MARINE GEODESY
A MULTIPURPOSE APPROACH
TO SOLVE OCEANIC PROBLEMS

by

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PREFACE

This project is under the supervision of Professor Ivan I. Mueller, Department of Geodetic Science, The Ohio State University, and the technical direction of Mr. James P. Murphy, Special Programs, Office of Applications, Code ES, NASA Headquarters, Washington, D. C. The contract is administered by the Office of University Affairs, NADA, Washington, D. C. 20546.

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ABSTRACT

This study aims at identifying various current and future problem areas of marine geodesy. These oceanic problem areas are highly diversified and include submersible navigation under iced seas, demarcation and determination of boundaries in deep ocean, tsunamis, ecology, etc., etc. Their achieved as well as desired positional accuracy estimates, based upon publications and discussions, are also given. A multipurpose approach to solve these problems is described. Finally, an optimum configuration of an ocean-bottom control-net unit is provided.

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1. INTRODUCTION

Since this study is conducted to evaluate the feasibility and to discuss the possible contributions of geodesy to oceanic problems of the Earth and Ocean Physics Application Program (EOPAP), the correlation of some specific points of this study with EOPAP [Anon, 1972b, pp. 1.1, 2.38-2.50, 3.18-3.19] will be mentioned below:

(1) According to EOPAP [Anon, 1972b, p. 2.38], there will be an increased need within the next decade to explore and exploit the world's oceans as the known reserves of resources on land and on continental shelf are exhausted. The fact that the nations of the world, through the Unite Nations, have recognized the need to establish international laws, regulations, and management policies for the open oceans, will be a circumstantial interest in reliable and accurate surveying in ocean areas. The specific problems, which we face in the open ocean, are dealt in section 2 of this study.

(2) One of the objectives of EOPAP is the refinement of the global geoid and the extension of the global geodetic control to inaccessible areas including the ocean floor, with a position accuracy of ±10m horizontally and ±1m vertically [Anon, 1972b, p. 2.39; Murphy and Williams, 1974, p. 6]. A conceptual and practically realistic approach to achieve this basic objective of EOPAP is given in section 3 of this study.

It is worth mentioning here that one of the objectives of the Geodesy Program of North American Datum Study concerns marine geodesy, which involves determining gravity at sea and establishing geodetic control for ocean studies and exploitation, particularly on the continental shelves. Due to insufficient funds a program for geodetic control at sea could not be still developed [Anon, 1971, p. 44-45].

During the discussions at the recently held International Symposium on Applications of Marine Geodesy, Columbus, Ohio, June 3-5, 1974, a need

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for better positioning in the ocean was repeatedly mentioned by Blankenburgh, Douglas, Ingram, Orlin, Siapno, Treadwell, and this author.

Since over a decade scientists have been involved with precise location of stations in the oceans for obtaining gravimetric, geophysical and oceanographic data. The first published paper, proposing a method for the establishment of such station, is the result of the research done at Lamont Geological Observatory [Ewing, et al. 1959, pp. 7-21]. Ewing called such stations as "Geodetic bench marks at sea", which were established by using the SOFAR sound transmission, by which the high geodetic accuracy could not be achieved. George Mourad [1965, p. 5-10] proposed a geodetic method for establishing the ocean-bottom bench marks, by using satellites, EDM - and sonar instrumentation. As sonar instrumentation is the only way for underwater measurements, Mourad introduced a new term "marine geodesy" to differentiate it from the classical geodesy. As we will see later in sections 3 and 4 that to solve most of the problems, precisely located stations on the ocean-bottom are needed, which could be considered partial or local "geodetic" nets, thus the term marine geodesy appears to be very appropriate. We would _define_ marine geodesy as the science which defines and establishes control-points in and/or on ocean, and the shape of the ocean, including its floor.

Professor Michele Caputo [Private Communication, July 3, 1974] also emphasizes that Marine Geodesy should really be a new branch of geodesy, and should not be considered as extension of land geodesy to the sea as is often understood, which supports the above definition of marine geodesy.

2. PROBLEM AREAS AND ACCURACY ESTIMATES

The problem (application) areas could be classified either according to the physical aspects of the ocean (on the oceanic surface or within oceanic water) or according to the scientific and practical needs. The following scientific problem areas have been partially mentioned in many publications

[Anon, 1972b; Kaula, 1969; Loomis, 1972; Mourad and Fubara, 1972]:

    a. Topography and Mapping
    b. Positioning and Navigation
    c. Boundary Demarcation and Determination
    d. Sea-level Slope Determination
    e. Tsunami Warning System
    f. Recovery of Underwater Objects and Equipment
    g. Ecology
    h. Gravity Measurements at Ocean floor
    i. Ground Truth and System Calibration

It is worth mentioning here that our effort will be concentrated on the subsurface (underwater) problems.

a. Topography and Mapping. As the resources of the ocean bottom become more developed, the need for an extensive survey of its topography increases. Projections indicate that by 1980 a third of the oil production – four times the present output of 6.5 millions barrels a day – will come from the oceans [Anon, 1969, p. 85]. Further for laying cables and oil pipe-lines, for emplacing geophysical and geodetic station at the ocean floor, for determining the dump-sites and new land acquisition (similar to Hawaii Experiment to acquire land from the ocean for airport expansion), and for bathymetric navigation a reasonably good knowledge of ocean-bottom topography is necessary. How far are the oceans mapped can be realized from the following statement [Cohen, 1970, p. ix]: "When a student recently requested a government agency to send him "a map of the uncharted areas of the Pacific," he received exactly that--a graphic based on extremely sparse and dated information. It is deplorable and dangerous fact that this situation still exists in vast areas of ocean. For much of the Pacific, the most recent source of information is the United States Exploring Expedition which Lieutenant Charles Wilkes led in 1838."

Clautice and Sheets [1973, p. 471-473] mention the discrepancy concerning the topography of certain parts of the Arctic on existing charts. The problem of chart accuracy can be solved by proper surveying. Once the need is established, available survey techniques could provide accuracies well within

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± 10 m.

A relatively new technique - Sonar Holography - might be a future way to map the ocean bottom [C. Elachi, Personal Communication, February 7, 1974].

b. **Positioning and Navigation.** Positioning and navigation constitute the base for marine geodetic work. Basically, a navigation system enables a user to determine his position with respect to a reference point/system. The user may need to fix his position for various reasons: general navigation (avoidance of hazards, collision avoidance, etc.), relocating fishing grounds or mineral resources, laying and repairing of pipe-lines cables, dredging and mining, demarcation and determination of boundary limits, search and rescue, etc., etc. Positioning and navigation can be divided into the following three catagories:

(i) **General Navigation (Long Range).** This includes ships and other vehicles on the ocean surface. The lack of a sufficiently accurate navigation system could be realized by the number of collisions and groundings, the later may be due to poor positioning and/or due to lack of a good ocean bottom topography information. In the North Atlantic during the four fiscal years 1969-72 there were an estimated of 14-20 collisions and groundings on the high seas compared to 104 in the offshore area. [Haislip and Goldsmith, 1973, p. 11]. It appears that with the implementation of Loran-C the accuracy requirements in the coastal confluence zone (*) would be met. Loran-C system would be implemented in four annual phases starting in Fiscal Year 1975 [Haislip and Goldsmith, 1973, p. 11]. Accuracy of Loran-C, which provides continuous and in real-time positioning during all weather conditions, is ±40 m up to 2200 km [Vogeler, 1973, p. 67], but according to Treadwell

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(*) For definition of Coastal Confluence Zone refer to [Anon, 1972d, p. 1-4].

