomic position with the Schuler period, with the plane of the apparent motion rotating about the astronomic position with the period of a Foucalt pendulum. In areas where the deflection of the vertical is negligible, this is no problem; however, where the deflection reaches an appreciable magnitude, it is necessary to reset the inertial navigator to the astronomic position, and to correct positions indicated by the navigator for the deflection of the vertical in order to obtain an accurate geographic position. This requires a dense gravimetric survey of the entire operating area and areas immediately contiguous thereto, with the density of observations diminishing away from the area of interest.

"Although a complete gravimetric survey is indicated as being essential, the density of observations required can be determined only after a preliminary investigation indicates the degree of gravimetric smoothness.

"In this discussion of navigation systems, I have completely ignored error sources other than geodetic, considering those to be without the purview of this symposium; however, let us keep in mind the fact that error sources do exist, and that

> the errors are significant. Other disciplines are concentrating on their identification and elimination or compensation.
>
> "If we summarize the requirements mentioned above to support navigational systems, even though I have been unable to give exact figures for accuracies required at sea, it can be seen that the Department of Defense has a requirement for the same type of geodetic information in the 70 percent of the earth constituting the marine areas as it has in the 30 percent constituting the land. There is an immediate requirement for detailed gravimetric surveys in the northern hemisphere, with the elimination of holiday areas in the southern hemisphere, and for the precise positioning of transmitter sites for navigational aids throughout the ocean areas."

The First Marine Geodesy Symposium held at Battelle, Columbus, Ohio in 1966 constituted the first clear evidence of international recognition of Marine Geodesy as a new and important discipline. Since then, progress in marine geodetic research has been slow. Consequently, the above statement of concepts and requirements are as valid now as they were then. Following is a brief discussion of the roles and relevancy of marine/satellite geodesy to the previously listed activities in support of national security.

Surveying and Mapping require that the geodetic location of the surveying vessel be known in a coordinate system tied into a known geodetic datum [35]. This is the requirement implied by Capt. Macomber's [59] statement "...we are confronted with the problem of how accurate the position of the survey ship was at the time it obtained the original survey data." Furthermore, in order to correlate and eventually match up correctly the current piecemeal surveying and mapping of various parts of the ocean, conducted at various times, accurate geodetic location of the survey vessels in a known geodetic datum is a requirement.

National Security has an interest in oceanographic, gravimetric, magnetic, seismic, geologic and biological research in the oceans. Such research is being carried out at various sites in the oceans. The geodetic location of the sites should be reliably known to permit accurate correlation of results from different experimental sites and/or return to the same site to repeat and/or conduct additional experiments.

Table 3-1, taken from [72], shows various marine operations and the approximate positional accuracy requirements. To meet the requirements stated in Table 3-1 one must find answers to the following questions: (a) what navigational or geodetic positioning systems are available for these requirements?

and (b) how can these systems be geodetically calibrated in real operational conditions to ascertain their operational accuracy at sea? Currently, no such unclassified calibrations have been conducted at sea. The present accuracy quotations of various marine navigation or positioning systems are only theoretical guesses.

TABLE 3-1. ESTIMATED POSITIONAL ACCURACY REQUIREMENTS

Marine Activities	Desired Relative Accuracy, m			Desired Absolute Accuracy, m		
	ψ	λ	H	ψ	λ	H
<u>Geodetic Operations</u>						
Control points	1	1	1	10	10	5
Geoid	--	--	0.1	--	--	0.5
Calibration standards	1	1	0.3	10	10	5
Gravity base stations	10	10	1	10	10	5
Surveying and mapping	10-300	10-300	1	10	10	1
<u>Ocean Physics & Oceanography</u>						
Mean sea level	--	--	--	50-100	50-100	0.1
Tides	--	--	--	50-100	50-100	0.1
Ice sheet motion	1-5	1-5	--	--	--	--
Stationary buoys location	10	10	--	10	10	--
Drifting buoys location	50-100	50-100	--	50-100	50-100	--
<u>Ocean Tracking Stations</u>	--	--	--	10	10	5
<u>Search & Rescue & Salvage</u>	1-10	1-10	--	20-100	20-100	--
<u>Ocean Resources</u>						
Geophysical surveys	10-100	10-100	5	--	--	--
Drilling	1-5	1-5	1-5	--	--	--
Pipelines	1-10	1-10	--	--	--	--
Cable laying	1-10	1-10	--	--	--	--
Dredging	2-10	2-10	--	--	--	--

Jury's [53] paper on "Marine Geodesy and Navigation at the Air Force Eastern Test Range" states:

> "Definitions of system accuracy and performance are as varied as the product of the number of systems used and the number of using agencies. Attempting to compare the accuracy of system A as reported by agency A with system B as reported by agency B can be a frustrating experience. The accuracy of system A may be reported as total radial error of the mean in international feet on a world geodetic system, while system B accuracies may be defined as component mean biases and circular standard deviations in meters on a local datum. Invariably, the data needed to relate the errors of systems A and B will not be given in either report.

"Care should be taken in the evaluation of certain satellite dependent systems to assure that the standard position of the ship and the geodetic/navigation system output are on the same datum. Another consideration of primary importance is whether the error identified is the standard error of a random observation or the standard error of the mean for all observations. Although these errors may differ by a factor of 5 or 0, there is often no distinction as to which error is being identified. Use of a standard that is less accurate than the system being evaluated should, of course, be avoided. Often the system to be evaluated is compared against itself. This approach does give an indication of system precision, but allows system biases to go undetected."

Five major navigation systems are available. These are satellite, "electronic" such as Lorac, astronomic, inertial and underwater acoustic systems. Captain Macomber's statements quoted earlier describe the operational and accuracy limiting factors for the satellite, "electronic" and inertial systems. In the absence of geodetic calibration in real operational conditions, and the non-existence of intersystem comparisions with real data, it is not known to what extent these systems can or are satisfying the positioning requirements for surveying and mapping at sea. The use of underwater acoustic transponders for establishing geodetic control at sea to within 10 meters in latitude and longitude has been demonstrated [57,71]. Such geodetic control can be established at low cost as a means for evaluating positioning and navigational aids.

The views and requirements for "Marine Geodesy and Navigation at the Air Force Eastern Test Range" have been stated by Jury [53] as follows:

"Accurate geodetic positioning of instrumented ships is required at the Air Force Eastern Test Range (AFETR) for shipboard measurements of missile trajectories and to locate broad ocean area hydrophones used for missile impact scoring. Several different techniques and instruments are used for ship positioning, depending on the area of operation and the accuracy required. Systems used at the AFETR include Hiran/Photography, Gyrostabilized Optics, BRN-3/SRN-9 Satellite Doppler, Lorac, Loran, Omega, SINS/Star Tracker, Radar, and Acoustic Hydrophones/ Transponders....

"Marine geodesy and navigation activities at the Air Force Eastern Test Range (AFETR) result from trajectory measurement and impact scoring requirements related to missile testing.

"Instrumented ships used for missile trajectory measurement must be positioned continuously during the missile tracking event. Accurate missile impact location is achieved by measuring the travel time of acoustic energy from the point of impact to each of several ocean-bottom hydrophones which have been positioned in prior surveys....

"Geodesy is often defined as that science which treats mathematically the size, shape, and gravity variations of the earth and the determination of exact positions of points on the earth. Marine geodesy, then, is an extension of geodesy to the ocean environment. It will be assumed here that the points used for marine geodesy will be fixed, long lasting, ocean-bottom markers, either natural or artifical, that can be readily identified - certainly a rather comprehensive assumption. A liberal interpretation would be necessary to include acoustic transponders which would be tethered a short distance above the ocean bottom to suppress unwanted acoustic reflections. Nevertheless, certain fixed points are essential to establish geodetic control in the oceans to allow the redundant measurements required for statistical adjustment....

"The following comments are considered appropriate to future activities in marine geodesy and navigational areas.

1. Controlled tests should be conducted against an adequate standard to determine the accuracy and performance of geodetic/navigation systems prior to commitment for operational missions.

2. An unambiguous report should be published defining the accuracy and performance of the system.

3. More emphasis should be placed on three-dimensional evaluation and error analysis of geodetic/navigation systems used for marine geodesy purposes.

4. A national committee is needed to establish test procedures and accuracy definitions. Fortunately, the Marine Geodesy Committee of the Marine Technology Society has already initiated action on this item.

5. A national committee is needed to evaluate and select missile ranges or other test facilities suitable not only for geodesy/navigation system testing but for general oceanographic and aeronautical testing programs. Use of existing facilities, rather than the development of new facilities, can lead to substantial cost savings and should be given serious consideration.

6. The current National Geodetic Satellite Program (NGSP) is concerned with the establishment of primary control on the 30 percent of the earth consisting of land mass. It would seem most desirable and certainly economical to establish selected primary marine control points in conjunction with the present NGSP. A few such points would be most useful until a full scale marine geodesy program is implemented to map the remaining 70 percent of the world."

The Space and Missile Test Center (SAMTEC) performed an experiment in 1972 [57], which confirms that (1) there is a requirement for accurate marine geodetic controls and (2) that these requirements can be met through research. The objectives of their experiment were to:

> "(a) evaluate the accuracy of ship positions obtained from ASPS relative to the geodetic positions of the VAFB launch sites and mainland sensors;
>
> "(b) evaluate the metric accuracy of a shipborne tracking radar and consequently its contribution to the best estimate of trajectory of typical Western Test Range missile operations."

This experiment clearly showed that marine geodetic controls are indispensable to evaluation of missile guidance and navigational systems. Prevention of hazard related to weapon disposal, search and rescue operations and boundary determination at sea require reliable geodetic positioning information.

The U.S. Coast Guard views on national security requirements for marine geodesy expressed by Capt. S. G. Putzke [76] and captioned "Marine Positioning - The Now and The Need" included:

> "This paper thus becomes a preliminary report to the marine navigational community of the results to date of the Coast Guard's Navigational Planning Staff. To the extent that marine positioning is relevant to marine navigation, it will speak of certain issues germane to our findings....
>
> "As you know, there is what might be called 'an undefined' relationship between position fixing and navigation. Or it may be said that a relationship exists, since knowing ones general position is an inherent part of the art of navigation....
>
> "More specifically, it might be asked whether or not marine positioning in the sense of marine geodesy is a U.S. Coast Guard responsibility. A review of TITLE 14 USC. 2 states, in part, that the Coast Guard "...shall develop, establish, maintain and operate, with due regard to the requirements of National defense, aids to maritime navigation. TITLE 14 USC 81 expands this function as follows: In order to aid navigation and to prevent disaster, collisions, and wrecks of vessels and aircraft, the Coast Guard may establish, maintain and operate:
>
> (1) Aids to maritime navigation required to serve the needs of the Armed Forces...
>
> (2) Aids to air navigation required to serve the needs of the Armed Forces of the United States peculiar to warfare and primarily of military concern as determined

by the Secretary of Defense and as requested by any of those officials; and

(3) Electronic aids to navigation systems

(a) required to serve the needs of the Armed Forces of the United States peculiar to warfare and primarily of military concern as determined by the Secretary of Defense or any department within the Department of Defense; or...

"These aids to navigation other than electronic aids to navigation systems shall be established and operated only within the United States, the waters above the Continental Shelf, the territories and possessions of the United States, the Trust Territories of the Pacific Islands, and beyond the territorial jurisdiction of the United States at places where naval or military bases of the United States are or may be located. To complete the definition it is necessary to refer to TITLE 33 CFR to define an aid to navigation as: 'any device external to a vessel or aircraft intended to assist a navigator to determine his position or safe course, or to warn him of dangers or obstructions to navigation.'"

"...The Marine Sciences Council and other influential members of the Marine Sciences Community continue to press for a worldwide navigation accuracy of 0.1 NM and a coastal (100 mile) accuracy of a few tens of meters....

"There is a strong opinion, in many quarters, that it is in the best interest of the United States to encourage marine sciences and engineering development, and the provision of precise position fixing service is often cited as a productive area of support."

The other major marine geodetic operation which is necessary to National Security is determination of the geoid and/or the gravity field. Satellite altimetry is being investigated to replace conventional methods that are costly and time consuming. The geoid and/or the gravity field is required for (1) computations of satellite orbits and ICBM trajectories, (2) deflection of the vertical for orienting weapon systems and inertial navigation equipment, and (3) oceanographic and meteorological research in modeling the dynamics of the oceans in connection with ocean/atmospheric energy exchange that affect weather and its prediction, currents which affect navigation, sound propagation which is of interest to underwater acoustics.

In other words, all current indications agree that Capt. Macomber was right in stating that "...it can be seen that the Department of Defense has a requirement for the same type of geodetic information in the 70% of the earth constituting the marine areas as it has in the 30% constituting the land" [59]. What is now needed is a National Marine Geodesy Program to address the needs of the nation for national security, and for the environment, resources and energy and transportation discussed in this report.

3.4 Requirements for Marine Geodesy in Space Technology Applications and Scientific Research

There is general agreement that the inputs from marine geodesy of (1) geodetic coordinates and (2) the geoid or the gravity field defined at "undisturbed" mean sea level, are requirements in various space and other scientific research. In the process of discussions in Section 3.1 through 3.3, these requirements have been extensively dealt with, sometimes explicitly but implicitly at other times. The report [72] on the interactions of satellite technology, marine geodesy and its ocean physics applications has elaborate discussions on these requirements. The report [1] on the NASA supported Williamstown study--"The Terrestrial Environment, Solid-Earth and Ocean: Application of Space and Astronomic Techniques" has also documented these requirements.

As a summary, we state that there are requirements for marine geodesy in space and earth science research related to:

(1) Accurate orbit determination and computation of the "absolute" three-dimensional geodetic coordinates of tracking stations and other scientific control stations.

(2) Definition of the geoid and/or the earth's gravity field, both for the global problem and especially at "ground truth" areas. (Appendix C describes the extent of inaccuracy and inconsistencies in the present day knowledge of the earth's gravity field.) Upon these two geodetic outputs hang the success of many geodetic, oceanographic, geophysical, geological and even biological and meteorological research discussed earlier in this chapter. Satellite altimetry missions' objectives and the proposed EOPAP with their tremendous impacts on the ability for science, technology and man to accommodate our environmental problems related to the oceans all depend on marine geodesy. However, first, marine geodesy has to stand on its own feet before it can provide the effective supporting roles

for other sciences. This spells, as Rear Admiral Jones put it, "...an urgent need to initiate planning, research, and development for marine geodesy" [92].

APPENDIX A

SATELLITE GEODESY TECHNOLOGY

A.1 Existing and Planned NASA Programs Relevant to Marine Geodesy and Ocean Physics Applications

In the attempt "... to determine how and to what extent NASA-developed satellite technology could be utilized advantageously in more national programs related to marine geodesy, precise ship positioning, and ocean physics research", existing and planned NASA programs/missions relevant to marine geodesy and ocean physics were analyzed.

Table A-1 indicates the main NASA satellite missions, existing of planned, that are or could be relevant to marine geodesy and ocean physics (MG/O) for solving man's environmental problems according to the results of Phase 1 of this study. By design, some of the satellites are directly applicable, or are either indirectly or potentially applicable subject to further applications research and/or hardware modification(s). Up until the launch of GEOS-C scheduled for 1974, PAGEOS 1 and GEOS-1&2 appear to be the only NASA missions specifically directed towards solving geodetic and geophysical problems on earth. Although many metorological satellites exist and could have indirect bearing on ocean physics research, EREP/SKYLAB (1973) and GEOS-C (1974) appear to be the first and only approved missions addressed to solving earth and ocean physics problems for the benefit of man's environment.

Beyond GEOS-C (scheduled for launch in 1974) there are now (1972) no other approved missions designed to solve these problems. All currently proposed missions relevant to geodesy and ocean physics are under the umbrella of the proposed "Earth and Ocean Physics Applications Program" (EOPAP). Besides, both SKYLAB and GEOS-C missions can only demonstrate hardware and software feasibility or lack of it because they carry the first generation of unproven spacecraft equipment. It seems imperative, therefore, that EOPAP be approved and implemented or else we shall create a vacuum that could cause irreparable damage to our limited ability for environmental monitoring, prediction, and quality control. The following gives brief details of operational, approved, and proposed programs/missions.

TABLE A-1. EXISTING AND PLANNED NASA PROGRAMS RELEVANT TO MARINE GEODESY AND OCEAN PHYSICS

Program/ Mission Name	Status/ Schedule	Applicability to Marine Geodesy: Geodetic Control/ Mapping	Geoid and Gravity Field, Polar Motion	Geodetic Ground Truth	Navigation	Plate Tectonics	Applicability to Ocean Physics: Sea State	Ocean Tides	Circulation, Mass Transport, Air-Sea Interaction
PAGEO SI	Launched 1966	DA	Limited DA	NA	NA	NA	NA	NA	NA
ATS 1, 3	Launched 1966, 1967	Could have been used for MG/O but satellites lack necessary hardware							
GEOS 1, 2	Launched 1965, 1968	DA	DA	DA	PA	PA	NA	NA	NA
ATS 5	Launched 1969	PA	NA	NA	PA	NA	NA	NA	NA
EREP/SKYLAB	Approved Partially Designed for MG/O 1973	NA	PA	NA	NA	NA	DA	PA	DA
ATS-F, G	Approved Partially Designed for MG/O 1974 - 1975	DA	DA	IA	PA	DA	IA	IA	IA
GEOS-C	Approved Specifically Designed for MG/O 1974	DA	DA	IA	DA	DA	DA	PA	DA
SATS ALTIMETRY	Proposed under Earth and Ocean Physics Applications Program (EOPAP) 1975 - 1977	DA	DA	IA	PA	DA	DA	DA	DA
GEODYNAMICS (Cannon Ball and Bullet)		DA	DA	PA	IA	DA	NA	IA	NA
Earth Harmonics GRAVMAG (Drag free)	Proposed under EOPAP 1976	DA	DA	IA	IA	DA	NA	IA	IA
GEOPAUSE A & B	Proposed under EOPAP 1977	DA	DA	IA	PA	DA	IA	IA	IA
Earth Physics Observatory	Proposed under EOPAP 1981	DA	DA	DA	IA	DA	DA	DA	DA
TDRSS	Under Evaluation 1977	PA	IA	IA	PA	PA	IA With additional equipment it could have DA	IA	IA
EOS	Under Evaluation 1977	DA (Mapping)	PA	NA	NA	NA	DA	DA	DA
SEOS	Under Evaluation 1979	NA	PA	PA	NA	NA	DA	DA	DA
ATS- H, I, J, K	Under Evaluation 1978/79 1981	DA and IA, depending on the success of ATS-F, G, and plans for spacecraft instrumentation							
TIROS - O	Under Evaluation 1981	NA	PA	IA	DA	NA	DA	DA	DA

Key: DA - Directly Applicable
IA - Indirectly Applicable
PA - Potentially Applicable
NA - Not Applicable
MG/O - Marine Geodesy/Ocean Physics

A.1.1 Operational Missions

There are in operation at least six NASA satellite missions directly or potentially applicable to solving certain problems in geodesy and ocean physics. These are GEOS-1,2, PAGEOS 1, ATS-1,3,5. The GEOS and PAGEOS series were specifically designed for geodesy but equipped mainly for station position determination, earth gravity field, and polar motion investigations. The current design and instrumentation of GEOS-C are not only for advancement in technology but also to make up for the limited utility of PAGEOS-1 and GEOS-1,2 in obtaining urgent needed solutions to geodesy/earth and ocean physics application problems. ATS-1,3, still in orbit, lack the necessary hardware to adapt them to geodetic and ocean physics uses. These satellites in orbit with equipment which cannot be modified for geodesy and ocean physics will not be discussed further.

The ATS-5 L-band system is potentially usable for navigation and position determination provided that certain conditions discussed below are fulfilled. Due to equipment malfunction a C-band up-link is required to operate the L-band transponder. An efficient portable receiver needs to be developed. A limited demonstration experiment has shown that ATS-5, simultaneously observed from two stations, one whose geodetic coordinates are already known, can be used to define a "line of position" along or close to which the coordinates of the unknown station lie. In order to determine the unknown position uniquely in two dimensions, one other satellite must be observed simultaneously from the unknown position and a known position. Three-dimensional coordinates require at least three satellites not vertically coplanar. The geometric configurations or relative positions of the satellites, the known and unknown positions are critical to avoiding position indeterminancy. Communication linkage with the known and unknown positions must be established in real time, time synchronization, computing facilities at the unknown position are required for stationary position determination.

For navigation or nonstationary position determinations, in addition to the above requirements, the two or more satellites involved must be observed almost simultaneously. In all cases a command ground station for the up-link transmission to the satellites is required. The analytical basis for computing the position lines is too crude to satsify geodetic accuracy. There is a need to know fairly accurately the approximate coordinates of the new position to be determined. The assumptions for calibration of range data and refraction correction need drastic refinement, especially to make them applicable for widely separated ground stations. Refined techniques have to be developed to permit multiple user capability. The use of three (non-vertically coplanar) or more satellites does eliminate some of the problems discussed.

ERTS-1 is an operational mission with sensors relevant to ocean physics research.

A.1.2 Approved Missions

Already approved NASA missions relevant to geodesy and ocean physics include EREP/SKYLAB (1973), ATS-F (1974), GEOS-C (1974), and ATS-G (1975). ERTS-B (1973) is an approved mission whose sensors should contribute to oceanographic research. The following is a brief discussion on mission-relevancy for the application of geodesy and ocean physics to the solution of environmental problems.

A.1.2.1 EREP/SKYLAB, ATS-F, and GEOS-C

One of the specific objectives of this mission is "To study the earth--synoptic survey of selected areas on the earth in visible, infrared, and microwave spectral wavelengths". It is a technology development mission to test, among other things, the use of Infrared Spectrometer (S191), Multispectral Scanner (S192), Microwave Radiometer/Scatterometer and Altimeter (S193), and L-Band Radiometer (S194) for geodetic and ocean physics research in topics indicated in Table A-1. The success or failure of the mission, and experience gained in both hardware and data processing and analyses, are prerequisites to future NASA missions for application of satellite technology to geodesy, earth, and ocean physics solution of problems on earth.

The unmanned ERTS-B, which is a follow-up of ERTS-1, is a companion mission to SKYLAB and is expected to make valuable contributions to cartography and oceanography.

ATS-F and G: The project objectives of ATS-F and G are to

(1) Develop the application of space technology to meet unique educational and informational needs of individual professions and public services.

(2) Develop the technology required to establish an independent worldwide tracking and data acquisition satellite system to support near-earth satellite missions.

(3) Develop the technology for maximizing the communications use of the synchronous orbit.

(4) Determine the utility of satellite systems to meet the aircraft and ship navigation and traffic control needs.

(5) Assess the use of and develop the technology for laser satellite communications systems.

This project will provide a technology base for prototype systems such as Tracking and Data Relay Satellite System (TDRSS) and other systems demonstrations requiring large antennas and accurate pointing which are necessary for designing information network operational systems. These missions, by current design, do not directly solve geodetic and ocean physics problems. ATS-F will be used to demonstrate feasibility and usefulness of satellite-to-satellite tracking with GEOS-C and Nimbus F. The success of this experiment will greatly enhance the ability of GEOS-C to fulfill its mission objectives for geodesy and ocean physics to solve environmental problems.

Besides these indirect applications, its C-band and L-band instrumentation could be used for position fixing and navigation. These satellites could be used as sources for VLBI development. The VLBI has great potential for solving the problems listed in Table A-1. Since the ATS will have retro-reflectors they will be extremely useful for geodetic control, earth gravity, polar motion, continental drift, sea floor spreading, and other crustal movement investigations.

GEOS-C: This is the fourth and last in a series of geodetic satellites developed to provide the transition between the on-going National Geodetic Satellite Program (NGSP) and the emerging Earth and Ocean Physics Applications Program (EOPAP). The program objectives are to

(1) provide a precise and accurate geometric description of the earth's surface,

(2) provide a precise and accurate mathematical description of the earth's gravitational field,

(3) determine the time variations of the geometry of ocean surface, the solid earth, the gravity field, and other geophycical parameters. In keeping with these overall objectives, GEOS-C is designed to

(1) demonstrate and calibrate a satellite radar altimeter to absolute accuracy of 5 meters and relative accuracy of 1-2 meters,

(2) establish precision capability of satellite-to-satellite tracking (ATS-F/GEOS-C),

(3) better define the structure of the earth's gravity field. Other expected benefits include ability to measure sea state, ocean tides, shape of ocean currents, the ocean geoid and its separation from sea surface topography, geodetic control, polar motion, and crustal movements in areas such as the San Andreas fault. GEOS-C is a mission that is extremely responsive to the use of geodesy and oceanograpyy for solving the various environmental problems that are related to earth and ocean physics.

A.1.3 Planned Programs/Missions

Currently (1972), the only future program of relevance to geodesy and oceanography is the proposed Earth and Ocean Physics Applications Program (EOPAP). This program, in some form, must be implemented. If not, a disastrous vacuum will be created in technology development, geodetic, oceanographic, geologic, geophysical, and meteorological research needed to preserve the environment as a habitat for man.

Environmental and scientific areas that would benefit from the implementation of EOPAP include (1) earthquake damage alleviation (study of its mechanism, prediction, and eventually its prevention), (2) tsunami, storm surge, sea state, (3) ocean circulation, mass transport and their influence on pollution control, and protection of ocean environment, (4) air-sea interaction, weather, and climatic forecasts and eventual control, (5) fishing and ocean food resources, (6) mineral and oil exploration, (7) ocean and solid earth tides, (8) geodetic control and mapping, station positions, the geoid, and the earth's gravity field, (9) polar motion,

(10) Techonophysics-continental drift, sea floor spreading, crustal/fault movements, (11) geomagnetism, (12) astrodynamics, (13) the atmosphere and the ionosphere, (14) air and marine navigation and traffic control, (15) defense agencies' needs, and (16) technology development.

The various satellite missions that have been proposed under EOPAP include SATS-Altimetry, GEODYNAMICS (cannon ball and bullet), Earth Harmonics--GRAV MAG (drag-free), and GEOPAUSE A and B. Other planned missions of great relevance to the objectives of EOPAP include GRAVSATS, LAGEOS, TDRSS, SEOS, EOS, ATS-H, I, J, M, TIROS-O. Plans about these missions have not been finalized. Specific discussions of each mission are, therefore, omitted. However, each of them is a necessary means for effectively pursuing the objectives to derive all the benefits previously outlined.

APPENDIX B

NATIONAL AND INTERNATIONAL MARINE PROGRAMS AND THE ROLES OF SATELLITE/MARINE GEODESY

A number of national and international marine programs were studied to identify the possible ways that satellite/marine geodesy techniques can assist in meeting their objectives and the objectives of national interest more effectively. These programs include:

- International Decade of Ocean Explorations (IDOE),
- Azores Fixed Acoustic Range (AFAR),
- Inter-Seamount Acoustic Range (ISAR),
- Ocean Sediment Coring/Deep Sea Drilling Project (DSDP),
- Cooperative Investigation of the Caribbean and Adjacent Regions (CICAR),
- DoD and NOAA Marine Mapping and Charting,
- International Field Year for the Great Lakes (IFYGL),
- Integrated Global Ocean Stations System (IGOSS),
- Marine Resources Monitoring Assessment and Prediction Program (MARMAP),
- National Data Buoy Project (NDBP),
- Geochemical Ocean Sections Study (GEOSECS),
- Mid-Ocean Dynamic Experiment (MODE),
- French American Mid-Ocean Undersea Study (FAMOUS),
- Trans-Atlantic Geotraverse (TAG),
- Sea Grant
- Manned Opean Sea Experimentation Station (MOSES),
- Undersea Long-Range Missile System (ULMS),
- Long-Term and Expanded Program of Ocean Research (LEPOR),
- Global Atmospheric Research Program (GARP),
- GARP Atlantic Tropical Experiment (GATE),
- Coastal Zones, and
- Arctic Ice Dynamics Joint Experiment (AIDJEX).

In addition, the implications of the marine-resources activities of a number of industries (offshore oil, gas, minerals, etc.) were studied as were the implications of marine legislation and laws of the sea.

Although all these programs and activities were considered during this study, only the following were selected for further discussion here: NDBP, IDOE (MODE, NORPAX, GEOSEC, Seabed Assessment, etc.), DSDP, GARP, IGOSS, LEPOR, GATE, AIDJEX, Ocean Resources, and Marine Legislation/Law of the Sea. The following criteria were used for this selection:

(1) Relevancy of marine and satellite geodesy

(2) Availability of descriptive and technical information

(3) Duration to at least 1975 (to allow sufficient lead time for NASA planning and interaction with lead agencies)

(4) Operation in deep water areas rather than in coastal and Great Lakes areas (where most of geodetic requirements may be satisfied by existing and/or non-satellite systems).

Obviously, marine mapping and charting programs and activities are prerequisites for many ocean operations, and are highly dependent on marine geodesy and satellite technology. However, mapping and charting activities are not discussed separately, but they are considered in details in Section 3, "The Case for Marine Geodesy".

All marine programs and activities discussed in this report require accurate geographic location. This can best be provided by satellite/marine geodesy techniques. Some of the programs require accurate knowledge of the geoid "mean sea level" which, in the oceans, can best be obtained through satellite altimetry in combination with geodetic and oceanographic ground truths determined by conventional methods. Other programs have requirements for sea state and wave height information that could also be provided by satellite altimetry and/or the bistatic satellite radar technique under development for NASA [79]. On the other hand, some of NASA's satellite programs such as GEOS-C and Skylab require ground truth data that the marine programs can help to provide.

B.1 National Data Buoy Program (NDBP)

The overall objective of NDBP is to establish a system for measuring oceanic and meteorologic environmental parameters required to serve the national interest. The program is designed to improve research and the description, prediction, monitoring, and management of the atmospheric and marine environment and of the living resources of the sea through the acquisition of data via direct and/or satellite communications link [2,3,24]. The program was established in 1968 under the responsibility of the Coast Guard. Currently the program is under NOAA's responsibility.

B.1.1 Justifications for the Program

The best justification for the program is provided by the participation in the Industrial Data Users Meeting (IDUM) which was attended by representatives from various groups such as, off-shore oil and gas industry, marine hard-mineral mining, marine surface transportation, commercial airlines, fishing industry, commercial meteorology and ship-routing firms, coastal engineering and construction organizations, agriculture, recreation, and government agencies.

Various national interests make extensive use of environmental data in planning, designing, scheduling, and conducting their operations. Such data include wind speed and direction, air and sea-surface temperatures, barometric pressure, sea state (especially in the form of wave spectra), humidity, and visibility [3].

The IDUM expressed the following potential benefits. "in the offshore oil and gas sector, potential savings were anticipated from improved operations and better design (i.d., less over-design) of equipment and facilities; and through the mechanism of better forecasts, there would be reduction in losses from actions taken in response to false alarms. Benefits in offshore construction would stem from more efficient operations due to better daily environmental reports (weather, oceanic) and better long-range forecasts; savings would also accrue from avoidance of over-design of structures and equipment. Data from buoys could provide savings to the marine transportation industry by affording reduction of transit time and cargo and hull damage, thus reducing repair time and insurance rates. Better rainfall forecasting would benefit coastal agriculture; the citrus industry is financially vulnerable to frost, and in the Florida region millions of dollars per season might be saved, if better information--such as might be developed from buoy-collected data--were made available. Many sectors of industry would derive benefits from archived rather than real-time data; well-defined recording of extreme wind and wave conditions is important in this regard."

B.1.2 Priorities of Industrial User Categories

The major categories of industrial users were identified at the IDUM as:

(1) Off-shore oil, gas and hard-mineral mining
(2) Marine transportation
(3) Commercial fisheries
(4) Commercial meteorological and oceanic consultants
(5) Marine Recreation
(6) Agriculture

The hard core or top priority parameters are: wind velocity, wave conditions (wave spectra) or sea state, current velocity, air and sea temperature, barometric pressure. The middle priority parameters included sea ice conditions, sea water transparency, salinity, dissolved oxygen, incoming radiation, dew point, and precipitation. The lower priority parameters are visibility, biological fouling, ambient noise, cloud base, carbon dioxide and nutrients.

B.1.3 Some Specific Potential Benefits

Specific potential benefits to industrial users are itemized below:

(1) Better wind and wave forecasts to improve operations capability, prevent losses due to false alarm and avoid losses due to more severe conditions than those forecasted.

(2) Much more reliable statistics of extreme waves and winds, which would improve efficiency in the design of equipment. The important

needed statistical information is about height, period, direction and velocity of swells, waves, tides, and currents.

(3) More accurate daily longer range (1 to 2 weeks) weather reports and forecasts, including reports on the condition of the sea. This will result in more reliable scheduling of operations and minimization of emergency situations due to weather.

(4) Reduction of the time for ocean-going vessels to achieve crossings, thus setting and maintaing schedules effectively.

(5) Optimization of the earning capability of steady-cost operations for a fleet's vessels via more crossing due to faster turnarounds.

(6) Reduction of the damage to hull and cargo due to adverse weather enroute. The savings would include reduced repair time in a shipyard.

(7) Reduction of marine insurance premiums to safety conscious owners/operators.

(8) Better long-range (1 to 3 weeks) weather forecasts to provide data for agricultural and recreational decision-makers whose industrial activities are affected by cold temperatures and/or precipitation. Typical operational questions to be answered are:

(a) when should field irrigation start?

(b) when and for how long can pleasure boats put out to sea safely?

(c) when and for how long will a tourist attraction have a large or small crowd?

(d) what final actions are needed and when must they be taken to provide freeze protection for growing crops?

For instance, it is estimated that such reliable forecasts could result in savings of about a million dollars per night for the Florida citrus industry.

Items 1 and 2 were stressed by representatives of the oil, gas and hard-mineral industry, items 2 and 3 by off-shore construction, items 4 through 7 by marine transportation, and item 8 by Recreation/Agriculture.

B.1.4 NDBP As An Aid to Navigation and Surveying

The NDBP involves two main categories of buoys--the "limited-Capability Buoys" (LCB) and the "High-Capability Buoys" (HCS) often referred to as "monster" buoys because of their immense size. The HCB would weigh about 100 tons and carry more than 100 sensors for measuring and reporting oceanic and atmospheric conditions. The LCBs which are smaller and less costly, measure and report fewer environmental parameters, and have a shorter deployment life expectancy than the HCB. There will be two versions of the LCBs, one for moored and another for drifting applications. The HCBs are only expected to be moored. Both the LCBs and HCBs are to be designed to withstand hurricane conditions; 150-knot winds, 60-foot waves and 10-knot currents.

The drifting buoys can be continuously tracked using geodetic satellite techniques, to determine their geographic coordinates. Thus, they can be made to serve as navigation aids.

Moored data buoys, being fixed stations in the open ocean, have the valuable potential of serving as (a) navigational aids to marine and air traffic and (b) surveying control points for marine gas, oil and hard-mineral prospecting, bathymetric mapping, physical boundary establishment and reidentification at sea, marine geophysical research, and oceanographic research, and (c) an aid to determination of ground truth in support of Slylab, GEOS-C and Apollo-Soyuz and similar future earth observation space missions. Such moored buoys should carry (1) clearly visible markings and a light for day and night visibility, (2) a radar target suitable for use with standard commercial X- and S-band radars, (3) an under water sonar beacon for submarine traffic, and (4) a radiobeacon for air traffic position location.