[Personal Communication, July 16, 1974] it is only ±75-100 m up to 1000 km. Thus even the navigational requirements for certain fishing "boats" of ±45 m may be met by Loran-C system, as these boats are used up to 480 km off coast in up to 450 m depths [Anon, 1972d]. It appears that the problem of achieving the desired navigational and positional accuracy within the coastal confluence zone will be met by Loran-C system.

Yet remains the problem of achieving high positional/navigational ac-curies on high seas. The association representing the deep-sea merchant ships has not yet come up with a definite position on navigation requirements; but most likely their conclusion will be for a system to enable a continuous positioning to an accuracy of at least ±180 m in all areas (global) [Fiore, 1973, p. 20]. There exist no individual navigational system which could satisfy this requirement on a global and continuous basis. Figures 1 and 1a, prepared by Mr. B. Van Gelder, represent accuracy vs. coverage for various existing navigation systems. It is anticipated that the Global Positioning System (GPS) would provide global, continuous and in real-time coverage with a positional accuracy of a few feet by 1985.

The search for minerals and oil has extended from continental shelves to deep ocean. The potential oil deposits in the South Atlantic Ocean and Gulf of Alaska are up to 650 km off coast and up to 4500 m depth [Davin, 1974, p. 2; Thurnheer, Personal Communication, July 17, 1974]. According to Thurnheer and Blakenburgh [Personal Communication, June 6, 1974], there is no system to provide accurate positioning for the needs of oil industry in open ocean; the absolute accuracy requirement is ±10-30 m. Similar accuracy requirements for mining in deep sea was mentioned in [Siapno and Zahn, 1974]. According to H. Ingram (Personal Communication, June 5, 1974], the desired accuracy for pipeline work is ±1-2 m, planned accuracy is ±3-4 m but achieved accuracy today is ±15 m within 150 km offshore and up to 60 m depth. The future potential areas for pipeline work are in open ocean up to 300 m depth with a desired positional accuracy of ±1-2 m.
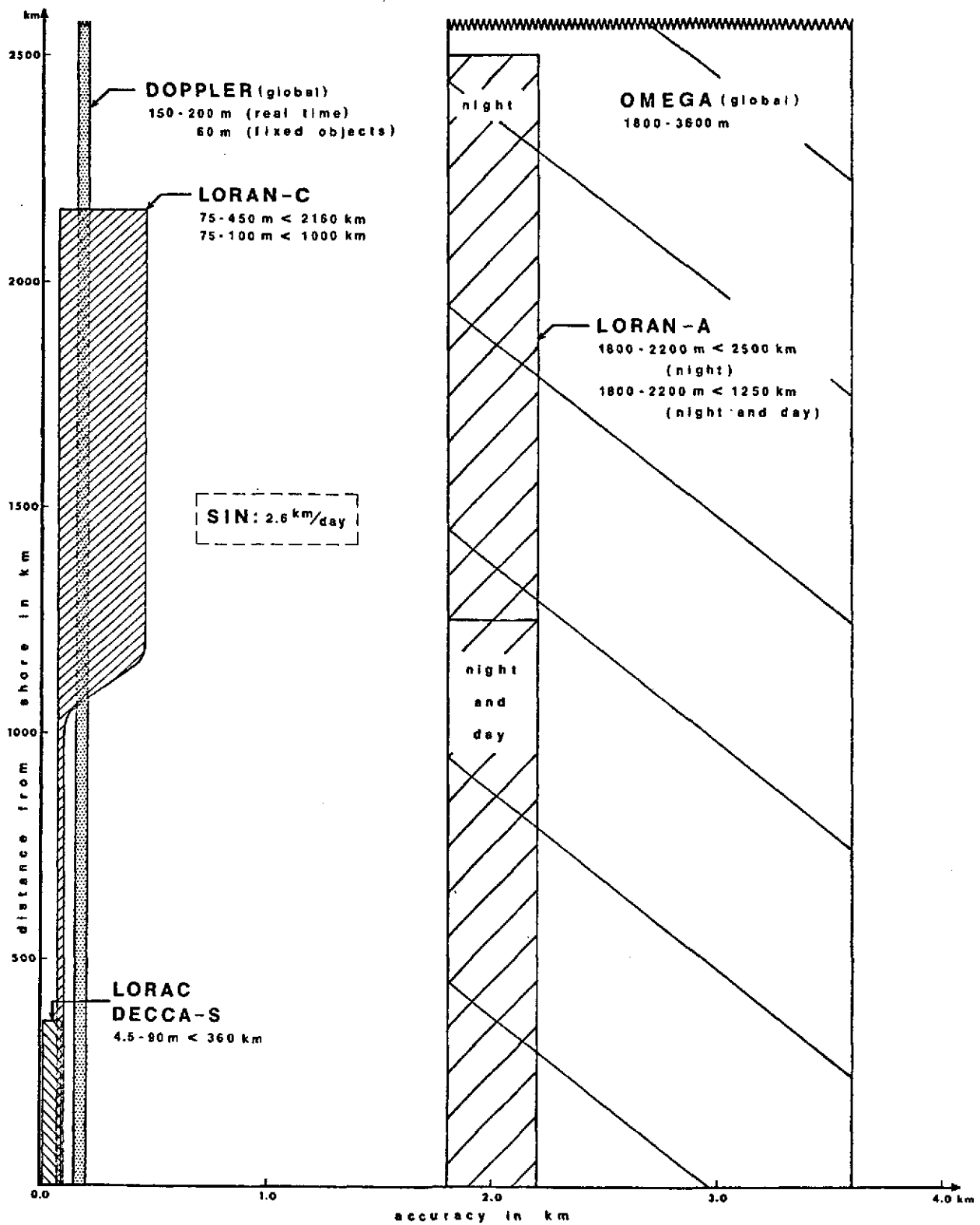
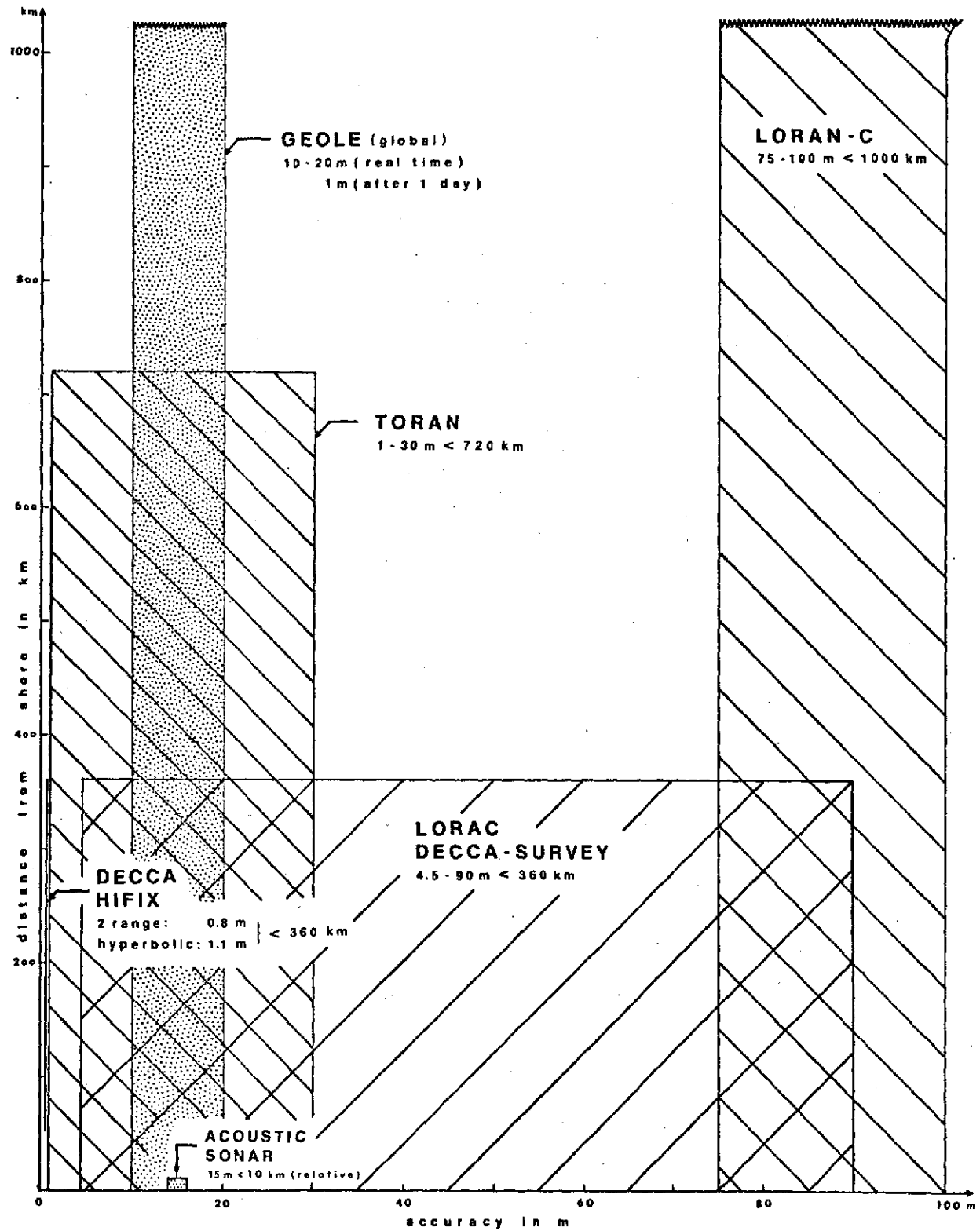Figure 1. Accuracy vs coverage of surface navigation system.