B.1.5 The Role of Marine Geodesy and Satellite Technology

The suggested spacing between buoy locations is about 120 to 600 miles in deep ocean and 60 miles in coastal zones and the Gulf of Mexico. To become useful aids to navigation and surveying, the geodetic coordinates (on an uniform geodetic datum) of each buoy should be known accurately to between 10 meters and 1 km. depending on the type of marine operation involved. The feasibility of 10 meter accuracy in the determination of geodetic positions at sea has been proven. Currently, in the open oceans, only satellite and marine geodesy techniques can determine the coordinates of each buoy to the required accuracy referenced to a consistent geodetic datum. What is needed now is to blend this operational philosophy into NDBP planning and thoroughly investigate how to implement this additional use of the buoys. Ocean transponders can be used for geodetic-acoustic tracking of the buoys and to monitor the time-varying positions of a moored buoy. Benefits from implementation of such a plan have been identified above and are in keeping with the overall philosophy of the NDBP.

Currently, there is no fully operational device for accurate and remote monitoring of sea state. Ocean wave spectra, wave heights and directions have been particularly emphasized by all IDUM participants. A Battelle/NASA Wallops team is developing a Bistatic Radar system for remote sea state monitoring. This system can be adopted for use aboard spacecrafts, aircrafts, buoys and ships. The system requires ocean-surface-based transmitters which can be on either drifting or moored buoys.

B.2 International Decade of Ocean Exploration

The International Decade of Ocean Exploration (IDOE) was established in 1969 and funded in 1971 under the leadership of National Science Foundation (NSF). The program is expected to continue through the 1970's. Its goals include

(1) Preservation of the ocean environment by accelerating scientific observations of the natural state of the ocean

(2) Improving environmental forecasting to help reduce hazards and permit more efficient use of marine resources

(3) Expansion of seabed assessment activities

(4) Development of an ocean monitoring system to facilitate prediction of oceanographic and atmospheric conditions [7].

IDOE supports research programs of both Federal and non-Federal organizations. Coordination with governmental agencies is achieved through the Interagency Decade Planning Group, and coordination of non-governmental programs is provided by panels of the National Academies of

Sciences and Engineering. International scientific coordination has been provided by the Scientific Committee on Ocean Research (SCOR) of the International Council of Scientific Unions and Intergovernmental Oceanographic Commission (IOC) Advisory Body [12]. So far, four major program areas have been established toward achieving the above goals. These are: (1) Environmental Quality, (2) Environmental Forecasting, (3) Seabed Assessment, and (4) Living Resources.

B.2.1 Environmental Quality Program

The Environmental Quality Program includes several projects which involve baseline data-acquisition studies in the East and West coasts of the United States, the Gulf of Mexico and Caribbean. The largest of these baseline projects is the Global Baseline Data Project known as the Geochemical Ocean Section Study (GEOSECS). GEOSECS is a multi-year project involving geochemists from several Universities, Woods Hole and Scripps, and participation from Canada, France, Germany, India, Italy, and Japan. The basic task of the program is the detailed measurement of the oceanic constituents and mapping the distribution of the important oceanic tracers and properties along continuous longitudinal sections of the three major oceans. The U. S. project calls for the occupation of 120 oceanographic stations along the main survey tracks between the Arctic and the Antarctic areas. The parameters to be measured include temperature and salinity at all depths, carbon-14, tritium, nutrients and dissolved organic carbon, oxygen and carbon dioxide samples. The program is expected to establish baselines of ocean conditions against which to measure future changes and predict the impact of these changes on biological processes.

B.2.2 Environmental Forecasting Program

There are several projects conducted under the Environmental Forecasting Program which focus on the role of the oceans in shaping global weather and climate. Examples of such projects include Climate Longrange Investigation, Mapping, and Prediction (CLIMAP), the Coastal

Upwelling Experiment (CUE), the Mid-Ocean Dynamics Experiment (MODE), and the North Pacific Experiment (NORPAX) which is conducted jointly with the Office of Naval Research. Only the latter two projects MODE and NORPAX to which satellite and marine geodesy are relevant will be discussed further.

B.2.2.1 Mid-Ocean Dynamic Experiment (MODE). The long-range goal of MODE is to investigate the role of medium-scale geostrophic eddies in the general circulation of the oceans by combining oceanographic observations with numerical theory. The immediate purpose of Phase I of MODE is to provide a kinematic description of these eddies. The first experiment is designed to ascertain what phenomena exist, so that later and more comprehensive experiments can be designed to test specific hypotheses and determine how the mid-ocean phenomena interact with the general circulation. It is also planned to study large eddies in the sea motion, and to determine the dominant motions and density fluctuations that occur below the surface of the ocean over distances of 10 to 200 km and from day to day [7,12,50].

NSF is cooperating with ONR, about eight United States universities, WHOI and England for the execution of the program. The first experiment is scheduled for March to June, 1973. Future experiments will depend on the results of MODE-I. The National Institute of Oceanography, England, has supported large portions of related field experiments since November, 1971. The experiment's site is 500 km southwest of Bermuda and bounded by latitudes 23°N and 28°N and longitude 68°W. The area is about 200 km square and 5 km deep. Instrumentation to be used includes bottom pressure gages, fixed-moored arrays, vertical profilers, and current meters. In addition, an array of ocean-bottom hydrophones will be used to track surface floats carrying sensors for the experiment. About three U. S. and one British ships will be used [12].

B.2.2.2 North Pacific Experiment (NORPAX). The Office of Naval Research (ONR), has over the past several years, supported research programs in the North Pacific for identification of the oceanic processes related to anomalous "weather" conditions. Recently, the resources of

IDOE and ONR were combined to produce a larger and more comprehensive effort than either could support alone [31]. The major objective of NORPAX is to describe and develop a basis for explaining the mechanisms responsible for the large-scale oceanic and atmospheric fluctuations that occur in the mid-latitudes of the North Pacific Ocean affecting the North American weather.

NORPAX, though still in the planning stage, is expected to continue throughout the Decade [50]. A time/phase diagram for NORPAX has been published in Reference [31] showing a four-phase program covering the period from FY 72 to FY 82. The NORPAX Program Office at NSF/IODE is working on plan modification which are expected to be released sometime in the spring of 1973. The published information [31] shows several test sites in the North Pacific Ocean covering large areas ranging in size from 5° x 2° to 20° x 30° rectangles. Several buoy systems (moored and drifting) are being planned for data gathering and radio telemetry of such data. Telemetry ranges up to 1000 nmi are expected. The project administration and overall management will be located at Scripps. ONR and NSF hope that other Government agencies such as NOAA/NDBP and other nations could be represented in NORPAX.

B.2.3 Seabed Assessment Program

The Seabed Assessment Program has three projects aimed at exploring the petroleum and mineral resources on the Continental margins, the deep sea floor, and the ocean ridges and trenches [50]. Broad justification for these projects is based on the significant resources of petroleum, sulfur, and hard minerals already found in some areas of the continental margins and deep ocean floor [7]. Continental margin studies include those of the East Atlantic (off West Africa) and Southwest Atlantic (off South America). The East Atlantic study being conducted by WHOI involves making reconnaissance geophysical surveys and maps (seismic, magnetic, gravity, bathymetry, etc.) for the continental margins. The research vessel ATLANTIC II, equipped with satellite navigation equipment is used for the surveys. There are other participants involved from the U. S., Europe, and Africa.

Similar studies are also conducted on the mid-ocean ridges and trenches which presumably hold the key to answering questions about mineral deposits. A major investigation underway is the NASCA Lithospheric Plate Study (NLPS) off the west coast of Peru. The purpose of the NLPS is to examine in detail the processes of crustal formation and destruction that take place at the diverging and converging edges of a well-defined lithospheric plate. The diverging edge of the plate has been identified as potentially important for mineralization. The convergence zones of the plates are also of social importance because they often cause crustal uplift, volcanos, and earthquakes. The NLPS is focused on the plate active boundaries, which include the rift valley of the East Pacific Rise and the Peru-Chile Trench. The project involves participants from the U. S. and South America.

B.2.4 Living Resources Program

The Living Resources Program is the latest addition to IDOE. It seeks to combine biological and physical oceanography for better understanding of the marine ecosystem and the coastal upwelling processes.

B.2.5 Relevancy of Satellite and Marine Geodesy to IDOE

Several important contributions can be made from applying satellite and marine geodesy to the various IDOE programs. For example, in the MODE Project there is a need to know relative positions of the hydrophones and the research ships. Accurate geodetic (geographic) locations of these various components should be known so that the experiment's results can be correlated with results of other oceanographic, meteorologic, geodetic and geophysical experiments in the Atlantic and, hence, worldwide. Geodetic-acoustic techniques are necessary for the precise surveying of the hydrophones relative positions. Satellite geodetic positioning in combination with simultaneous acoustic ranging to the hydrophones from ships is the most effective means of accurate geographic location in the oceans to meet the objective of global correlation of results. Future experiments of MODE could furnish useful surface truth data for the GEOS-C satellite altimetry program.

One of the most difficult problems, the NORPAX project will be attempting to determine the departure of the sea surface topography from the geoid (sea slope) in the North Pacific Ocean between the U. S. and the Japanese coasts. This departure is less than 1 meter. The future goals of satellite altimetry programs are to determine the geoid to the sub-meter accuracy. Hence, the departure will also be determined to that accuracy. NORPAX could also benefit from satellite geodesy techniques in determination of the geographic coordinates of the buoys and the ship in the same geodetic datum and GEOS-C altimetry program could use sea state data for ground truth.

Similarly, position information will be valuable for the seabed resources assessment program. This requirement is discussed in more detail under the ocean resources topic in this section.

B.3 Ocean Sediment Coring Program

The objectives of the Ocean Sediment Coring Program of NSF is to explore the earth's crust covered by the sea to learn about the origin and history of the earth. The major activity of this program is the Deep Sea Drilling Project (DSDP). DSDP was established in 1966 under a contract from NSF to Scripps. However, it was not until 1968 that the Project began operations when the drilling ship GLOMAR CHALLENGER of Global Marine Inc. was completed with capability to drill in the very deep oceans. Cores have been taken from the seabed at water depth up to 20,000 feet, with some samples taken from holes drilled 4000 feet into the ocean floor. Plans are to continue drilling operations through August 1975. The scientific guidance on DSDP is provided to Scripps through a consortium of five U. S. academic groups, Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) [4,12].

The DSDP has achieved many significant scientific results. Perhaps the most important of these results is the verification of the hypothesis of continental drift and sea-floor spreading. Core analysis have helped to confirm sea-floor spreading, which explains the horizontal movement of continents away from midocean spreading centers. Other accomplishments of DSDP included proving that many minerals form in deep-sea sediments, after deposition, by chemical action. Recent drilling in the middle of the Red Sea found rich deposits of gold, silver, and other metals. The extent of the deposits (estimated at $2.4 billion value) is about ten miles long, two miles wide, and 33 feet deep [13]. Other discoveries proved that much of the deep Gulf of Mexico is underlain by salt, some of which has been forced up into salt domes trapping oil deposits.

The DSDP, using the drill ship GLOMAR CHALLENGER, demonstrated the use of marine and satellite geodesy techniques effectively. The ship employs dynamic ship positioning techniques for deep drilling. Ocean-bottom transponders are used for relative positioning of the ship and the drill pipe. In addition, a satellite navigation receiver is employed to provide the geocentric location of the drill sites. The position accuracy obtained from navigation satellites is satisfactory for "coarse" positioning while the ocean-bottom transponders provide "fine" positioning for locating drill holes. Marine and satellite geodesy and VLRI techniques can, however, conceivably design an experiment for direct measurement of the rate of ocean floor spreading for verifying the results of DSDP.

B.4 Global Atmospheric Research Program (GARP) and Other Related Programs

The Global Atmospheric Research Program (GARP), is designed to help improve the range and accuracy of weather forecasting of the nations, to assess the consequences of man's pollution of the atmosphere, and to determine the feasibility of large-scale weather modification. The approach is to measure the various parameters descriptive of the state of the atmosphere and the oceans and their interactions. GARP involves development of theoretical models and their validation by experiments and observational techniques. Every effort is expected to be made to accommodate peripheral observational programs (oceanographic experiments) on a non-interference-basis [5].

NOAA is the lead agency. The list of participants include other United States agencies, universities, and other nations. The first GARP global experiment is scheduled for 1976/1977. Other collaborating and interacting programs include Integrated Global Ocean Stations System (IGOSS), Long-Term and Expanded Program of Ocean Research (LEPOR), and World Weather Watch. The NOAA ITOS satellite series is expected to make key contributions to these programs.

B.4.1 IGOSS

IGOSS is a major marine monitoring and prediction program initiated by IOC with the collaboration of the World Meteorological Organization (WMO). The purpose of IGOSS is to bring together a number of national systems to form, ultimately, a dynamic worldwide system for observing and measuring the marine environment. The NOAA National Data Buoy Program and its related satellite relay systems are expected to be a major contributor to IGOSS [6,12].

B.4.2 Long-Term and Expanded Program of Ocean Research (LEPOR)

The scope of LEPOR includes studies to obtain adequate understanding of physical processes such as ocean-atmosphere interactions, ocean circulation and variability, upwelling, tsunami and parameters for oceanic mathematical modeling. Included will be research on living resources, geology, geophysics and mineral resources and oceanic mathematical modeling. NOAA is coordinating its effort in LEPOR with the NSF, IDOE Program [6].

B.4.3 GARP Atlantic Tropical Experiment (GATE)

The first of a series of major international field experiments associated with GARP is the GARP Atlantic Tropical Experiment (GATE). GATE is planned for a three-month duration in the summer of 1974. The experiment calls for the placement of coordinated arrays of buoys and ships for measuring atmospheric and physical oceanographic parameters at two separate locations: (1) the A-array along the equator between longitudes 10° and 30°W and (2) the B-array along longitude 24°W and between latitudes 5°N and 15°N as shown in Figure B.1. The objectives of GATE are to study the structure and evolution of weather systems in the tropical eastern Atlantic and to assess the extent to which these tropical disturbances affect the behavior of the atmosphere. Some 20 research ships, 10 research aircraft, satellites and automated data buoys involving many nations will participate in GATE. The experiment area covers tens of thousands of square miles of ocean surface and the vertical column from the seabed to the atmosphere. The oceanographic portions of GATE are still being formulated [14,16].

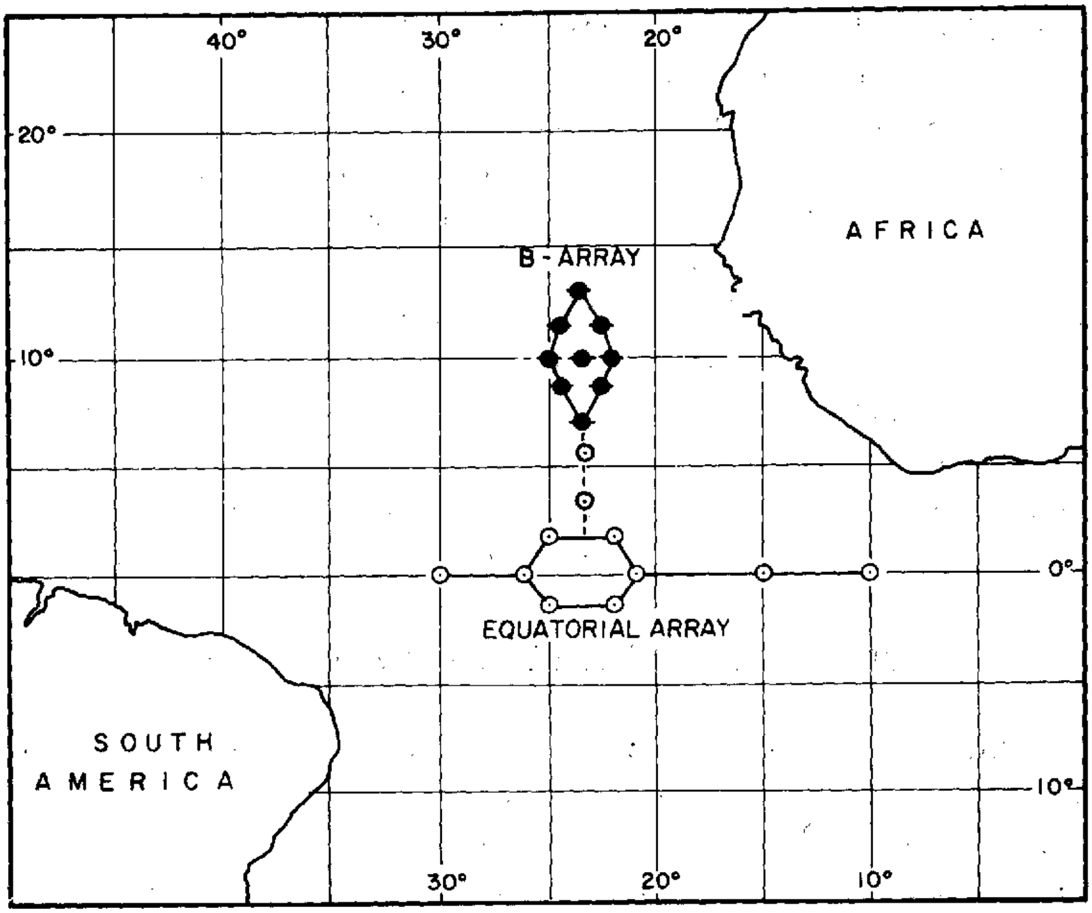


FIGURE B.1. GATE GEOGRAPHIC LOCATION

Positions in B-array indicate stationary vessels; positions near equator indicate a variety of buoys [16].

B.4.4 Relevancy of Satellite and Marine Geodesy to GARP and Related Programs

Knowledge of the true geographic locations of the various stations comprising the experiment's arrays will be required. For this, satellite geodesy techniques for position determination are indispensable. Some of the ships and buoys are required to be stationary as in the B-array of GATE and will have to be anchored. The type of anchors used in the past, in the BOMEX program for example, and which failed are expected to be improved upon and used in GATE. The plan to use anchors necessitates the use of ships less than 1,000 tons. The application of satellite geodesy and marine geodetic-acoustic techniques to locate the ships and monitor their positional time history relative to fixed ocean bottom transponders can relax the current stringent plans related particularly to ship size and anchors. It will also furnish a backup system if the anchor systems fail as in BOMEX. In fact, the anchor systems could be completely eliminated particularly since the cost of ocean bottom acoustic transponders is competitive with deep ocean anchoring systems. One of the transponders could be a nuclear-powered permanent type (about 20-year life expectancy) so that the exact site of the experiment could be returned to for future confirmation experiments.

GATE will be in operation during the early part of the GEOS-C mission. With a little coordination of efforts, GATE should furnish useful surface truth data for GEOS-C altimetry data processing and evaluation.

B.5 Arctic Ice Dynamics Joint Experiment (AIDJEX)

AIDJEX is a national and international program of research in the Arctic. There is now a recognized need to exploit the Arctic's vast storehouse of natural resources and perhaps open it up for commerce and transportation without environmental destruction or degradation. For instance, shipping distance between East Asia and Western Europe will be cut in half if done via the Arctic. Before this need can be met, the structure and dynamics of the Arctic environment must be studied and understood. Consequently, following the success of IGY programs, AIDJEX was formed in late 1969 to accomplish the research needed in the Arctic.

The Office of Naval Research (ONR) and the Defense Research Board of Canada, through the Arctic Institute of North America (AINA), provided the initial funding. NSF followed with the award of a substantial contract, in July 1970, to the University of Washington for assistance in coordinating, planning and execution of AIDJEX. Currently, the program is supported by Canada, Japan, and United States agencies--ONR, ARPA, NASA, NAVOCEANO, NOAA, Army, USCG, USGS, and NSF Office of Polar Programs [21,61].

The objective of AIDJEX is to reach, through coordinated field experiments and theoretical analyses, a fundamental understanding of the dynamic and thermodynamic interaction between arctic sea ice and its environment.

Sea ice cover is an earth surface variable most sensitive to climate conditions. Unlike the massive continental ice caps of Antarctica and Greenland, whose variations occur on a time scale of millennia, sea ice is a thin veneer of frozen sea water whose size varies rapidly with environmental changes on a time scale of weeks to years. An ice cover changes the transfer of momentum from air to water and suppresses drift currents and wind mixing. Sea ice effectively reduces heat exchange between the atmosphere and the ocean by reflecting solar radiation during summer and suppressing heat loss from the ocean to the atmosphere during winter. The role of sea ice in modifying the global circulations of the atmosphere and the oceans is not understood quantitatively. The basic objective of AIDJEX is the basic understanding of the complete ocean-ice-atmosphere system.

B.5.1 Implementation Plans

The plans for AIDJEX are designed to answer four basic questions: (1) how does large-scale ice deformation relate to the external stress fields, (2) how can these external stresses be derived from a few fundamental and easily measurable parameters, (3) what are the mechanisms of ice deformation, and (4) how do ice deformation and morphology affect the heat balance?

Three pilot studies have been conducted in the Arctic, one in each of spring 1970, 1971, and 1972. A fourth pilot study is planned for spring 1973. The main experiment is scheduled to begin in March, 1975, and last for about one year.

B.5.2 Relevancy of Satellite and Marine Geodesy to AIDJEX

In addition to many oceanographic and meteorological measurements, there will be sea-ice observations involving the determinations of position, azimuth control, sea-ice velocity, and acceleration and strain. Determination of these parameters depends on geodetic techniques exclusively.

The strain measurements involve the use of theodolites and geodetic electronic distance measuring (EDM) systems to monitor time varying angular and linear displacements, respectively. The best angular measurement precision so far reported in AIDJEX reports is ±5" rms by the Japanese team. This should be improved to ±1" through the use of experienced geodetic observers but is subject to the stability of the ice floe. The current use of laser or EDM equipment for surface-to-surface linear measurements is adequate for local strain studies based on hourly observations. For extended ice-floes and inter-ice-floe monitoring, the geodetic satellite translocation technique should be used. This will be similar to the San Andreas Fault Experiment (SAFE) for monitoring crustal movements. In this case, ideally at least one of the stations should be permanently located on a continental ice cap not subject to perceptible motion.

Sea-ice velocity and acceleration are currently being measured by a geodetic-acoustic technique. Reported precision is ±10-20 meters rms in the time varying positions of ice floes. Current AIDJEX practice determines velocity as a derivative of position with respect to time. Their acoustic tracking technique for position determination leads to position ambiguity due to freedom of rotation of the ice floe and the consequent unknown orientation. This can be remedied by more accurate geodetic-acoustic techniques developed by Battelle and applied in the NASA Bahamas experiment which can give ±1 meter rms per unit time in monitoring sea-ice positions for velocity determination.

The positions of the research stations on the ice floe must be determined at regular intervals and with great precision. The time series of positions will define the ice drift, its deformation and a geographic reference for the meteorological and oceanographic measurements. The Navy Transit Satellite System is currently used for geographic or geodetic position determination. The ice floe time varying relative positions must be accurately monitored in order to make the satellite position determination accurate enough for the experiments objectives. These, again, are purely geodetic problems which are complicated but readily soluble.

Azimuth control is required to furnish the orientation of the ice floe so that measured parameters can be related to geographic (or geodetic) coordinates. Also changes in floe orientation are needed to measure local floe rotations to be compared with the large scale vorticity and shear. Azimuth control is required to eliminate position ambiguities discussed above. For this in the Arctic, magnetic compasses are virtually useless, gyrocompasses are reasonable only below latitude 80°N (or S). The obvious answer is azimuth determination by geodetic astronomy but this is precluded by weather conditions most of the time. The only choice, as of now, is the use of geodetic-acoustic techniques of the type developed by Battelle for NASA [71].

The application of satellite-marine geodesy is clearly relevant to the success of AIDJEX.

B.6 Ocean Resources--Industry's Efforts and Relevancy of Marine/Satellite Geodesy

The following is a preliminary detailed description of ocean resources, the problems associated with exploration and exploitation of such resources and their implications. One of the purposes of this discussion is to show the importance of resources to national needs and the amount of industrial effort and investment involved and the role of satellite/marine geodesy to make these operations most effective. This role is only briefly discussed here. More details are given in Section 3.2.

It appears inevitable that exploration and exploitation of ocean resources will increase extensively during the next decades because of energy shortages and depletion of land natural resources. Ocean resources can be classified broadly into living and non-living resources. The living resources include marine organisms that provide food and food derivatives as well as drugs and other products. For exploitation of living resources, the requirement for marine/satellite geodesy is primarily for position determination. Although the basic positioning accuracy requirements for exploitation of the living resources are not demanding and perhaps can be satisfied by general navigation systems such as Omega (±1 mile), they can use more accurate positioning capability if available. Accordingly, the living resources will not be considered any further in this report.

The non-living resources, on the other hand, are treated in some detail. These resources, because of their economic potential, have attracted world attention and concern. For the purpose of this report, the non-living resources are restricted to (1) the mineral deposits found on the surface of the seabed (such as manganese nodules and phosphorites), and (2) the subsurface seabed deposits (such as oil, gas, and sulfur). Beach sand, gravel and other heavy minerals such as gold, tin and platinum found in or near coastal areas will be excluded, and chemical treatment or recovery of water (such as desalination) will also be omitted.

B.6.1. Seabed Surface Mineral Deposits

Offshore mining has been a reality for many years. During 1970 and 1971 alone, more than 85 new or on-going exploration programs were reported worldwide [8]. Examples of major marine mining activities that are in operation include sulfur along the U. S. Gulf Coast, diamonds along South West Africa, tin placers off Thailand and Indonesia [91] and England, [22], argonite in the Bahamas, barite off Alaska, iron sands off Japan [91], "heavy mineral" off Australia, monazite, ilmenite and others off Brazil and India and magnetite off New Zealand [22]. These mining activities are mostly near coastal areas and on the continental shelf in less than 200 feet of water. Because of closeness to land, the mining requirements for marine/satellite geodesy are not critical.

Most of the marine mining industry effort of interest to marine satellite geodesy is that in deep water. So far this effort involves either exploration to find ore deposits that can be economically produced or engineering studies to develop the necessary technology for mineral exploitation [91]. Exploration for deep resources however tends to be more selective with a great deal of preliminary work. The increased demand for minerals suggests that deep mining activity will increase. However, this will depend on several factors such as

(1) Discovery of rich ore bodies (readily available) at little cost

(2) Technology to explore and define deepsea ore rich areas

(3) Technology for mining such ore bodies

(4) Legal problem - right of ownership

(5) Environmental considerations - ecology, pollutants, conservation, etc.

(6) Finances - consortium (to minimize risk)

(7) Economic from exploration and exploitation to transportation to user and making profit.

The seabed deposits with potential economic value which make them most likely to be recovered first include phosphorites and manganese nodules and perhaps some of the "heavy minerals" discovered in the Red Sea. Surface deposits of phosphorite and manganése nodules blanket large areas of the ocean floor. The continental shelves of the world contain an estimated 300 billion tons of phosphorite. Equally extensive on the ocean floor are nodules containing manganese and iron oxide, cobalt, nickel, and copper.

B.6.1.1 Manganese Nodules. One of the most interesting discoveries made some 100 years ago by the "Challenger" Expedition (1873-76) was that of the manganese nodules on the floor of the Pacific, Atlantic, and Indian Oceans. From an economic standpoint, they are the most important sediment of the deep-ocean floor [60]. Manganese nodules are known to exist particularly beyond the continental shelf, in the abyssal plains and oceanic deeps. Various experts estimate the amount of manganese nodules on the floor of the Pacific to be several 100 billion tons. Analysis of over 6000 piston cores [47] and ocean bottom photographs [34] taken from most parts of the world oceans revealed that the highest concentration of manganese nodules are in the North Pacific Ocean from the deep waters of Central America to the seaward wall of the Mariana Trench (between 6°N and 20°N). The distribution of nodules is associated with red clay deposition which dominates much of the North Pacific Basin. The nodules are found in water depths between 10,000 and 20,000 feet [47]. Many other isolated deposits are found in the Indian and the Atlantic Oceans. Major deposits are found in the Indian and the Atlantic Oceans. Major deposits of nodules occur where rates of sedimentation are lowest.

A more recent discovery of massive heavy metal deposits covering an area 1400 miles long and 300 miles wide was made by U. S. and Soviet scientists during the expedition of the Soviet research vessel DMITRY MENDELEEV in the South Pacific [15]. The metal deposits include iron, manganese, copper, zinc and barium, which are combined in brown mud in 12,000 feet of water. However, unlike the North Pacific deposits and despite such extensive deposits, no one metal is present in sufficiently rich quantity in the mud to make it feasible for mining.

B.6.1.2 Phosphorites. Phosphorite which is used in fertilizers has been found in extensive areas on the continental margins and the ocean floor. Phosphate nodules blanket large areas of the ocean floors. Occurrences of phosphorites are known to exist from near shore to more than 200 miles offshore, in depths ranging from 60 feet to more than 11,000 feet. However, mining of ocean phosphorites will depend mainly on economics and supply and demand. As long as sufficient land deposits exist to take care of the demands, ocean floor deposits must be of better quality to make their mining more economical. In addition, the problem of balance of payments is of importance. To cut down on imports and decrease the dollar outflow, ocean mining of minerals that would otherwise have to be imported becomes a necessity. John L. Mero [60] estimated about 36,000 square miles of phosphorite nodules available for mining in offshore California.

B.6.1.3 Other Minerals. Other deep ocean mineral deposits of economic value are those associated with hot brine of the Red Sea referred to as geothermal deposits. The heated waters (from geothermal heat) dissolve the salts from sedimentary rocks and create a metal saturated brine. This brine contains lead, zinc, silver, copper and gold. These heavy metals have been estimated to have a value of $2.5 billion [33].

Investigation of the Red Sea muds have been undertaken by a German combine and Woods Hole with the U. S. Geological Survey, on behalf of one of the bordering nations. Technical data are now available which suggests that this resource merits economic evaluation and development of the required dredging and metal-winning technology. Forecasts regarding the economic viability of the deposits are premature [36].

B.6.1.4 Environmental Considerations. Several studies are underway by industry and Government attempting to define the environmental problems that will result from recovering minerals from the ocean floor and methods of their solution [44,77,78].

Roby [27] of the Marine Mineral Technology Center of NOAA indicates that the probable effect of mining mineral deposits on the marine environment has a common relationship to the problems of turbidity, possible changes in littoral drift, and changes in the habitat of the marine biota in the mine area. He maintains that during evaluation of sea floor deposits, much environmental data such as turbidity, pollutants and nutrients should be determined during drilling.

The assessment and preservation of the existing marine ecology is recognized by the industrial firms contemplating ocean mining operations as a normal and required objective in the development of an acceptable ocean mining endeavor. Preliminary studies have shown that the benefits to the world community resulting from the availability of deep ocean resources can be achieved without environmental degradation [44]. For example, nodule resources of high potential value except as a connection between more productive regions of the ocean. As a food producing region, the area can be ranked as an "oceanic desert" [44]. According to [44] an analysis of several mining systems under current development revealed no major problems related to the protection of the ocean environment.

> "Deep ocean mining is a new industry being developed at a time when environmental impact is recognized as an important element of the system. In a way this is fortuitous since it will be readily possible to economically design in into the operation all required protection that may be needed....By starting fresh with a new industry, utilizing proper environmental planning, design, testing, and evaluation and monitoring, the mineral resources of the deep ocean can be effectively tapped to furnish the future needs of mankind" [44].

B.6.1.5 Legal Considerations. The problem of seabed ownership and mineral exploitation is perhaps the most difficult one to resolve and stands in the way of industry's sea mining commitment. The U. N. Continental Shelf Convention gives the basic legal framework necessary for securing, holding, and operating mineral deposits on the continental shelves. Jurisdictional disputes between adjacent states and between Federal and Local administration still must be resolved [91]. For deep sea mining, the problem, however, still extends beyond questions relating to territorial waters. Several countries have proposed plans concerning deep sea mineral exploitation. Perhaps the situation is best summarized by Flipse [37].

"Perhaps the most disappointing aspects of an otherwise exciting year (1972) are the continued lack of progress of the U.N. Seabeds Committee and the administration's continued reluctance to implement President Nixon's 1970 Oceans Policy Statement. The Deep Seabed Hard Minerals Act gained support during the year with significant congressional testimony by the industry segment. Postponement of a position until January, 1973, was the administration's tactic.

"The plea to defer interim legislation until the U.N. negotiations are complete is wearing thin. The sterile August Geneva debate and the polarization, rather than consolidation, of positions was disappointing. The December deliberations in the General Assembly clearly indicate that the earliest possible date for substantive sessions of the Law of the Sea Conference will be late 1974 and that results before 1976 cannot reasonably be anticipated. Early action in the next Congress is expected to assure that U.S. interim investments are protected. Outcome of the Law of the Sea Conference is critical."

The U. S. Congress is considering two Bills (H.R. 13904 and S2801) for protection of U. S. investment. These Bills would permit U. S. private enterprise in the absence of international agreement. The Bills [39] provide essentially the following interim measures for seabed surface mineral exploitation:

- "A licensed 'surface block' is 40,000 square kilometers or 15,430 square miles, and extending 10 meters, or 32.8 feet, below the bottom.
- License will remain in force for 15 years provided recovery continues.
- Minimum development investment per block will be $100,000 for the first year and build to at least $700,000 by the 15th year.
- Within 10 years after start of commercial recovery the licensee will relinquish 75% of the block.
- Licensing is on a first-come, first-served basis. License fee is $55,000 for each block.
- In general, licenses will be limited to 40% control of a 1,250 kilometer circle.

Other provisions are for an international registry clearinghouse, an escrow fund reimbursement to companies for losses due to future international rules, and insurance at a stipulated premium to cover any losses caused by interference by any other person of recovery of hard minerals."

It is apparent from all the above that until the question of exploitation rights have been settled, companies will be reluctant to risk the large capital required without some assurance of protection.

B.6.1.6 Industry's Investment and Effort. According to Flipse [37], industrial investment in deep sea mineral recovery by major companies such as Tenneco, Hughes, Kennecott and others now exceeds $100 million. Resolution of the political uncertainty is needed in 1973 if the American effort is to continue at its present, or an expanded level. Deepsea Ventures Inc., a subsidiary of Tenneco, has been collecting data on location, depth and composition of manganese nodules since 1962 [8]. The company [36] operated in 1971 a mini-pilot plant and recovered manganese nodules from 2700 feet of water. It also developed a hydrochloric acid leach method to test the nodules and recover marketable copper, nickel, cobalt and manganese. According to Flipse [36], "This accomplishment places Deepsea in a position to undertake commercial ocean mining upon the completion of legal, financial business arrangements." Commercial extraction of manganese nodules from 18,000 feet of water is expected to begin in the mid-Pacific in 1974 [8].

The testimony of Freeman, Chairman of the Board of Tenneco, before the Subcommittee on Oceanography of the House Committee on Merchant Marine and Fisheries [39], is reported as follows

> ..."the U.S. is dependent upon imports for 19% of its copper, 84% of its nickel, 92% of its cobalt and 98% of its manganese. The mining industry, he said, has sought political stability to protect its investments. Nevertheless, these foreign sources still represent an outflow of capital.
>
> "An alternative, he said, is the deepsea nodule. Deepsea has invested $20 million over a period of 10 years to develop the resource, technology and commercial strategy for recovery of these strategically needed metals...
>
> Freeman made these points:
>
> - Detailed definition of these ore bodies will entail extensive costly and highly visible operations on location. As soon as operations begin, the location will become public information.
> - Deepsea has located economically viable deposits that are candidates based on a 40 year operation at one million short tons of dry nodules per year.
> - Different ore bodies are enough unalike as to require widely varying engineering to effect recovery.
> - National and international monitoring of environmental impacts will make disclosure of sites mandatory...If his company is granted one claim, the company intends to spend 24 months and $16 million additional, to further

> define the ore body and refine engineering to site requirements. After the 24-month period, he added, another $150 million would be spent, with metals being delivered to market within 36 months of the start of capital construction.