Figure 1a. Accuracy vs coverage of navigation system.

(ii) <u>Submersible Navigation (short range)</u>. The short range submersibles are used for underwater research, for multipurpose exploitations on the continental shelf and deep oceans. These small vehicles are usually battery operated, and are brought to the work-area from where they initiate their operation. Their navigation system is limited within 5 mile range with capability of pinpointing their position to ± 1 foot in each of the three dimensions of movements; this ± 1 foot accuracy is with respect to local control.

To achieve this accuracy three basic types of devices are used: sonar doppler system to obtain speed and distance, sector display system for passive target location and general collision warning, and sonar buoys for position fixing. The last system using sonar buoys is of interest to us. The conventional position determination underwater is done by emplacing three transponders on the ocean-bottom, whose known positions along with sonar range data are used to determine the unknown position of the submersible. Details of this system and its drawbacks will be dealt with in section 3.

(iii) <u>Submersible Navigation (long-range)</u>. To this group belongs the submarines (Polaris i.e., missile and non-missile) and the submarine cargo tankers. The systems used for submarine navigation include 3 SINS (ship's inertial navigation system), Doppler and Loran-C. Due to the lack of precise information regarding submarine navigation, which is a classified area, let us evaluate the accuracies of the above-mentioned systems.

Although SINS is a self-contained system, which needs no external reference, its accuracy is low, caused by an inertial drift of 108 m/hr which is accumulative with respect to time. To update SINS, Doppler observations are regularly made by "popping up" the doppler pole antenna over the ocean surface after a few days, and also continuous positioning is done using Loran-C floating antenna, which always remains on the ocean surface. The positional

accuracies obtained by Doppler (Navy Navigation Satellite) is ±180 m and by Loran-C ±75-100 m up to 1000 km, which decreases sharply beyond 1000 km. As such the total accuracy of submarine navigation can not be better than ±180 m up to 1000 km, beyond which the accuracies decreases to ±8-25 km [Beck, 1971, p.48-50].

These accuracy estimates might be satisfactory for long-range submarine navigational requirements so far as they can obtain measurements from Loran-C and Doppler. But the problem remains for the following two submarine navigational needs:

1. Submarine navigation under ice-capped oceans, where one has to depend only upon the SIN-systems, which have a drift rate of 2.6 km/day. To update SINS under iced seas, the only possible way is sonar navigation by providing ocean-bottom transponders along the desired route. Such a technique could open an easy and fast way of transporting oil from the North Slope of Alaska. In this context two studies are of importance: [Clautice and Sheets, 1973; Lassiter and Devanney, 1970]. The M.I.T. study [Lassiter and Devanney, 1970] deals with the economics of Arctic Oil transportation and compares costs involved by tankers (ice-breaking) vs. pipelines whereas [Clautice and Sheets, 1973] compares various navigational modes of submarine tankers for transporting Arctic oil.