This would result in the production, he stated, of the following approximate quantities of pure metals to the world markets:

- Manganese, 500 million pounds.
- Nickel, 25 million pounds.
- Copper, 20 million pounds.
- Cobalt, 4.5 million pounds.
- Others, including molybdenum, vanadium, and zinc, 5.5 million pounds."

Other companies such as Hughes and the Japanese activities are summarized by Flipse [37],

"The ocean mining industry made major progress during 1972 with the launching of two vessels for the Hughes/Global Marine interests and the completion of a continuous line bucket system test sponsored by the Japanese Resources Agency.

"In January, 1972, the Hughes Tool Company launched a 324-foot barge to be used as an ocean mining support vessel. The top secret project was contracted through the Lockheed Missiles and Space Company and built by National Steel and Shipbuilding of San Diego, California. Very little is known about the barge or its intended use except that it is capable of being submerged to allow it to handle massive equipment.

"The mining ship for the Hughes operations was launched at Sun Shipbuilding and Dry Dock Company, Chester, Pennsylvania, in November, 1972. Named the Hughes Glomar Explorer, the vessel is 618 feet long, 115-1/2 feet wide and displaces 51,000 tons. Secrecy is again the byword with Paul Reeve, manager of the Hughes Ocean Mining Division, revealing only that the vessel is a prototype and will be employed in solving problems of manganese nodule acquisition.

"The Japanese Continuous Line Bucket system development program included a full scale application test this summer conducted by Sumitomo of Japan supported by a group of American and overseas companies. Results of the "Japanese Rope Trick", as it is affectionately called, have not been made public. Unofficial reports vary from abject failure to moderate success. We look forward to the facts.

"In other activities, offshore deposits of argonite are being mined by the Dillingham in the Bahamas and Inlet Oil's mining of barite in Alaskan waters continues. Diamond operations off the coast of South Africa have ceased."

As for the future of ocean mining, the following statements by Padan [74], Acting Director of NOAA Marine Technology Center, summarized the situation:

> "I would term the 70's the decade of exploration, research, and development and perhaps the 80's will witness the acceleration of large scale seafloor mining. There is no question that we are progressing steadily towards such a goal, and during this past year a good foundation has been laid by government and industry in many countries of the world. American leadership is not in doubt but, like the minerals in the sea, it will not be kept without effort. Within this framework it behooves us to assure that as mining develops off our shores, as it has off many foreign nations, the quality of the marine environment is not placed in jeopardy. This is the real challenge to the marine mining engineer of the 70's."

Similar predictions have also been made by others such as shown below from Oceanology International [8],

> "There is no question that ocean mining is a viable, if embryonic, industry with a future as positive and as long term as that of terrestrial mining.
>
> "Marine minerals are a substantial natural resource, and the development of a technology to exploit them is governed only by need for the resource.
>
> "Although at all times our world supply of mineral commodities is maintained on a competitive basis, costs no longer can be measured only in terms of immediate economic gain. Environmental and human factors will play a large part in the development of oceanic minerals. The concept of multiple use of our environment will require us to give thought not only to maintaining the integrity of the oceans and seas, but in many cases to utilizing them to avoid catastrophic disturbance of alternative resource areas on land.
>
> "A great deal of fundamental research on the natural balance of the many and various marine environments, such as estuaries, beaches, enclosed seas, and deep oceans, must be carried out in many cases before informed decisions can be made on the choice of alternatives for mining.
>
> "The pending entry of industrial giants such as International Nickel Co., Kennecott Copper Corp., Hughes Tool Co., and Tenneco, through Deepsea Ventures Inc., together with the massive programs of national research being mounted by the Soviet Union, hopefully may give impetus to this country's so far meager efforts in the development of technical and environmental standards on which decisions can be based."

B.6.2 Seabed Subsurface Deposits - Oil and Gas

The offshore oil and gas industry is, by far, leading all other mineral and commercial industries marine activities. Ikard [49], President of the American Petroleum Institute, estimates that offshore oil and gas expenditures will exceed $2.5 billion in 1973 for exploration, drilling, completion and production. U. S. offshore wells account for 18% of the crude oil and 17% of the natural gas produced in this country. Potentially important oil fields are being discovered continually, and most of the world nations are investing considerable capital in offshore minerals. For example, December's 1972 sales of offshore lands in the Gulf of Mexico produced bids from petroleum firms of a record $6.2 billion, of which about $1.7 billion was accepted. The price of $3,187/acre was about three times as high as in the sale two years earlier [19]. Ikard [49] cites a new study by the National Petroleum Council which indicates that offshore lease sales totalling 21 million acres would be required by 1985. This compares with seven million acres made available from 1954 to date. Most predictions also indicate that world demand will increase from its present 52 million barrels per day (bpd) to 100 million bpd in the early 1980's [87].

B.6.2.1 Energy Shortage. The energy crisis is certain to bring increasing demands for more offshore sales as petroleum resources are considered the best immediate answer to energy supply needs. According to Ikard [49],

> "The growing gap between available domestic supplies and increasing consumer demands for petroleum energy requires that government take a more realistic and positive view toward marine exploration and the vast potential reserves of oil and gas thought to exist in U.S. seabed areas. The petroleum industry has urged, consonant with environmental goals, that the frequency of lease sales and amount of federal offshore acreage leased to be increased."

"The following information on energy shortage is summarized from a Seminar on "What's ahead for offshore oil, 1973-1985, and from interviews, conducted by ocean industry with (1) Owen Thomas, Philips Petroleum Co., (2) Bob Palmer, Rowan Companies, Inc., (3) George E. Kitchel, Transworld Drilling Co., and (4) Kerr McGee Corp. [8].

"The sharp upward trend of GNP curves which represent economic growth of nations throughout the world is paralleled by soaring energy consumption curves. Generally, the nations having the most plentiful supplies of low cost energy lead in GNP or "economic advancement." But now the days of cheap energy are drawing to a close. The primary reason is that in the near future, most nations must depend on oil and gas to supply the major part of their energy mix; and the demand for these products is sharply increasing as the supply is decreasing, see Figure B.2.

"Because most land areas (with the exceptions of USSR, China, Amazon Basin and Arctic islands) have been thoroughly explored, the industry must turn to the sea for most favorable prospects. Hence, as the demand soars upward; the offshore oil industry must step up the tempo of its offshore operations. Prospects in deeper water and further from shore will become more economic, and the drilling rate will spiral upward."

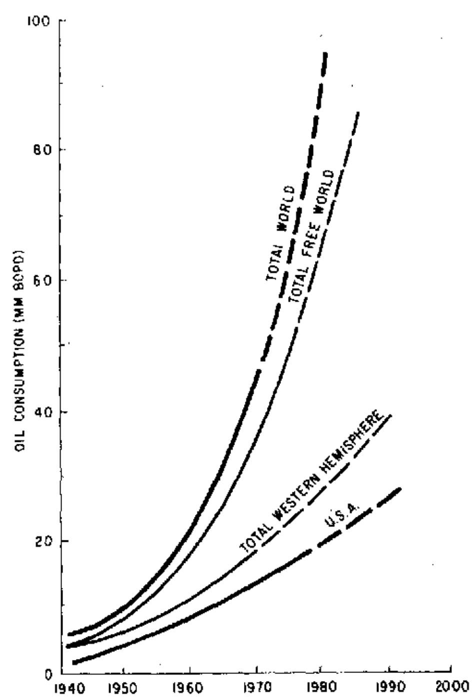


FIGURE B.2. GROWTH IN WORLD OIL CONSUMPTION [18]

It appears that there is no doubt that the United States will experience a shortage of energy [18]. The seriousness of oil shortage will depend largely on what we do in the immediate future to minimize its effects. Oil and gas amounts to about 75% of the total energy used in the U. S. At present U. S. consumption is about 16 million barrels of oil per day of which about 4 million bpd are imported. By 1985, imports are projected to reach 15 to 20 million bpd, and this could produce a serious deficit in our balance of payments [18].

What Can Be Done About Energy Shortage. In order to overcome the energy shortage, Thomas [18] recommends the following steps:

(1) Remove the controls of wellhead prices of natural gas

(2) Increase the price of crude to provide the industry with the capital required to search for and develop additional reserves

(3) The Federal Government must open for exploration our remaining unexplored areas, lying mainly offshore

(4) Accelerate the development of equipment and methods to drill and complete wells in deep water. "Exploratory drilling has been carried out in water depths exceeding 1700 ft., and there are a growing number of sea floor completion systems. This is only the beginning. Ultimately, we must be able to reach and produce all prospective areas under the sea" [18].

(5) Devote more research effort toward the development of improved exploration and drilling tools, such as new seismic and other geophysical techniques

(6) Use our energy more efficiently and reduce waste

(7) Prepare for large-scale imports that are inevitable.

Extent of Future Energy Development. The extent the major offshore oil producing areas will be developed by 1985 will depend on the following:

(1) Time lag required of 10-12 years between "discovery peak" and the "production peak" in a given oil province. For example, if the Atlantic coast and Gulf of Alaska were opened up to exploration in 1973, it would probably be in the mid-1980s or later before the production peak is reached.

(2) Pace of exploration drilling in the sea - It is imperative that the pace of exploratory drilling be increased if we are to avoid a drastic deterioration in our standard of living.

(3) Finances - oil industry cannot provide the capital for a great increase in the rate of exploration and production without substantial increases in the prices of oil and gas.

It is estimated that the industry will need $1,000,000,000,000 to meet all of its requirements by 1985. At current prices the industry will fall short by $400,000,000,000 [18].

Effect of Technical Innovations. Research and development work has produced new deep water production systems. The most dramatic innovation will be the development of (1) subsea facilities to produce oil in deep waters and (2) techniques for laying pipelines and providing other facilities in deep water. Deep water technology development is expected to accelerate because of the discovery of known basins in the Gulf of Mexico and other areas.

B.6.2.2 Trends and Problems in Offshore Oil and Gas. The offshore oil and gas industry is enjoying a boom at the present and is expected to continue into the future. This boom is helped by the discovery of giant oil fields in the North Sea. According to O. D. Thomas, Vice President of Exploration and Petroleum with Philips Petroleum [87]:

> "No event in recent years has captured the imagination of the oil industry as has the discovery of a series of giant oil fields in the North Sea beginning with Ekofisk field... in offshore Norway...North Sea discoveries have defined a major petroleum basin 100 miles wide and 380 miles long... The fulfilling of a dream, finding reserves capable of supporting large-scale production in Western Europe, which few people ever expected to become a reality, has amazed Europeans and excited even the most cynical members of the industry...The North Sea is likely to be top priority for the industry for years to come...While no one can say at this time with any degree of certainty what level of production can be attained from the North Sea, a level of 10 to 20% of Western Europe's Consumption by 1980 would be highly gratifying considering that projected demand by that time is on the order of 30 million barrels of oil per day...It is likely that the development of the fields found to date will entail the expenditure of several billions of dollars before 1980 and many observers believe what has been found so far is only a small part of the potential of the area."

Another example contributing to the boom is the discovery of oil and gas in the deep waters. Oil was found on the Knolls on the Gulf of

Mexico's continental rise by a scientific group on board the R/V ALAMINOS, research vessel of Texas A and M University [25], by the Deep Sea Drilling Project [45], and by the U. S. Geological Survey in conjunction with the Navy Oceanographic office [90]. The latter made 11,000 miles of deep Gulf sub-bottom seismic profiles and found many salt domes of potential oil deposits.

The strength of this offshore boom is expected to continue according to a group of experts [63] because of the need for energy throughout the world and because of the pressure of politically unstable areas of the world with oil supply; offshore oil will be pushed even at higher cost and greater risk.

The major problems or obstacles for the offshore industry are due to environmental, political/legal and economic considerations. For example, in recent years ecology control and pollution prevention have made a sudden appearance and added to the cost of oil exploration and exploitation. According to Ikard [49],

> "Concern about the environmental impact of marine drilling has been primarily responsible for delayed lease sales and proposals to ban all further petroleum exploration of U.S. seabed areas. For example, one lease sale in the Gulf of Mexico, originally scheduled for November 1971, was held up some eight months: a second lease sale, initially scheduled for May 1972, took place only last month...Environmental fears are based on the mistaken belief that offshore drilling has had a widespread adverse impact on the marine ecology. Actually, more than 16,000 wells have been drilled in the U.S. waters over the past quarter-century, but only three blowouts--two in the Gulf and one in the Santa Barbara Channel--resulted in significant oil spillage. And there is no evidence that these three spills caused any permanent environmental damage."

From the economic point of view it appears that the balance of payments the U. S. will incur by importing oil is going to be one of the biggest problems this country must face. Another problem obviously is due to increased costs.

From the political/legal point of view there are several problems that must be solved. These are due to,

(1) Uncertainty as to ownership of areas beyond the 600 ft. depth

(2) Uncertainty in lease policy and

(3) Regulation of prices.

In the North Sea the legal/political problems were resolved somewhat when the neighboring countries settled their own dispute as Taylor [86] notes:

> "The genesis of this area as an oil province came in 1964, when all of the countries surrounding the North Sea agreed to the Geneva Convention on the Continental Shelf. The Convention gave the coastal nations soverign rights over natural resources below the seabed out to a water depth of 200 meters - or deeper if mineral exploitation is possible. The countries also agreed on the boundaries (with several notable exceptions), and the North Sea oil boom commenced."

The oil and gas industry appears optimistic about moving out to deeper waters in the future. Dr. R. J. Howe of ESSO Production [48] summarized the situation for the 1980's.

> "It appears, however, that the water depths in which the petroleum industry will be operating in the year (1987) will be governed by economics rather than technical factors. By that time the industry should have the capability to explore for and produce hydrocarbon reserves in almost any ocean area of the world; however, there are many alternate sources of energy which will probably enter the market before petroleum deposits are produced in ultradeep water...
>
> "...In 1980, oil production from offshore fields will total 20 million barrels of oil per day, representing approximately one third of total Free World production, compared with 5 million barrels and 17 percent today. Total investment in offshore petroleum resources will then stand at $55 billion, compared with $18 billion today (1968)".

Offshore drilling is a multi-billion dollar effort. The industry is concerned about the number of rigs to be built to meet the demands and whether subsea completion systems will replace fixed rigs. Most operators agree that the break-even-point for a rig in the North Sea is about $24000/day operating 90% of the time. Although tests have been made on reentry systems, dependable subsea completion technology will not occur soon. Subsea completion will require mobile rigs and therefore this should accelerate mobile rig development. Other problems facing offshore drilling are

- Increased rig construction costs,
- Increased insurance costs,
- Maintenance, and
- Personnel training.

One of the most pressing technical problems is the need for accurate information on wave heights and wave forces that can be expected in a given area [63]. Such information is significant in the design of rigs. Overdesigning increases the cost considerably and underdesigning is dangerous. For example, rigs used in the North Sea are designed for about 100 ft. waves. Accordingly, the design for overturning moment is about 10 times that in the Gulf of Mexico [86]. Yet recent updated information on wave heights for the North Sea caused the insurance companies to demand higher premiums or moving the rigs to other areas.

The offshore industry is preparing now to explore for oil in deep water. The dominant factors influencing deep water production include technology, production costs and seabed ownership [11]. The technological problems include dynamic ship positioning, which has already been demonstrated, and reentry problems. Dynamic positioning tests have been completed for 20,000 ft. of water by Institute Francais du Petrole (IFP) and Centre National d'Exploration des Oceans (CNEXCO) and IHC of Holland [11]. The drill ship SEDCO 445, designed to Shell Oil Co.'s specifications, drilled a 5,893 ft. hole in water depths beyond 1300 ft. off northwest Borneo using dynamic positioning (without use of anchor) for the first time in drilling for oil [20,10]. The source indicates that the ship can drill in water depth of more than 2000 ft.

Reentry which was impractical only a few years ago, now seems to be a reality. The Glomar Challenger is developing efficient economic methods to reenter holes at 20,000 ft [11].

> "Although no one yet claims that the re-entry problem has been totally solved, reentry systems are well beyond the test stage and like ultradeep drilling rigs, wait only to be put in common use."

Two important trends involve moves toward deeper water and the move into hostile environmental areas such as the North Sea and eastern coast of Canada. These "will produce changes such as larger rigs, higher horsepower, better wave construction, deeper mooring capability and dynamic positioning systems" [63].

Industry's most pressing problem during 1973-1985 will be to convince the public, Government officials and political leaders of the critical nature of oil and gas shortage and the need for removing barriers to finding reserves.

B.6.3 Requirements in Ocean Resources Development for Marine/Satellite Geodesy

In view of the above discussions on ocean resources, it is apparent that marine/satellite geodesy capabilities can make significant contributions in practically all phases of the oil and gas and mineral industry from exploration to production, to pipe-laying and transportation to users. The most important requirements are

(1) Accurate and continuous position information which are required for geophysical surveys and explorations

(2) Accurate bathymetric mapping

(3) Lease boundary determination and re-identification

(4) Dynamic ship positions for mobile rigs and for use of submersibles in sea-floor oil well completions

(5) Accurate wave height information.

As oil and gas production move out to deeper water, these requirements will have more importance. As have been shown in the foregoing discussions the trend is toward deeper water and world-wide exploration and production. This will make accurate geodetic position information more essential for efficient operations and reduction of the cost of offshore operations.

Geophysical exploration expenditures are on the order of $200-million per year with about 75% going to marine geophysical contractors. "Commitment for at least $3 to $4-Million for several sea-going marine survey vessels, superbly equipped with multi-sensor systems, ready to explore offshore areas around the world for potential petroleum and/or mineral deposits, and one or more sophisticated digital computer processing centers" are required to be competitive in offshore exploration [58].