2. Short range submersible navigation beyond 1000 km off coast. As the short range submersible is brought to the work-area due to its limited 8 km range navigation system, their "carriers" - the long-range submersibles - should have their positional accuracy within ±8 km when they are beyond 1000 km. This is however not the case. Thus we require better navigational system at least for those long-range submersibles which cooperate with short-range submersibles.

c. Boundary Demarcation and Determination. The boundary demarcation could be either for national, international or commercial purposes. Inter-

national boundary limits, which include national limits, for territorial seas and fishing jurisdiction are mostly within 12 n. m from the coastal line, seldom up to 200 n. m [Anon., 1972a, pp. 118-121]. Boundary determination and demarcation up to 12 n. m from the coast can be done by using EDM-Instrumentation. The demarcation in free ocean, such as 200 n. m limits, remains an unsolved problem.

Further continental shelves/slopes and free oceans are being searched for mineral resources and fuel (gas and oil). As the existing port facilities are inadequate for huge oil tankers, plans are to construct super-ports in the ocean far away from the crowded not-deep enough coastal area. Recommended are construction of large nuclear power plants in the ocean for the ocean will serve as the logical coolant [Shoupp, 1973]. A nuclear power plant is under consideration for Pacific Ocean - off the California Coast [Hwang, February 7, 1974 - Personal Communication]. All these developments make the ocean very valuable. To accomodate all these groups interested in getting their share of ocean, it should be divided in cells and leases granted to the interested group. Leasing of cells involves legal definition of underwater boundaries and their practical demarcation becomes necessary specially when the lease bid from the oil industry went as high as $27,400 per acre [Anon., 1970a, p. 215]. According to Jones and Sheriff [1970, p.219]. an accuracy of ± 25 feet is satisfactory for practically all work performed in the development of an offshore oil field. In deep-ocean after 100 miles from the coast this accuracy is not yet available, though perhaps technologically feasible.

Thus the situation remains the same whether the boundary determination is for oil exploration, for superport site or for nuclear power plant site. Due to the high leasing costs the boundaries in the oceans have to be determined accurately up to ± 10 m.

d. <u>Sea-Level Slope Determination.</u> The oceanographic results,

on both the Pacific and Atlantic Coasts of the U.S., indicate a slope downward to the north, with the large magnitude on the Atlantic Coast. Whereas U.S. Leveling Net. adjustment of 1963 indicate a rise in sea-level from south to north, with a slope of 2.8×10^{-7} on both sides [Sturges, 1974 p. 90]. A discrepancy of about 1 m exists between geodetic and oceanic leveling in north-south direction.

If a $\pm$ 10 cm accuracy could be achieved in determining the ocean depth at a particular point, i.e., between the ocean surface and the ocean-bottom transponder, the discrepancy between the geodetic and oceanic levelling could be resolved.

Once the three-dimensional position of the ocean-bottom transponders is known, change of water column height with an accuracy of $\pm$ 1 mm could be measured by the water-pressure sensor [Loomis, 1972, p. C-15]. Thus the average sea-levels for certain stations on the Pacific and the Atlantic coasts could be determined, from which the comparison of geodetic and oceanic levelling results can be made.

e. Tsunami Warning System. Tsunamis are long sea waves, which are generated by a sudden vertical faulting (shift) of the sea-floor associated either by an earthquake with its hypocenter (focus) beneath the sea bed (Figure 2, or by a submarine landslide caused by an earthquake with its epicenter possibly on land (Figure 3).

The abrupt vertical displacement of the sea floor is transmitted to the sea surface as a crest or a trough. The wave then propagates in all directions across the entire ocean basins with a speed, which is a function of water depth, given by $\sqrt{g.h}$, where h = water depth. In the open ocean 1000 meter deep, a tsunami wave will have the speed of 100 m/sec and the wave height is limited to a few meters, normally a few tenths of a meter according to [Bullen, 1963, p. 319-20; Loomis, 1972, p. C-9 to C-10]; and about 30 cm [Zetler, 1972, p. 26-22], but the principal wave-length may be of the order of some hundreds of kilometer, and the principal wave-period
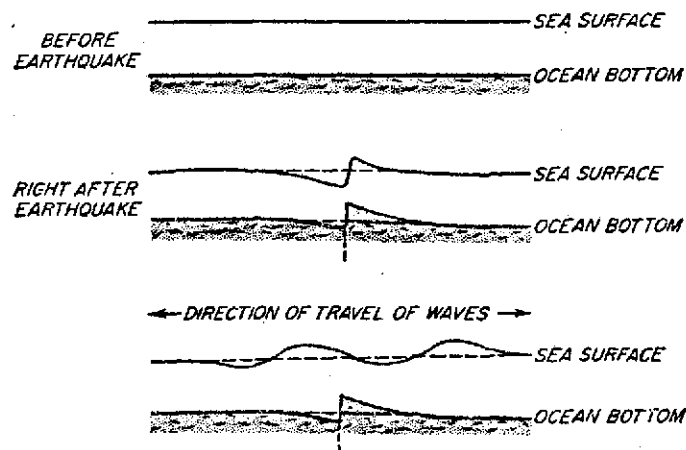
Fig. 2   Schematic diagram showing the theory of the formation of a tunami by faulting of the sea floor. Waves spread in both directions from the location of the fault. Vertical scale greatly exaggerated.
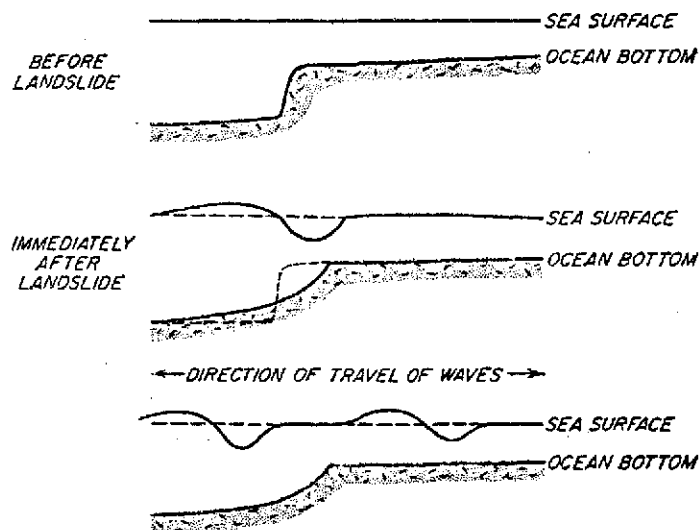

Fig. 3   Schematic diagram showing the theory of the formation of a tunami by a submarine landslide. Vertical scale greatly exaggerated.

(Figures taken from [Howell, 1959])

of the order of some tens of minutes [Bullen, 1963, p. 319].

As these waves approach the coastal slopes, the wave-length decreases and the amplitude increases, building up to destructive heights. In U- and V- shaped inlets the tsunami wave can reach a height of the order of 20-30 meters with an on-rush speed of above 10m/sec (36 km/hr).

Destructive tsunami waves have been almost entirely restricted to the Pacific Ocean where 90 to 95% have occurred [Loomis, 1972, p. C-10]. They have tended to be generated in approximately 15 specific seismic areas in the approximately 36,000 mile earthquake and volcanic belt circumscribing the Pacific; only about half of these are currently active. However, the active areas are limited to approximately 15,000 miles.

The existing tsunami warning system (Fig. 4) with headquarters at the NOAA Honolulu Observatory uses an array of 21 seismograph and 41 tide stations around the Pacific. The initial warning of a potential tsunami is the recording at the Honolulu and Tokyo Centers, of an earthquake of 7.0 magnitude or larger within the Pacific area. The location of an epicenter for such an earthquake is usually computed in less than an hour. The tide stations near the epicenter are then asked to report their data and to confirm if a tsunami wave has actually been generated.

After reviewing the seismic and tide-gauge data, and the past histories of the known tsunami origin points and their destruction areas, a decision to issue a tsunami warning is made. For localities near the epicenter warnings may be issued on seismological data only [Zetler, 1972, p. 26-27]. Two-thirds or more of all tsunamis warnings are false alarms [Loomis, 1972, p. C-11].

Thus we face three problems:

(i)   Our present ability to predict tsunamis is practically unsatisfactory;

(ii)   Even after a tsunami has been generated, its energy density and its velocity of propagation in open sea is impossible to predict; and

(iii) The most serious problem is the fact that the propagation velocity of tsunami in shallow areas is strongly affected by the ocean bottom topography and shore line contours, and as a result a substantial portion of energy in a particular tsunami can be focussed on a relatively small segment of the ocean shoreline, where the most destructive effects are experienced.
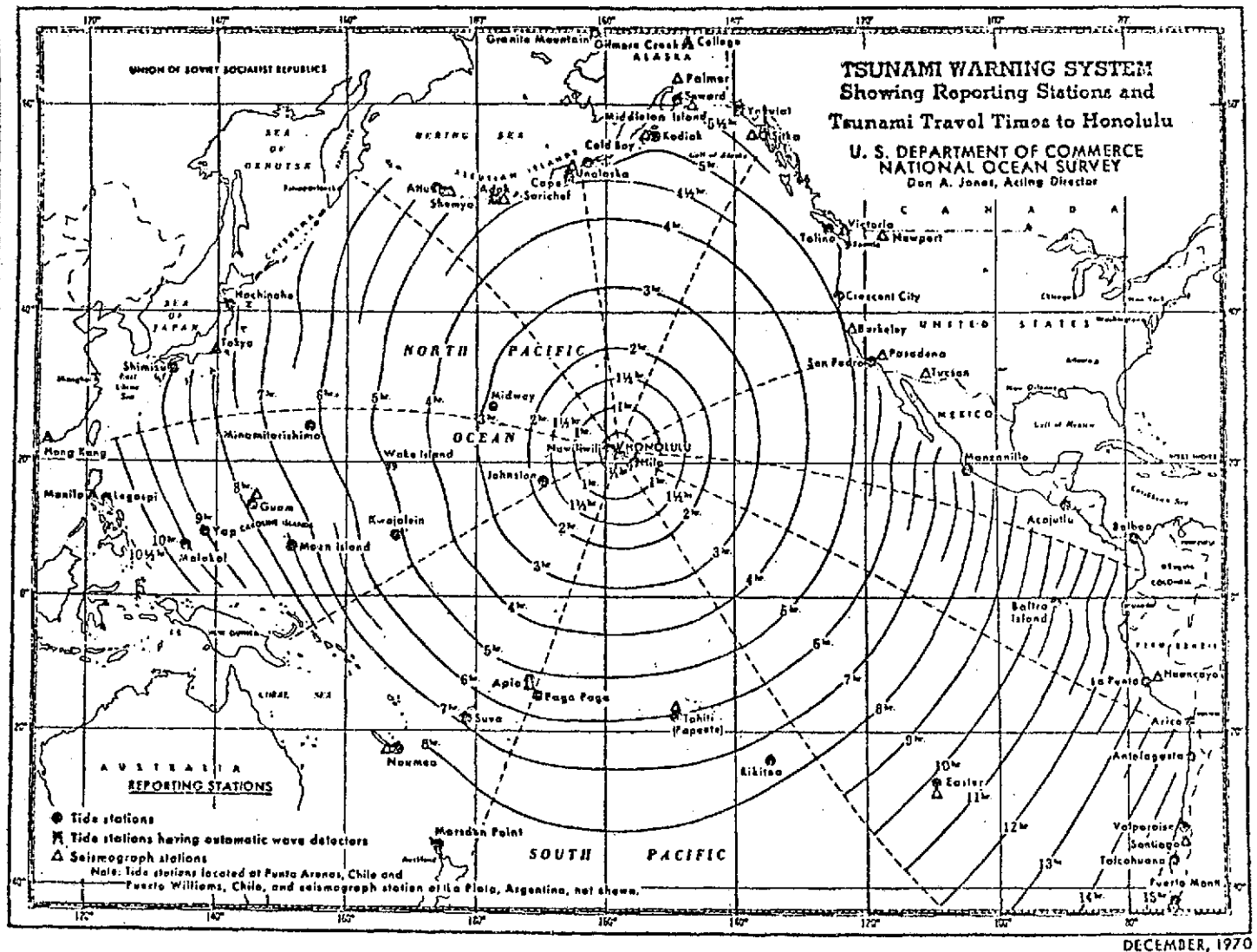

Figure 4   Tsunami warning system, January 1971.
(Figure from [Zetler, 1972])

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f. Recovery of Underwater Objects and Equipments. Scientists working with submerged instrumentation face a basic uncertainty about the recovery of the instrumentation from the ocean. Oceanographers and geophysicists have often mentioned their failure to recover most of their submerged equipment. The fact that the ocean bottom transponder net with 3 transponders-array-configuration is used in the test areas, it appears that either this 3 transponder configuration is not functional, or the geodetic technique is not clear to the users. Whatever may be the reason, the problem to recover the valuable scientific equipment from the ocean remains to be solved.

g. Ecology. For ecological reasons trend is to dispose of the garbage in the oceans at pre-selected sites. Experiments are being conducted here in America and in Japan for finding a suitable way for ocean waste disposal. The by-products of this ecology experiment are: (i) cities have no more dump site problems, and (ii) acquisition of "new land" from the oceans; such ideas exist to obtain "new land" from the ocean for airport expansion in Hawaii.

The garbage undergoes chemical tests and treatment; before compacting the garbage in rectangular bundles, it should have a well-defined chemical composition and density. These garbage rectangular packages can then be dumped at pre-selected sites, for which a good knowledge of ocean bottom topography and a good positional accuracy of the dump vehicle (ship/boat) are necessary. Both of these requirements are lacking.

h. Gravity Measurements at Ocean Floor. Gravity work and other geophysical surveys in the oceans could neither be interconnected nor connected to a datum. According to Hendershott [Loomis, 1972, p. C-14] for meaningful results these surveys should be connected to some ocean-bottom control net, which does not yet exist.

i. Ground-truth and System Calibration. It is surprising that the existing instrumentation for measuring water depth in free ocean can not be tested

for its claimed accuracy due to non-existing civilian facilities for calibration [Thompson, July 24, 1973-Personal Communication]. However there exist 5 naval calibration sites [Anon, 1970b, p. 118].