According to Luehrmann [58] "continued increase in the use of satellite-doppler-sonar systems, both integrated and semi-integrated, was evident as the need became urgent to remove field operations from dependence on shore-based stations and to provide around-the-clock operation for higher cost effectiveness. (Overall survey costs to the client may be as much as 30 to 50% lower in remote areas where satellite-doppler-sonar navigation is used in lieu of the two- or three-base station systems." Actually, if the trend towards deeper water continues, doppler sonar would be ineffective and other systems must be developed and integrated with satellite navigation to provide continuous position information. It is apparent that the "systems which can provide maximum flexibility, minimum capital investment, and minimum cost per survey mile will dominate this phase of the exploration industry. These developments eventually will make obsolete the expensive shore-dependent systems for offshore seismic exploration except for special applications such as mining studies or where large, fixed networks already exist" [58].

Additional information on the requirements and the relevancy of marine/satellite geodesy were already discussed in Section 3.2.

B.7 Marine Legislations and Law of the Sea

The legal delineation and reidentification of territorial boundaries at sea are regulated by national marine legislations and international laws of the sea. However, the actual physical delineation and reidentification have to employ marine geodesy and satellite technology. The interdependency of the legal and physical boundary problems are inseparable. Therefore, in examining this practical application of marine/satellite geodetic technology, pertinent marine legislations and laws of the sea are briefly reviewed. Territorial limits have often been a major issue of national and international controversy. The nations of the world have taken different attitudes and actions in regard to territorial boundary claims. Table B-1 shows the breadth of territorial seas and other jurisdictions claimed by selected countries [33].

The question of territorial limits continues to be dealt with legally and without detailed consideration of the technical implications. For example, investigations of the marine geodetic technology required to define and establish boundaries have been limited to adaptation of classical geodetic methods for the three or 12 miles limits only. As resource explorations (already feasible in the deep ocean) expand to deeper waters new technology must be developed.

It is important that the U. S. assume a leadership position and be prepared technically for dealing with the international community conferences on the law of the sea scheduled for 1973 and 1974 (discussed later). A U. S. marine geodetic program can contribute to the resolutions

TABLE B-1. BREADTH OF TERRITORIAL SEAS AND OTHER JURISDICTIONS CLAIMED BY SELECTED COUNTRIES [33]

Country	Territorial sea (miles)	Fishing limit (miles)	Other
Albania	12	12	
Algeria	12	12	
Argentina	200	200	Sovereignty is claimed over a 200-mile maritime zone but the law specifically provides that freedom of navigation of ships and aircraft in the zone is unaffected. Continental Shelf—including sovereignty over superjacent waters.
Australia	3	12	
Belgium	3	[1] 12	
Brazil	200	12	
Bulgaria	12	12	
Burma	12	12	
Cambodia	12	12	Continental shelf claimed to 50 m—including sovereignty over superjacent waters.
Cameroun	18	18	
Canada	12	12	
Ceylon	6	6	Claims right to establish conservation zones within 100 nautical miles of the territorial sea.
Chile	[2] 50	200	
China	3	3	
Colombia	12	12	
Congo (Brazzaville)	3	3	
Congo (Kinshasa)	3	3	
Costa Rica	3		"Specialized competence" over living resources to 200 miles.
Cuba	3	3	
Cyprus	12	12	
Dahomey	12	12	100-mile mineral exploitation limit.
Denmark	3	[1] 12	
Greenland		12	
Faroe Islands		12	
Dominican Republic	6	12	Contiguous zone 6 miles beyond territorial sea for protection of health, fiscal, customs matters, and the conservation of fisheries and other natural resources of the sea.
Ecuador	200	200	
El Salvador	200	200	
Ethiopia	12	12	
Federal Republic of Germany	3	[1] 12	
Finland	4	4	
France	3	12	
Gabon	25	25	
Gambia	12	18	
Ghana	12	12	Undefined protective areas may be proclaimed seaward of territorial sea, and up to 100 miles seaward of territorial sea may be proclaimed fishing conservation zone.
Greece	6	6	
Guatemala	12	12	
Guinea	130	130	
Guyana	3	3	
Haiti	6	6	
Honduras	12	12	
Iceland	4	12	
India	12	12	Plus right to establish 100 miles conservation zone.
Indonesia	12	12	Archipelago concept baselines.
Iran	12	12	
Iraq	12	12	
Ireland	3	[1] 12	
Israel	6	6	
Italy	6	[1] 12	
Ivory Coast	6	12	
Jamaica	12	12	
Japan	3	3	
Jordan	3	3	
Kenya	12	12	

See footnotes at end of table.

ORIGINAL PAGE IS OF POOR QUALITY

TABLE B-1. (Continued)

Country	Territorial sea (miles)	Fishing limit (miles)	Other
Korea	3	20 to 200	Continental Shelf including sovereignty over superjacent waters.
Kuwait	12	12	
Lebanon	...	6	
Liberia	12	12	
Libya	12	12	
Malagasy Republic	12	12	
Malaysia	12	12	
Maldive Islands	6	....	
Malta	3	3	
Mauritania	12	12	
Mauritius	3	3	
Mexico	12	12	
Morocco	3	12	Exception--6 mile fishing zone for Strait of Gibraltar.
Netherlands	3	[1] 12	
New Zealand	3	12	
Nicaragua	3	200	Continental Shelf including sovereignty over superjacent waters.
Nigeria	12	12	
Norway	4	12	
Pakistan	12	12	Plus right to establish 100-mile conservation zones.
Panama	200	200	Continental Shelf including sovereignty over superjacent waters.
Peru	200	200	
Philippines	...	...	Archipelago concept baselines. Waters between these baselines and the limits described in the Treaty of Paris, Dec. 10, 1898, the United States-Spain Treaty of Nov. 7, 1900, and United States-United Kingdom Treaty of Jan. 2, 1930, are claimed as territorial sea.
Poland	3	3	
Portugal	([2])	[1] 12	
Romania	12	12	
Saudia Arabia	12	12	
Senegal	12	18	Fishing zone beyond 12 miles does not apply to those nations which are party to the 1958 Geneva Convention on the Territorial Sea and the Contiguous Zone.
Sierra Leone	12	12	
Singapore	3	3	
Somali Republic	12	12	
South Africa	6	12	
Southern Yemen	12	12	
Spain	6	[1] 12	
Sudan	12	12	
Sweden	4	[1] 12	
Syria	12	12	Contiguous zone--an additional 6-mile area to control security, customs, hygiene, and financial matters.
Tanzania	12	12	
Thailand	12	12	
Togo	12	12	
Trinidad and Tobago	3	3	
Tunisia	6	12	Fisheries zone follows the 50-meter isobath at specified areas of the coast (maximum 65 miles).
Turkey	6	12	
Ukrainian S.S.R.	12	12	
U.S.S.R.	12	12	
United Arab Republic	12	12	
United Kingdom	3	12	
Overseas areas	3	3	
United States of America	3	12	
Uruguay	12	200	Sovereignty is claimed over a 200-mile maritime zone but law specifically provides that the freedom of navigation of ships and aircraft beyond 12 miles is unaffected by the claim.
Venezuela	12	12	
Vietnam	3	[3] 20	
Yemen	12	12	
Yugoslavia	10	10	

[1] Parties to the European Fisheries Convention which provides for the right to establish 3-mile exclusive fishing zone seaward of 3-mile territorial sea plus additional 6-mile fishing zone restricted to the convention nations.

[2] No claims.

[3] Kilometers (1 km = 0.62 mi).

Source: Information available to the National Council on Marine Resources and Engineering Development as of Jan. 1, 1970, as updated to Sept. 1, 1970, by the Department of State.

of international boundary disputes, particularly in the open ocean. Having experimentally evaluated available capability, including satellite technology, the U. S. could assume a leadership role during the development of international treaties and agreements.

Marine law and legislations during the past years are summarized; and major events (and implications) since the 1958 Geneva Convention are discussed below.

B.7.1 Geneva Convention - 1958

The 1958 Geneva Convention on the Continental Shelf which was ratified by the United States in June 1964 gave new incentive to scientific exploration and economic development of coastal and offshore areas. This United Nations agreement recognizes the rights and responsibilities of coastal nations with respect to their continental shelves "...to a depth of 200 meters..." But this definition cannot be interpreted narrowly for it goes on to say, "...or beyond that limit, to where the depth of the superadjacent waters admits of the exploitation of the natural resources...." The seaward limit of the "Continental shelf" thus becomes dependent upon a nation's capability for exploration and development.

The Geneva Convention essentially (1) failed to delineate the territorial sea boundaries, (2) ignored the physical characteristics of the Continental shelf; the arbitrary (200 meter) isobath is scientifically unfounded and inequitable in resource allocations, and (3) introduced ambiguity inherent in the extended definition [33].

B.7.2 United Nations Seabed Resolution - 1967

The controversy over the 1958 Geneva Convention of extending exploitation limits to the nation's capability arose in the middle sixties when various scientific literature described the potential wealth of the oceans. The underdeveloped nations became concerned about the technologically advanced industrial nations stripping the ocean resources. They mounted a campaign to insure the resources of the oceans would be exploited under international agreement over which they would have predominant control. They passed the UN 1967 Resolution by an overwhelming majority for establishing an ad hoc Committee on the Seabeds and calling for a convention to design an international authority under which extraction of subsea minerals would be conducted.

B.7.3 Malta Proposal - 1967

Malta submitted in August 1967 to the UN Secretary General, proposing "Declaration and treaty concerning the reservation exclusively for peaceful purposes of the sea-bed and of the ocean floor, underlying the seas beyond the limits of present national jurisdiction, and the use of their resources in the interest of mankind" [33]. On December 18, 1967, a resolution was passed by which the General Assembly created an Ad Hoc Committee to study the Peaceful Uses of the Seabed and the Ocean floor beyond the limits of national jurisdiction. It suggested that the oceans be declared a "common heritage of mankind". The underdeveloped nations still felt that the seabed mining would be dominated by industrialized nations who possess the technology and capital. The developing countries felt that deep sea production may drive prices of land resources down and hurt their own resources.

B.7.4 United Nations 1969 Resolution

The following resolution was passed by the United Nations in 1969:

(1) Study of possible types of international machinery for governing the seabed

(2) Hold a convention

(3) Draft international agreement and in the meantime

(4) Hold a moratorium on all subsea exploration until international agreement could be established.

The U. S. voted against this resolution on the basis that moratorium would hurt technology.

B.7.5 President Nixon Proposal on Ocean Policy - 1970

President Nixon Ocean Policy Proposal aimed at calming the fears of developed countries. The proposal called for the Coastal States of the world to renounce their national claims to seabed mineral resources beyond the 200-meter isobath, establishing the area beyond as falling under international jurisdiction [23]. It also recommended:

(1) A 12-mile limit (rather than 3 at present),

(2) Establishment of an international agency charged with oversight of the exploration and production of undersea resources,

(3) Declaration of areas of continental margins beyond 200-m depth as an international trusteeship zone,

(4) Establish interim policy,

(5) Amendment of domestic tax laws to prevent discrimination against U. S. nationals operating in the trusteeship zone of other nations, and

(6) Maintenance of international policy of freedom of the seas and conservation of ocean resources.

The reaction to President Nixon's proposal varied. The oil industry opposed it stating that "the U.S. in common with other coastal nations, now has exclusive jurisdiction over the natural resources of the submerged continental mass seaward to where the submerged portion of that mass meets the abysal ocean floor and that it should declare its rights accordingly." The industrialized nations felt that the draft would give control of the international seabeds to the developing nations who hold a majority at the United Nations. The developing nations, particularly with economies depending on petroleum and mineral exports are in favor of sovereignty to the edge of the continental margin which would force oil companies to deal directly with them.

The biggest obstacle is the confrontation between the developing and industrialized nations. The developing nations can pass any resolution they want because of majority but the industrialized nations because of United Nation rules can ignore any measure they don't like.

B.7.6 Marine Legislation and Policy - 1971/1972

The U. S. Senate introduced in November 1971, a Bill, S 2801 Metcalf Bill and the House also introduced in February 1972, an identical Bill on Seabed Mining (HR 13076). These Bills would license U. S. mining companies on the seabed. The Bills will introduce a semblance of a legal regime to something that is going to happen. It may take the United Nations 15 years before it acts. In the meantime S 2801 is an interim measure and every nation can do the same thing. The Bill will provide law in order to avoid confrontation.

Potential investors in deep ocean oil and mineral exploitation want to know under what conditions exploration and production of ocean resources must be carried out before money is spent on deepwater operations.

B.7.7 Law of the Sea Conference - 1973

After many months of deliberating, the United Nations Political Committee finally has set a date of November, 1973, for the long heralded Law-of-the Sea Conference to be held in New York [17]. It appears that there are some 25 items on the agenda, and that the session is expected only to refine the agenda and perhaps make decisions on the less controversial items. Following this conference, another final session is being scheduled for Santiago, Chile, in 1974.

APPENDIX C

PRESENT-DAY ACCURAY OF EARTH'S GRAVITATIONAL FIELD

C.1 Summary

This Appendix includes a review of an investigation conducted at Defense Mapping Agency Aerospace Center (DMAAC), [32] related to the accuracy of determination of the geoid which features prominently throughout this report. Various earth gravitational models available in the U. S., Western Europe, and Australia, were investigated for different application environments to determine the accuracy with which the earth's gravitational field is known today. These models were based on satellite data alone, or surface gravity data alone, or a combination of both. The results of the study showed that the earth's gravitational field and hence the geoid is not known to great accuracy. This knowledge of the present-day accuracy of the earth's gravitational field, including current and projected data requirements, is necessary for efficient planning and execution of programs for improving the gravitational field representation.

The study examined the four commonly used methods of gravitational field representation: (1) mean gravity anomalies for various block sizes, (2) geopotential coefficients set for spherical harmonic representation, (3) point mass sets, and (4) mean densities for simple surface layers. Factors that affect accuracies in each method of representation were investigated. The factors include the type of data, the quantity and global distribution of data, the quality or accuracy of data, and the data processing methods in use.

Currently, the global coverage of surface gravity data is still grossly inadequate. Complete global coverage is a key factor in the use of surface gravity for representation of the earth's gravitational field. The efforts to collect surface gravity data tremendously increased during the last two decades but the percentage of global coverage has scarcely increased. With current efforts and level of funding, complete global coverage remains a distant dream. Errors in collected data, especially at sea, are still substantially above desirable levels. No rigorous accuracy determination of mean gravity anomalies exists. Prediction, extrapolation and computation errors for areas without observed data are still high. Accuracy estimates of mean anomalies for gravitational field representation range from ± 1 - 10 mgals on land to ± 10 - over 100 mgals in the oceans. There are as many varied techniques and numbers of computational parameters as there are investigators in existing geopotential models.

Using various comparison criteria, there were few intermodel agreements but the variability and magnitudes of the disagreements led to the conclusion that the present day accuracy of earth's gravitational field representation is poor. The resultant geoids from the various representations differ significantly. RMS geoid height differences range from ± 19 to ± 31 m for North America, ± 48 to ± 58 m for Europe/Asia, ± 13 to ± 26 m for Australia and ± 34 to ± 40 m on a worldwide basis when several models from OSU, SAO, GSFC, APL, UCLA, NOS/NOAA, and other organizations in Europe were compared. The report also indicated that due to current and near future data accuracy and lack of global coverage, the geoid deducible from applying Stokes' formula to gravity data is not accurate enough for use as a standard.

C.2 Supporting Investigations

The investigations from which these conclusions were derived are summarized in brief. First, we look at the material available for gravitational field representation.

C.2.1 Extent of World Gravity Coverage

Published information of importance concerning the extent to which at least one gravity observation exists in any $n^o \times n^o$ square, worldwide, are as follows:

(1) Zhongolovich (1952) - 10° x 10° in which 204 out of 410 had actual data - 50 percent. He developed a geopotential model to degree and order eight from the 26,000 gravity observations available.

(2) Kaula (1959) - 10° x 10° data as in (1) plus 1000 1° x 1° data. He also used the vailable surface gravity data to develop a set of geopotential coefficients to degree and order eight.

(3) Heiskanen (1959) - a graphic displaying 5° x 5° mean free-air gravity anomalies for 1349 of the 2592 5° x 5° global units. Data in some of the 1349 squares were predicted and not observed.

(4) Uotila (1961) - published "Existing Gravity Material" for all 1° x 1° squares having one or more gravity observations. This showed that only 30 percent of the earth had this type of data.

In 1962 Uotila published 1049 of the 2592 global 5° x 5° mean free-air gravity anomalies in two separate reports. Each report contained three geopotential coefficient sets of fourth degree and order.

At the IUGG XIII General Assembly in 1963, Uotila presented a worldwide 5° x 5° field of gravity anomalies determined from a spherical harmonic expansion to degree and order 36, using mean elevation data. He published a related representation in 1965 using satellite derived coefficients, to the seventh degree and order, instead of the former mean elevation data.

A 1964 presentation by Uotila showed that 35 percent of the earth had 1° x 1° squares containing at least one observed gravity data.

(5) In 1966, Kaula published a worldwide 10° x 10° mean gravity anaomaly field, using 16331 60 x 60 ± 30 nautical mile areas covering about 25 percent of the earth's surface.

(6) Rapp (1968) developed from a combination of satellite and gravimetric data a worldwide 10° x 10° mean free-air gravity anomaly field. The gravimetric data were 1426 (out of 2592 for the whole world) mean free-air anomalies. The satellite data were from SAO 1966 Standard Earth geopotential coefficient set. This combination solution also produced an adjusted set of geopotential coefficients to degree and order 14.

(7) In 1971, DMAAC published 19,164 1° x 1° mean free-air gravity anomalies covering about 30 percent of the earth's surface. Some of these anomalies were predictions from gravity/geophysical correlation techniques. Ten years earlier, Uotila's publication also showed 30 percent. This emphasizes the slow growth of global gravity data acquisition coverage.