In Table 1 are shown the accuracy requirements for various tasks as estimated by various studies. In the last column are given our estimated accuracies, which are mostly based upon information given by users.

3. SOLUTION OF PROBLEMS AND APPROACH CONCEPTS

The above-mentioned problem areas can be solved by means of (A) a Global Marine Geodetic Control-Net (GMGCN) on the ocean-floor, (B) Advanced Satellite Instrumentation (ASI), and (C) Underwater Sonar Instrumentation (USI).

a.   Global Marine Geodetic Control-net (GMGCN)

The idea of a global marine geodetic control net (GMGCN) was first mentioned by Ewing and his associates [1959], and later modified by Mourad [1965]. Ewing proposed SOFAR sound transmission to measure distances between two bench-marks where a bench mark was defined as the point on or below the water surface from which the round-trip travel time to all the three ocean-bottom acoustic transponders, placed at the corners of an equilateral triangle, would be equal. Mourad proposed geodetic (electronic distance measuring instruments), acoustic (sonar instrument) and space (satellite instrumentation) techniques. Knowles and Roy [1972] describes a system basically similar to that of Mourad and Fubara [1972] but with 6 ocean-bottom transponders instead of 3 in each array.

The deficiencies of the above-mentioned systems are:

(1)   The accuracies given by them are not "realistic", as these ocean-bottom arrays were neither connected to any geodetic coordinate system nor any provision was made for such a connection, which is one of the main objectives of EOPAP.

(2)   Although a ship is used to determine the positions of the ocean-bottom transponders, its (ship's) coordinates are considered errorless, which

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Table 1

Positional Accuracies Requirements [in meters]

TASKS	Chart Acc. [Cohen, 1970]	Battelle Study						Achieved	OSU Estimated Desired Accuracy+
		Desired Absolute			Desired Relative				
		φ	λ	h	φ	λ	h		
Navigation:									
General Navigation (L.R.)[1]	± 3000								± 45-500
Submersible* (S.R.)[1]	± 300								± 5-10
Submersible* (L.R.)[1]	± 2000								± 100
Ocean Resources									
Geophysical Surveys (oil expl.)	± 200				± 10-100	± 10-100	± 5		± 30-50
Drilling (Oil)	± 25				± 1-5	± 1-5	± 1-5		± 10
Pipelines					± 1-10	± 1-10	--	±15	± 3
Cable laying	± 100				± 1-10	± 1-10	--		± 3 - ± 10
Dredging/Mining	± 25				± 2-10	± 2-10	--		± 2
Geodesy & Ocean Physics									
Control Stations	± 10	± 10	± 10	± 5	± 1	± 1	± 1		± 10
Geoid		--	--	± 0.5	--	--	± 0.1		± 0.1
Calibration Standards		± 10	± 10	± 5	± 1	± 1	± 0.3		± 1
Mean Sea Level					± 50-100	± 50-100	± 0.1		± 0.1
Stationary Buoys Loc.		± 10	± 10	--	± 10	± 10	--		± 0.1
Boundary Demarcation								± 50-300	± 10
-National									± 10
-International									± 10
-Ocean Cadastral									± 1-10
Ecology	± 250								± 10-50
Search & Rescue	± 25	± 20-100	± 20-100	--	± 1-10	± 1-10	--	± 12-200	± 10-20
Tsunamis									± 0.1

*Excluding Submarines - No Estimate Available

+[Jones and Sheriff, 1970; Putzke, 1970; and Anon., 1972b; Beck, 1971; Treadwell, Personal Communication, July 10 and 16. 1974: Thurnheer, Personal Communication, July 17, 1974; Ingram, Personal Communication, June 6, 1974]

(1) L. R. = Long Range: S. R. = Short Range

are either obtained by Navy Navigation Satellite or by airborne techniques (Lorac) to an accuracy of a few dekameters or more (30-100m)[Loomis, 1972, p. IV-6]. Thus the accuracies of transponder positions are derived from in-error ship positions.
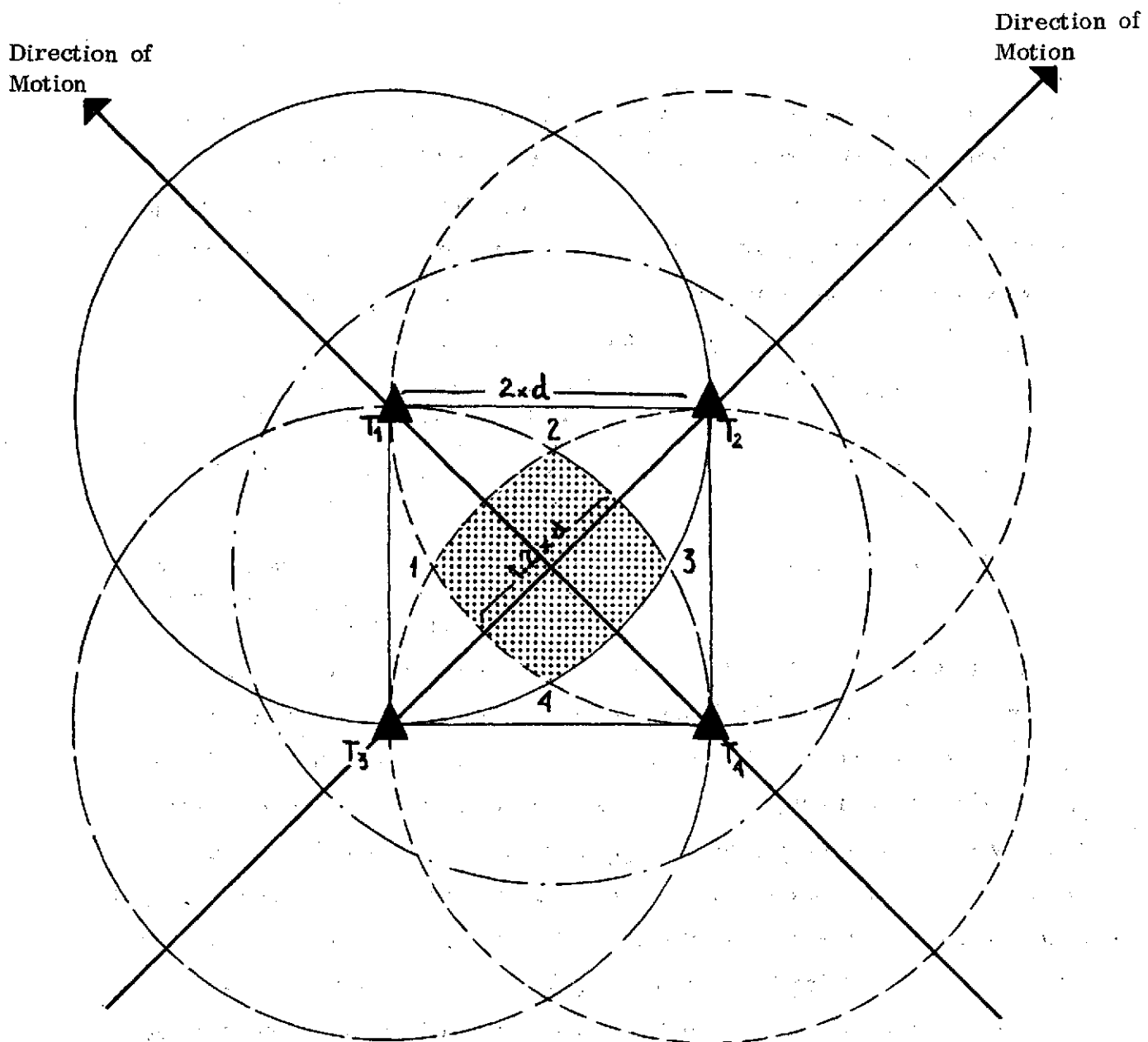
(3) Transponder depths are used in the computations. These are not the measured quantities, but are computed from slant ranges between the ship and the transponders. To be mathematically rigorous, the depth should be measured quantities and due weights should be applied to them.

(4) The mathematical derivations are rigorous in the beginning, but are approximated later, thus introducing modelling error.

The above-mentioned deficiencies can be overcome in the following way:

(1) An ocean-bottom transponder array should consist of 4 transponders instead of the conventional 3 in each array; this will not only avoid the singularity of the system but will also provide redundancy, and also will be useable if one transponder ceases functioning. However, a study is imperative to find how many transponders are necessary in one ocean-bottom transponder array, specially because Mourad thinks 3 transponders in each array are required and Knowles thinks 6. We have also to think how these transponder arrays are placed: before emplacement of these transponders a reasonably large area (25-40 miles squares) of the ocean bottom is mapped using Depth Sounders. Then a smaller flat area proportional to its water depth is selected for transponder arrays. This water depth-flat area ratio limits the array configuration, and hence the number of transponders in each array. For practical reasons the term bench-mark should be defined physically as a particular transponder of a particular array and not as a fictitious point as defined by Ewing, et al. [1959] and Mourad [1965].

Figure 5 shows the configuration of an ocean-bottom control net unit (Case II) with four transponders T_1, T_2, T_3, and T_4. The distance between the transponders is dictated by the ocean bottom topography, and the depth

Figure 5. Ocean-bottom Control-net Unit Configuration –
Case II.

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which determines the coverage on the ocean surface from each transponder. A preliminary study conducted by the author indicates that the non-diagonal distance between any two transponders is 2.d, where d is the average depth of the transponder unit, for optimized ocean surface coverage with only one tracking along the diagonal; the three cases dealt to determine the non-diagonal distance (T_1T_2) between any two transponders are:

I T_1T_2 α 3.46xd   (theoretical; line crossing technique for position determination necessary)

II T_1T_2 α 2xd   (optimized coverage; only one diagonal tracking required for positioning)

III T_1T_2 α 1.7xd   (best configuration; lesser coverage than in case II; only one diagonal tracking required for positioning)

In case II and III at least three transponders can alwyas track any surface vehicle if it moves along the diagonal, whereas all the four stations can track for a distance of 1.2xd in Case II and 1.7xd in Case III.

The unit configuration of Figure 5 can be further modified to regional nets, where two or more such units are needed, or to global nets where two or more such units are needed, or to global nets where a combination of many regional nets will be necessary. The unique feature of this unit configuration is that if at least two transponders are equipped with various sensors, it can solve various oceanic problems mentioned in Section 2, thus making it a multi-purpose unit. Clautice and Sheets [1973] give various configurations which can only be used for navigation; their prime concern is economy for transporting Alaskan oil by submersible tankers.

(2) The number of transponders in each array could be decreased to 3 if somehow the directions between the ocean-bottom transponders and the ocean-surface transducer could be determined. These directions would provide necessary constraint to the control-net, thus avoiding the singularity and providing a unique solution. A system to measure the directions

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precisely between two sound sources can be designed with the existing technical knowledge similar to that of Electronic Angles Measurement Systems.

(3) The depths of the transponders should be actually measured, and then compared with the computed depths. The only problem in this is that there are no exactly known depths in the free ocean, which can be used as ground-truth to verify the accuracy of these modern sonar instruments [Thompson, July 24, 1973-Personal Communication]. The instrument (Innerspace Autotrack Model 404) can measure depths up to 10,000 meters with an accuracy of ±4.36 m. This optimistic accuracy estimate takes into account three sources of error (assuming a constant velocity of sound 4800 ft/sec.): (i) timing accuracy of the oscillator (±0.00 25%) (ii) resolution of the display (± 0.3 m) (iii) reply integrator time constant (.1 to 10 ms).

However the above accuracies are quite small compared to the effect caused by the difference between the actual and assumed velocity of sound. A 10 ft/sec velocity difference will contribute to an error of 2.04%, which is one magnitude larger than the accuracy of the system (0.04%). Thus to obtain geodetic accuracies, it would be necessary to determine a profile of the sound velocity vs. depth and then to calculate the average velocity at the location of interest.

(4) The transponder arrays should be connected to some geodetic datum, which can be achieved by using an Active Satellite similar to Geole system of DIALOGUE Project [Thieriet, 1972], "floating buoy reflectors" on the ocean surface and ground-based reflectors at known stations.

The unique feature of DIALOGUE Satellite is that the satellite makes the measurements, stores them in memory and transmits them to the computing center through the telemetry-telecommand ground station. Thus purely

geometrical method, where simultaneous observations are a necessity, can be used as the satellite is capable of obtaining observations simultaneously from more than 4 stations. Pieplu [1974 , p.6] mentions that the results obtained by long arc technique are globally 2 or 3 times not so accurate as those obtained by geometrical method. The positional accuracies of a slowly moving object ±10 - 20 m from one single observation obtainable every 2 hours, with a time delay of a few hours, and ±1 m over one day's observation, with a time delay of about one day [Thieriet, 1972]. Hence a truly unified global network of geodetic precision can be achieved even in the remotest ocean areas.

(5) A rigorous mathematical model is necessary, and the use of the gravity information should be made.