(8) In 1972 a NASA report prepared by CSC indicated 20,538 1° x 1° mean free-air gravity anomaly data were available from all over the world.

(9) As of July, 1972, the largest number of 1° x 1° mean free-air gravity anomalies available from DMAAC (the world's largest and most authoritative gravity data agency) is 23,946 or about 31 percent of the earth.

This is a brief survey of available gravity data and the slow rate of increase in global coverage with time. It was made because global coverage is a critical factor in assessing the capability of mean gravity anomaly sets to accurately represent the earth's gravitational field. The conclusion is that the rate of increase in global coverage and the existing coverage cannot in the foreseeable future satisfy the need to accurately represent the earth's gravitational field, using gravity data alone.

C.2.2 Accuracy of Gravity Data

Besides the extent of worldwide coverage, the report showed that large errors in observed as well as predicted gravity anomalies, which strongly influence the accuracy of gravitational field representation, exist. The accuracy of the DMAAC July, 1972, 1° x 1° mean free-air gravity information which contains all the best available, is as shown by the following rms values

Northern hemisphere	± 27 mgals
Southern hemisphere	± 20 mgals
Worldwide	± 24 mgals.

C.2.3 Gravitational Model Analysis

Earth gravitational field representation in the form of geopotential coefficient sets has been extremely popular in the last two decades. Since 1965, over 24 different models have been published. The models range in size from one of 44 coefficients by Kaula in 1966 to 326 coefficients in a 1972 GSFC model. DMAAC is preparing a 437 coefficient set. Data used in developing the models vary and include satellite Doppler and optical satellite tracking, surface gravity, geoidal undulation, etc., or various combinations of these data. Some of the developments also simultaneously solved for geodetic and earth physics parameters other than the geopotential coefficients. The weighting schemes and/or mathematical techniques used are as varied as the number of models. Data from different satellites of different altitudes and inclination affected the various solutions differently. The practice of preassigning values to certain coefficients, the number and locations of tracking stations providing data also influenced solutions using the various models. Some models had more data or more accurate data or improved mathematical techniques as experience increased.

To establish how well the different models represent the ture earth's gravitational field, each was used to derive other forms of gravitational field representation for independent comparisons.

C.2.3.1 Comparison of Terrestrial Mean Gravity Anomalies With Those Computed From Gravitational Models. Terrestrial gravity data represent the best standard against which to estimate the accuracy of earth gravitational models. Table C-1 shows the results from probably the best 14 models, expressed in terms of rms differences which ranged from ± 7 mgals to ± 20 mgals. Errors in the gravity data used as a standard were neglected. If not, these rms values would be nearly twice as large.

C.2.3.2 Comparison of a Conventional Geoid With Geoid Derived From Gravitational Models. The relative accuracy of earth gravitational models were inferred by calculating a geoid from each model and determining how well each geoid agreed with a standard geoid. A geoid based on surface gravity data, using Stokes' formula, as the standard was avoided because a gravimetric geoid demands a global coverage of accurate surface gravity data which has been shown to be nonexistent. An absolute geoid on a single datum was derived from the best existing astrogeodetic geoids through the application of necessary transformations, rotations, datum shifts, Molodensky corrections, and changes in reference ellipsoids. About 275 geoid spot heights located about 4 degrees apart in North America, Europe/Asia, and Australia were used in the comparison.

Table C-2 shows the results of the geoid comparisons. The rms differences relative to the standard geoid ranged from ± 13 m in Australia to ± 58 m in Europe/Asia. Other comparisons for geoidal heights at tracking stations showed even greater gross variability. Pronounced geoidal highs and lows, e.g., the Indian low, demonstrated great variability both in location as well as in undulation magnitudes, see Figure C-1.

The report states: "The fact that geoid heights from various gravitational models disagree to a considerable extent at individual points is of concern since accurate geoid height data is required for certain applications. ...it is safe to conclude that the present geopotential models do not represent the earth's true gravitational field to great accuracy." Gravitational components computed from different gravitational models at points

TABLE C-1. MEAN GRAVITY ANOMALY COMPARISONS (300x300 ±30 NM AREAS)

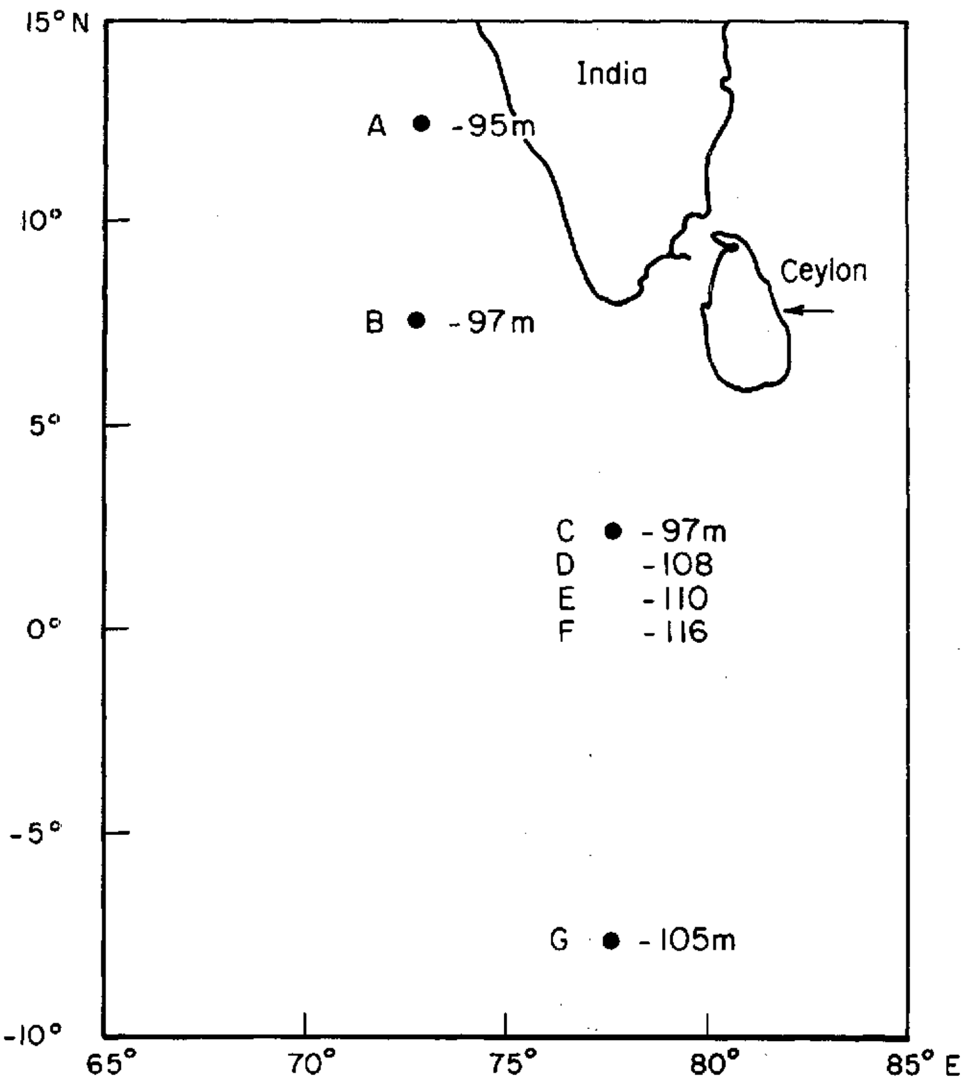
Observed minus those computed from gravitational models.

Gravitational Models		RMS Differences, mgals — Number of Observed 60x60 ±30 $\bar{\Delta g}$ Values Available in 300x300 ±30 NM Area: 25	≥20	≥10	≥1	Source of Data Used in Computation
Rapp	(OSU, 1972)	± 7.4	±10.1	±12.3	±13.4	Surface gravity
GSFC-C	(GSFC, 1972)	8.4	9.9	11.7	12.7	Optical/Electronic/Surface gravity
Kohnlein	(SAO, 1967)	9.7	11.1	12.3	12.6	Baker-Nunn Surface gravity
Gaposchkin	(SAO, 1969)	10.1	11.5	13.1	13.6	Baker-Nunn/Surface gravity/Laser
GSFC	(GSFC, 1972)	10.2	11.5	13.1	13.4	Optical/Electronic
Rapp-B	(OSU, 1968)	10.9	11.3	12.8	13.1	Baker-Nunn/Surface gravity/Topography
Gaposchkin-M1	(SAO, 1966)	11.0	12.6	13.8	13.7	Baker-Nunn
Witte-C	(NOS, 1971)	12.1	13.5	15.2	14.8	Doppler/Surface gravity
Koch	(Bonn, 1970)	12.5	13.0	15.4	15.7	Baker-Nunn/Surface gravity
Bjerhammar-C	(ETL, 1967)	12.7	13.2	13.9	13.7	Doppler/Baker-Nunn/Surface gravity
Kaula-CA	(UCLA, 1966)	13.7	14.1	14.3	13.7	Doppler/Baker-Nunn/Surface gravity
Kaula-C	(UCLA, 1966)	13.8	14.4	14.6	13.9	Doppler/Baker-Nunn
APL 5.0	(APL, 1972)	17.7	18.3	20.3	19.7	Doppler
Witte	(NOS, 1971)	19.0	20.0	20.4	18.9	Doppler
Number of Squares in Comparison		81	248	672	1249	

TABLE C-2. GEOID HEIGHT COMPARISONS BY GEOGRAPHIC AREA

Gravitational Models		RMS Differences Between N_{ag} (GRS 67) and N Calculated From Various Gravitational Models World-wide*	North America	Europe/ Asia	Australi
Koch	(Bonn, 1970)	±34.6m	±24.7m	±48.7m	±19.4m
Rapp	(OSU, 1972)	35.1	19.3	52.3	25.8
Witte	(NOS, 1971)	37.1	20.9	55.2	26.2
Witte-C	(NOS, 1971)	37.4	20.8	56.7	20.0
Gaposchkin-M1	(SOA, 1966)	38.0	25.4	55.2	16.6
GSFC-C	(GSFC, 1972)	38.2	23.1	57.1	17.2
GSFC	(GSFC, 1972)	38.6	23.1	58.0	16.4
Gaposchkin	(SAO, 1969)	38.7	24.9	57.2	15.9
Kaula-C	(UCLA, 1966)	38.9	26.5	56.6	14.0
Kohnlein	(SAO, 1967)	39.1	26.5	56.6	18.1
Kaula-CA	(UCLA, 1966)	39.8	29.1	56.1	18.2
Bjerhammar-C	(ETL, 1967)	40.0	30.0	56.3	13.3
APL 5.0	(APL, 1972)	40.3	31.1	54.7	24.4
Rapp-B	(OSU, 1968)	40.5	30.9	55.9	19.3

*Worldwide only in the sense that the rms geoid height differences in North America, Europe/Asia, and Australia were taken collectively.



A = Witte (NOS, 1971)
B = Witte-C (NOS, 1971)
C = Rapp (OSU, 1972)
D = GSFC-C (GSFC, 1972)
E = GSFC (GSFC, 1972)
F = Gaposchkin (SAO, 1969)
G = Koch (Bonn, 1970)

FIGURE C-1. VARIOUS GEOID HEIGHT VALUES - INDIA LOW in space were compared with one another. The report showed that "The differences were quite large and substantial enough in themselves to conclude that the earth's true gravitational field is not yet accurately modeled."

C.2.3.3 Comparison of Gravitational Components at Points on the Earth's Physical Surface. The extent of quantitative agreement between the magnitude of gravity determined from the earth's gravitational models and actual values observed at corresponding points on the earth's physical surface was investigated. Using the 14 gravitational models of Table C-1, the magnitude of gravitational force was calculated at each of 231 of the 1871 gravity base stations which form the International Gravity Standardization Network, 1971. The test sites were selected such that no 5° x 5° square had more than one site. An additional 106 gravity stations were randomly selected in various 20° x 20° blocks. Similar calculations of gravitational force magnitude and comparison with observed values were made at each of those sites.

All the gravitational models produced gross differences between the computed and observed values. The results of this type of comparison with the Gaposchkin (SAO, 1969) Gravitational Model, for example, are shown in Table C-3. Such large numerical differences reinforce the conclusions from the other tests "...that the present gravitational models due to accuracy and/or form limitations cannot systemmatically reproduce the gravity field at discrete points on the earth's surface..." to within ±50 mgals of the true values.

TABLE C-3. COMPARISON OF GRAVITY MAGNITUDES FROM SURFACE MEASUREMENTS WITH THOSE COMPUTED FROM THE GAPOSCHKIN (SAO, 1969) GRAVITATIONAL MODEL

	Gravity Magnitude Statistics, mgals			
Comparison Standard	Maximum Positive Difference	Maximum Negative Difference	Average of Absolute Differences	RMS Difference
IGSN 71 Gravity Base Stations (231)	286	-152	35	53
Gravity Stations (106)	291	- 71	40	66

The report justifies these comparisons and conclusions by stating:

"It may be claimed that the above comparison is unrealistic since satellite orbital analyses cannot be expected to define the detailed structure of the gravity field at or near the earth's physical surface because of the attenuation of the gravitational field at the sensing altitude of the satellite. In the same vein, it might be argued that from prior knowledge it is known that gravitational models containing a finite number of coefficients, such as those analyzed here, are incapable of accurately reproducing gravity magnitudes at points on the earth's surface. However, the comparison is valid from the standpoint that it is being made to establish how well (numerically) present gravitational models represent the earth's true field."

C.2.3.4 The Accuracy of Individual Geopotential Coefficients. There was no detailed analysis of the exactness of individual coefficients. Some of the reasons for omission of that analysis included the length of time required, the large numbers of models and coefficients to be considered, and the failure of the authors of gravitational models to determine or publish coefficient accuracy values. Most geopotential coefficient sets are derived from least squares solutions in which variable numbers of other parameters have been solved for 'simultaneously'. The number of gravitational and nongravitational parameters solved for does influence the magnitudes of individual coefficients and their variances and covariances which the authors do not publish.

However, the magnitude and accuracy of individual coefficients are important to the accuracy of gravitational field representation. The 1969 Kozai value for the 9th degree zonal harmonic coefficient is 4.5 times larger than his 1967 value. This discrepancy alone is enough to cause about 1 meter difference in geoid heights computed from spherical harmonic expansions in which Kozai's 1967 and 1969 values for $\overline{C}_{90}$ are the only changes. From model to model, coefficient magnitudes fluctuate even for recent representations and for coefficients such as $\overline{C}_{22}$ and $\overline{S}_{22}$ which are supposedly well determined. Various investigations, including analyses of gravity anomaly degree variances, performed on coefficient sets of the models in Table C-1 produced large disagreements, especially between the Gaposchkin (SAO, 1969), Rapp (OSU, 1972), Koch (Bonn, 1970), and Witte (NOS, 1971) gravitational models.

C.3.0 Conclusions

(1) The investigations were hampered by lack of any accurate independent standard for evaluating the different gravitational field representations.

(2) The report concluded that "...it is quite apparent from the numerical results presented (in 26 tables and 26 figures) that an accurate model of the earth's gravitational field does not exist today."

(3) The report posed several questions yet to be answered. How should the model be defined--is it from the standpoint of geophysics or geodesy/celestial mechanics? What form should the gravitational field take--spherical harmonics, mean gravity anomalies, point masses, or mean densities of a simple surface layer, etc.? Efforts to reach international agreement on surface element sizes for forming mean gravity anomalies encountered unexpected difficulties.

(4) To use surface gravity data for accurate representation of the earth's gravitational field requires a worldwide 5 x 5 arc-minute mean gravity anomalies, accurate to less than ± 3 mgals (1 σ). Geophysical and oceanographic needs require better than ± 1 mgal (1 σ) accuracy. Currently, only about 31 percent of the earth has 60 x 60 arc-minute data with an average 1 σ of ± 25 mgals. Accuracies estimates in the oceans range from ± 10 to over ± 100 mgals (1 σ). The oceans cover about 70 percent of the earth. At current and past rates of support for gravity data acquisition, 5 x 5 arc-minute global coverage with precise gravity observation is a very, very distant dream.

(5) If satellite altimetry and adequate incorporation of geodetic roles were implemented, the mapping, defense, oceanographic, geophysical, geodetic, and celestial mechanics needs for better representation of the earth's gravitational field could be met speedily and economically.

APPENDIX-D

REFERENCES

[1] Anonymous, "The Terrestrial Environment: Solid-Earth and Ocean Physics", Report prepared by MIT, NASA CR-1579, National Aeronautics and Space Administration, Washington, D. C., April, 1970.

[2] Anonymous, "Proceedings of Briefing to Industry--National Data Buoy Development Project, U.S. Coast Guard", Supplement Included, National Security Industrial Association, Washington, D. C., April, 1970.

[3] Anonymous, "Proceedings of the U.S. Coast Guard National Data Buoy Development Project Industrial Data Users Meeting", National Data Buoy Development Project, Washington, D. C., May, 1970.

[4] Anonymous, "Deep Sea Drilling Project - Ocean Sediment Coring Program", National Science Foundation, NSF 70-25, pp. 15, Washington, D. C., August, 1970.

[5] Anonymous, "Plan For U.S. Participation in The GARP Atlantic Tropical Experiment", National Academy of Sciences, pp. 25, Washington, C. C., 1971.

[6] Anonymous, "Proceedings of the 1971 OSTAC Annual Meeting and NOA/NSIA Symposium", National Security Industrial Association, Washington, D.C., June, 1971.

[7] Anonymous, "International Decade of Ocean Exploration", National Science Foundation, NSF 71-34, pp. 64, Washington, D. C., October, 1971.

[8] Anonymous, "Ocean Mining Comes of Age - Part 1", Oceanology International Offshore Technology, pp. 34-41, November, 1971.

[9] Anonymous, "Ocean Mining Comes of Age - Part 2, Oceanology International Offshore Technology, pp. 33-38, December, 1971.

[10] Anonymous, "SEDCO 445 Positioning System Now Operational", Ocean Industry, Vol. 7, No. 3, pp. 16-17, March, 1972.

[11] Anonymous, "Drillers Gear Up for Deeper Waters", Offshore, Vol. 32, No. 3, pp. 93-96, March, 1972.

[12] Anonymous, "The Federal Ocean Program", USGPO, pp. 121, Washington, D. C., April, 1972.

[13] Anonymous, "Oceanography Newsletter", Vol. VII, No. 13, May 15, 1972.

[14] Anonymous, "A Preliminary Oceanographic Program for GATE", National Academy of Sciences, National Research Council, pp. 61, July, 1972.

[15] Anonymous, "Heavy Metal Deposits Discovered in South Pacific", Ocean Industry, Vol. 7, No. 10, pp. 54-55, October, 1972.

REFERENCES
(Con't)

[16] Anonymous, "An Oceanographic Program for GATE", National Academy of Sciences, pp. 90, November, 1972.

[17] Anonymous, "Law-of-the Sea Conference Date Ste", Undersea Technology, Vol. 13, No. 12, p. 11, December, 1972.

[18] Anonymous, "Seminar - What's Ahead for Offshore Oil", Ocean Industry, Vol, 8, No. 1, pp. 19-30, January, 1973.

[19] Anonymous, "Gulf of Mexico Lease Sale", Ocean Industry, Vol. 8, No. 1, p. 30, January, 1973.

[20] Anonymous, "Dynamically Positioned Drillship Drills to 5,893 ft. in 1,300 feet Water", Ocean Industry, Vol. 8, No. 1, p. 36, January, 1973.

[21] Anonymous, "1972 AIDJEX Pilot Study", AIDJEX Bulletin No. 14, University of Washington, Seattle, Washington, July, 1972.

[22] Anderson, R. J., "Recent Developments in Offshore Mining", Paper No. OTC-1585, presented at Offshore Technology Conference, Houston, Texas, May 1-3, 1972.

[23] Beradelli, P. J., "International Politics Overshadows Drilling in Deep Waters", Offshore, pp 43-52, June 20, 1972.

[24] Booda, L. L., "NOAA Ocean Data Buoys", Under Sea Technology, Vol. 13, No. 6, pp 36-39, June, 1972.

[25] Bouina, A. H and Rezak, R., "Oil Found on Knolls on Gulf's Continental Rise", Ocean Industry, Vol. 4, No. 5, pp 73-77, May, 1969.

[26] Bryan, K. and Cox, M. D., A non-linear model of an ocean driven by wind and differential heating: Part I. Description of 3-dimensional velocity and density fields. Part II. An analysis of the heat vorticity and energy balance, J. Atmos. Science, 25, pp 945-978, 1969.

[27] Burg, K. E., "Marine Geodetic Problems of Industry and Commerce", Proceedings of First Marine Geodesy Symposium, Columbus, Ohio, September 28-30, 1966, pp 55-60, USGPO, 1967.

[28] Busby, R. F., Hunt, L. M. and Rainnie, W. O., "Hazards of the Deep", Part 2, Ocean Industry, Vol. 3, No. 8, pp 32-39, August, 1968.

[29] Clewell, D. H., "A Government/OSTAC Workshop on Marine Mapping, Charting and Geodesy", held at National Bureau of Standards, 27-28 October, 1969, National Security Association, August, 1970.

REFERENCES
(Con't)

[30] Cohen, P. M., "Definition of Geographic Accuracies for Various Marine Tasks," Proceedings of a Second Symposium on Marine Geodesy, 3-5 November, 1969, pp. 13-17, Marine Technology Society, Washington, D. C., 1970.

[31] Collins, C. A., Wilson, W. S. Carlmark, J., Merrell, W. J. and Arnett, T. P., "The North Pacific Experiment Probes Weather Phenomenon", Marine Technology Society Journal, Vol. 7, No. 1, pp. 10-13, January-February, 1973.

[32] Decker, B. L., "Present Day Accuracy of the Earth's Gravitational Field", presented at the International Symposium on Earth Gravity Models and Related Problems, Defense Mapping Agency Aerospace Center, St. Louis Air Force Station, Missouri, August, 1972.

[33] Doumani, G. A., "Exploiting the Resources of the Seabed", prepared for the Subcommittee on National Security Policy and Scientific Developments of the Committee on Foreign Affairs, U.S. House of Representative, pp. 1552, USGPO, Washington, D. C., 1971.

[34] Ewing, M., Horn, D., Sullivan, L., Aitken, T. and Thorndike, E., "Photographing Manganese Nodules on the Ocean Floor", Oceanology International, pp. 27-32, December, 1971.

[35] Fischer, I., Shirley, F. R. and Todd, S., "Specific Practical Applications of Satellite Geodesy", Surveying and Mapping, Vol. 30, No. 4, pp. 541-551, December, 1970.

[36] Flipse, J. E., "Ocean Mining --The Sleeping Giant", Under Sea Technology, Vol. 13, No. 1, p 37, January, 1972.

[37] Flipse, J. E., "Ship Launchings Highlight Active Year in Ocean Mining", Under Sea Technology, Vol. 14, No. 1, pp. 21-22, January, 1973.

[38] Frazier, N. A. and Buttner, F. H., "Activities and Developments in the U.S. Continental Shelf Regions--Motivations for Marine Geodesy", Proceedings of First Marine Geodesy Symposium, September 28-30, 1966, pp. 249-254, USGPO, Washington, D. C., 1967.

[39] Freeman, N. W., "Capital Report - Freeman Lays it on the Line", Under Sea Technology, Vol. 13, No. 6, pp. 22-23, June, 1972.

[40] Fubara, D. M. & Mourad, A. G., "Requirements for a Marine Geoid Compatible with Geoid Deducible from Satellite Altimetry", Proceedings of NOAA/NASA/NAVY Conference on Sea Surface Topography from Space, Key Biscayne, Florida, October 6-8, 1971, NOAA Technical Report ERL 228-AOML 7, J. R. Apel, Editor, USGPO, Washington, D. C., February, 1972.

REFERENCES
(Con't)

[41] Fubara, D. M. and Mourad, A. G., "Non-Classical Determination of Spatial Coordinates of Ocean Bottom Acoustic Transponders', paper presented at the Fifty-Second Annual Meeting of the American Geophysical Union in Washington, D. C., April, 1971, to be published in Bulletin Geodesique, 1973.

[42] Fubara, D. M. and Mourad, A. G., "Marine Geodetic Control for Geoidal Profile Mapping Across the Puerto Rican Trench", Report Prepared by Battelle's Columbus Laboratories, to NASA Wallops Station, under Contract Number NAS6-2006, April, 1972.

[43] Fubara, D. M. J. and Mourad, A. G., "Geodetic Determination of the Geoid from Satellite Altimetry", Paper presented at the 8th Annual Conference and Exposition, Marine Technology Society, September 11-13, 1972.

[44] Garland, C. and Hagerty, R., "Environmental Planning Considerations for Deep Ocean Mining", Preprints, 8th Annual Conference and Exposition, Marine Technology Society, pp. 381-393, Washington, D. C., September 11-13, 1972.

[45] Gealy, E. L. and Davies, T. A., "The Deep Sea Drilling Project", Geotimes, Vol. 14, No. 2, pp. 10-12, February, 1969.

[46] Greenwood, J. A., Nathan, A., Nuemann, G., Pierson, W. J., Jackson, F. C., and Pease, R. E., "Radar Altimetry from a Spacecraft and its Potential Applications to Geodesy", Remote Sensing Environment 1, pp. 55-70, 1969.

[47] Horn, D. R., Ewing, M., Horn, B. M., and Delach, M. N., "World-Wide Distribution of Manganese Nodules", Ocean Industry, Vol. 7, No. 1, pp. 26-29, January, 1972.

[48] Howe, R. J., "Petroleum Operations in the Sea--1980 and Beyond", Ocean Industry, Vol. 3, No. 8, pp. 25-31, August, 1968.

[49] Ikard, F. N., "Oil Industry Urges More Offshore Leases", Under Sea Technology, Vol. 14, No. 1, p 21, January, 1973.

[50] Jennings, F. D., "IDOE Starts Major Ocean Research Projects", Under Sea Technology, Vol. 14, No. 1, pp. 23-24, January, 1973.

[51] Jones, D. A., "Seaward Boundary Determination", Proceedings of a Second Symposium on Marine Geodesy, 3-5 November, 1969, pp. 265-274, Marine Technology Society, 1970.

REFERENCES
(Con't)

[52] Jones, G. E. and Sheriff, R. E., "Marine Positioning for the Petroleum Industry", Proceedings of A Second Symposium on Marine Geodesy, 3-5 November 1969, pp. 215-223, Marine Technology Society, Washington, D. C., 1970.

[53] Jury, H. L., "Marine Geodesy and Navigation at the Air Force Eastern Test Range", Proceedings of A Second Sumposium on Marine Geodesy, 3-5 November, 1969, pp. 89-99, Marine Technology Society, Washington, D. C., 1970.

[54] Kaula, W. M., "Application of Space and Astronomic Techniques to Solid Earth and Ocean Physics", Advances in Dynamic Gravimetry, Edited by W. T. Kattner, p. 130, Instrument Society of American, Pittsburgh, Penn., 1970.

[55] Kaula, William, M., "Solid Earth and Ocean Dynamics - Why Don't the Engineers Respond to the Needs in this Attractive Field?", Reviews of Space Science, Astronautics and Aeronautics, pp. 19-23, July, 1971.

[56] Kivioja, L., "Significance of Open-Ocean Gravity Base Stations and Calibration Lines", Proceedings of First Marine Geodesy Symposium, Columbus, Ohio, September 28-30, 1966, pp. 75-76, USGPO, Washington, D. C., 1967.

[57] Knowles, T. C. and Roy, R. E. Jr., "Geodetic Survey of Deep Ocean Acoustic Transponder Arrays and Evaluation of Recovered Ship Locations", Systems Performance Analysis Directorate, Western Test Range Division, Federal Electric Coporation, pp. 17, December, 1972.

[58] Luehrmann, W. H., "The High Cost of Offshore Exploration", Oceanology International, pp. 24-29, October, 1971.

[59] Macomber, M., "Requirements and Views of DoD in Marine Geodesy", Proceedings of First Marine Geodesy Sumposium, Columbus, Ohio, September 28-30, 1966, pp. 51-54, USGPO, Washington, D. C., 1967.

[60] Maro, J. L., "The Mineral Resources of the Sea", Elsevier Publishing Company, pp. 312, Amsterdam-London-New York, 1965.

[61] Maykut, G. A., Thorndike, A. S. and Untersteiner, N., "AIDJEX Scientific Plan", AIDJEX Bulletin, No. 15, University of Washington, Seattle, Washington, August, 1972.

[62] McKelvey, V. E., Tracey, J. I., Stoertz, G. E. and Vedder, J. G., Subsea Mineral Resources and Problems Related to Their Development," Geological Survey Circular 619, pp. 26, Washington, D. C., 1969.

REFERENCES
(Con't)

63] Moore, N. H., Ray, H., Hunt, W. H., Wilson, R. O. and Posgate, J.C., Industry Leaders Discuss Trends and Problems of Offshore Oil", Ocean Industry, Vol. 7, No. 1, pp. 19-40, January, 1972.

64] Mourad, A. G., and Frazier, N. A., "Improving Navigational Systems Through Establishment of a Marine Geodetic Range", Journal of the Institute of Navigation, Vol. 14, No. 2, pp. 187-194, Summer, 1967.

65] Mourad, A. G., "Marine Geodesy and Its Role in Expanding Marine Resources", The Encyclopedia of Ocean Resources, F. Firth, Editor, Reinhold Publishing Corp., pp. 383-389, 1969.

66] Mourad, A. G., et al., New geodetic marker. EOS, Trans. Amer. Geophys. Union, Vol. 50, No. 4, p. 104, see also p. 119, 1969.

67] Mourad, A. G., Frazier, N. A., Holdahl, J. H., Someroski, F. W., and Hopper, A. T., "Satellite Applications to Marine Geodesy", Final Report to NASA/OSSA under Contract No. NASr-100(11), prepared in 1968 by Battelle Memorial Institute Columbus Laboratories, NASA CR-1253, pp. 146, January, 1969.

68] Mourad, A. G., Holdahl, J. H., and Frazier, N. A., "Preliminary Results of the Establishment of a Marine Geodetic Point in the Pacific Ocean", Marine Technology Society, Marine Geodesy, pp. 39-54, and Bulletin Geodesique, pp. 107-124, No. 96, June, 1970.

69] Mourad, A. G., Hopper, A. T., Fubara, D. M., and Ruck, G. T., "Acoustic Data Reduction and Calibration for the GEOS-II C-Band Radar Marine Geodesy Experiment in the Bahamas", Proceedings of GEOS-II Program Review Meeting, Vol. III, pp. 167-188, 22-24, June, 1970, Edited by CSC, NASA, November, 1970.

70] Mourad, A. G., "New Techniques for Geodetic Measurements at Sea", Trans. Amer. Geophys. Union-EOS, Vol. 51, No. 12, pp. 864-873, Dec., 1970.

71] Mourad, A. G., Fubara, D. M., Hopper, A. T. and Ruck, G. T., "Geodetic Location of Acoustic Ocean - Bottom Transponders from Surface Positions", EOS, Transaction American Geophysical Union, Vol. 53, No. 6, pp. 644-649, June, 1972.

72] Mourad, A. G. and Fubara, D. M., "Interaction of Marine Geodesy, Satellite Technology and Ocean Physics", Report prepared by Battelle's Columbus Laboratories for NASA Wallops Station under Contract NAS6-2006, pp. 97, June, 1972.

73] Nygren, H. D., RAdm., "Opening Remarks: Mrine Law and Marine Boundaries", Proceedings of A Second Symposium on Marine Geodesy, 3-5 November, 1969, p. 255, Marine Technology Society, Washington, D. C., 1970.

REFERENCES
(Con't)

[74] Padan, J. W., "Ocean Mining Begins to Compete with Land Sources", Under Sea Technology, Vol. 12, No. 1, p. 31, January, 1971.

[75] Phillips, O. M., "The Dynamics of the Upper Ocean", Cambridge University Press, London, pp. 261, 1966.

[76] Putzke, S. C., "Marine Positioning-The Now and the Need", Proceedings of A Second Symposium on Marine Geodesy, 3-5 November, 1969, pp.5-11, Marine Technology Society, Washington, D. C., 1970.

[77] Roby, R. N., "An Environmental Analysis of A Simulated Sea-Floor Mining Operation", Preprints, 8th Annual Conference and Exposition, Marine Technology Society, pp. 375-380, Washington, D. C., September 11-13, 1972.

[78] Roels, O. A., Amos, A. F., Garside, C. and Malone, T. C., "The Environmental Impact of Deep Sea Mining", Preprints, 8th Annual Conference and Exposition, Marine Technology Society, pp. 369-373, Washington, D. C., September 11-13, 1972.

[79] Ruck, G. T., Barrick, D. E. and Kaliszewski, T., "Bistatic Radar Sea State Monitoring", Report prepared by Battelle, Columbus Laboratories for NASA Wallops Station under Contract NAS6-2006, June, 1972.

[80] Sheriff, R. E., "The Requirements and Problems of Navigation For Geophysical Exploration", Paper to be Presented at Symposium on Offshore Positioning for Petroleum Exploration and Production, Offshore Technology Conference, Houston, Texas, May, 1973.

[81] Stanley, H. R., "Puerto Rico Trench Experiment", NASA Wallops Station, pp. 9, 1971.

[82] Stommel, H. M., "The Gulf Stream." Univ. California Press, Berkeley, pp. 248, see pp. 19, 158-172, 177, 1965.

[83] Stommel, H. M. et al., "Summer Study Program in Geophysical Fluid Dynamics", Woods Hole Oceanographic Institute, Ref. No. 68-72, 1968.

[84] Sturges, Wilton, "Ocean Circulation with Regard to Satellite Altimetry", Proceedings of NOAA/NASA/Navy Conference on Sea-Surface Topography from Space, Key Biscayne, Florida, October 6-8, 1971, NOAA Technical Report ERL 228-AOML 7, J. Apel, editor, USGPO, February, 1972.

[85] Sverdrup, H. U., "On the Explanation of the Oxygen Minima and Maxima of the Oceans", J. Conseil Intern. Explor. Mer., 13, pp. 163-172, 1938.

REFERENCES
(Con't)

[86] Taylor, D. M., "North Sea Report - Overview", Ocean Industry, Vol. 8, No. 2, pp. 61-63, February, 1973.

[87] Thomas, O. D., "North Sea Oil Boom", Ocean Industry, Vol. 7, No. 3, pp. 12-15, March, 1972.

[88] Von Arx, William S., "Relationship of Marine Physical Geodesy to Physical Oceanographic Measurements", Proceedings of First Marine Geodesy Symposium, Columbus, Ohio, September 28-30, 1966, pp. 37-42, USGPO, Washington, D. C., 1967.

[89] Von Arx, William S., "Marine Geodesy", Volume 4, Part 1, of The Sea, Wiley-Interscience, pp. 597-635, 1970.

[90] Walter, E. A., "Gulf of Mexico...Giant Deep-Water Oil Province of Future?", Ocean Industry, Vol. 4, No. 5, pp. 68-72, May, 1969.

[91] Walthier, T. N., "Mining Panel Report", Proceedings of OSTAC Annual Meeting and NOA/NSIA Symposium, PP. IV-34-46, State Department, Washington, D. C. 2-3, June, 1971.

[92] Jones, D. A., "Plans and Programs of the U.S. Coast and Geodetic Survey", Proceedings of First Marine Geodesy Symposium, Columbus, Ohio, September 28-30, 1966, pp. 65-68, USGPO, Washington, D. C., 1967.