(6) To make the transponder arrays more versatile to be used also as a geophysical station for Tsunami warning, it should consist of a water-pressure sensor and a vertical seismometer, both of these would be on the ocean floor [Loomis, p.C-15]. A study of the essential instrumentation at the ocean-bottom transponder site to enable it a multi-purpose station is necessary, for which discussion with oceanographers, geophysicists and other users are needed.

b.   Advanced Satellite Instrumentation

An active satellite like Geole system of Dialogue Project could be very useful. The Geole system can obtain accurate positioning of slowly moving points (like buoys) to ± 1m over one-day measurements, and to ± 10-20m every two hours from one single measurement. The satellite will be at 3500 km height and will make the measurement [Thieriet, 1972].

c.   Underwater Sonar Instruments

As the only form of radiation, which propagates effectively underwater, is sound, it is most important for underwater measurement. The sonar in-

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struments operate on a fixed theoretical sound velocity (4800 ft/ sec), although velocity of sound depends upon the conditions of the water layers (salinity, pressure, temperature) and depth of water. How to calculate the correct velocity at required depth or the average velocity during many water layers has been achieved by determining a profile of the sound velocity vs. depth, and then to calculate the average velocity.

What has not been done and should be done is to verify the accuracies of these instruments, which indirectly will involve verification of the calculated average velocity. There is no calibration range for civil scientific purposes, although five test ranges exist for naval use [Anon., 1970b, p. 118].

A comparatively easy development of an acoustic instrument to determine directions precisely between two sound sources is necessary to lessen the number of transponders in each array. The directional bearing accuracy of 0.5 degrees mentioned recently by Heckman [1974] remained unchanged since World War I [Urick, 1967, p. 4]; this obviously needs improvement.

The conceptual approaches mentioned in this section can be summarized as follows:

(1) An active satellite around 3500 km high in circular is necessary. Thus the position of floating buoys/ships could be determined within ±1 to ±10 meters, which will further improve the ocean-bottom transponder position. It will also connect the ocean-bottom transponder net to a unified global datum, and demarcate and determine the boundaries (national, international, leasing) in the open ocean to a high accuracy.

(2) Underwater sonar instruments require calibration for which a Civilian Test Range is needed. A new development to determine the direction between the sound sources is necessary so as to lesen the number of transponders in each array.

Just to illustrate how our conceptual approach can be used to solve the problems mentioned in Section 2, it will be applied to improve the Tsunami Warning System, to demonstrate its practical application.

Conceptual Approach for an Improvement in Tsunami Warning System. As mentioned earlier that two-thirds or more of all tsunami warnings are false alarms, the existing Tsunami Warning System needs improvement.

Van Dorn [Loomis, 1972, p. C-12] suggested that stations should be located on the ocean floor (and not on the continental shelves) off the seismically active belt. He suggested a 6 station critical net as follows:

> 1 station off Japan
> 2 stations off the Aleutians
> 2 stations off South America
> 1 station off the South-western Pacific Island.

Zetler [1972, p. 26-27] mentions that if a tsunami could be detected on the open ocean, it would be very valuable to the warning system. According to Zetler, it does not seem likely that space craft/satellite measurements could be helpful for tsunami detection in open ocean.

It is quite evident that tsunami data from the open ocean is very valuable to improve the existing tsunami warning system; this could be achieved by combining Doppler/laser and ocean-floor station data.

A system could be designed using the existing technology: At "suitable" locations on the Pacific ocean-floor acoustical transponder arrays could be placed. Each transponder should be equipped with water pressure sensor, vertical seismometer and other essential instrumentation to make it a multipurpose station. On the ocean surface are placed stabilized platforms (floating buoys) whose bottom is mounted with acoustical transmitter/transponder and upper surface with a Doppler antenna. The active satellite of DIALOGUE type could position these reflectors (slowly moving objects) to ± 10 m for one measurement, and ± 1 m from one day data; the range accuracy is ± 2 m and radial accuracy ± 2 mm/sec [Thieriet, 1972].

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The sonar data from the ocean-bottom transponder net will provide the relative position of the "floating buoy" in all the three dimensions.

Note .that the sonar data will be always available on command; but satellite data will be available only when the satellite is in that region.

Operational Procedure: After the recording of an earthquake of 6.3 magnitude [Iida, 1970, p.3] and consequently locating its epicenter, the ocean-bottom transponders, the surface buoys and the satellite will be asked to report their "height difference" data at one minute interval. Thus a complete record of the wave-height and its speed can be computed. The sonar "height" (depth) data is measured automatically and with the speed of sound, which is approximately equal to the velocity of P-waves (1.5km/sec) [Bullen, 1963, p. 321]. Whereas the tsunami speed in open ocean of 1000 m depth is only 100 m/sec. Thus the tsunami warning - after reviewing the sonar, satellite and seismic data - could be issued more reliably within minutes after the earthquake occurence.

Due to the fact that a harmless tsunami wave of the open ocean may become destructive reaching the shore depends upon the topography of the continental slope and of the continental shelf, a few transponders/floating buoys have to be located in this region.

4. CONCLUSIONS AND RECOMMENDATIONS

In the recent few years navigators have repeatedly mentioned the necessity of a continuous and in real-time positioning system for long-range surface navigation and for submersible navigation. Until the completion of Global Positioning System (GPS) by 1985, which may satisfy the need of surface navigation only, there is currently no system which would fullfil navigational requirements. Even after the completion of GPS, the problem for submersible navigation will remain unchanged, until a hybrid system including space-, EDM- and acoustic instrumentation is designed and implemented.

Boundary demarcation and determination in open seas is another problem area, which will become actual in the near future, as oil deposits and minerals are concentrated in certain areas. The positional accuracy requirements for leasing "blocks of oceanic area" may become as high as ±1 m in areas of potential oil deposits. Fischer [1974, p. 130] mentions similar future problems. During the recently held International Symposium on Application of Marine Geodesy in Columbus, Ohio, a need for boundary demarcation was mentioned by Johnson, Orlin and others.

Another unsolved problem area is mean sea level as derived by coastal tide gauges. It is a proven fact that ocean surface topography is highly sensitive to bottom topography in shallow waters. This is why Höpcke [1970] proposed tide gauges in the open sea; similar ideas were discussed by Dohler, Perry and the author during the recent Seventh GEOP Research Conference. This may solve the well-known discrepancy between the oceanographic and the geodetic leveling.

In all the above-mentioned problems, as well as other problem areas of Section 2, we are faced with two basic problems: (1) precise positioning in open ocean of surface vehicles as well as of submersibles, and (2) precise depth determination. The solution of these basic problems has been given in Section 3. However, keeping users' requirements as well as economical aspects in view, an optimum solution can <u>only</u> be achieved by a considerably well-thought and well-planned study, which could be in the following way:

(a) <u>Accuracies Available and Required.</u> The instrumentation accuracies as given by the manufacturer have to be evaluated. This will require study of investigations done by various users using the instrument under evaluation. After this evaluation it could be decided which instruments should be used for obtaining the specific accuracies.

Also needed is a scientific survey of user's accuracy requirement.

This is a very difficult task as most users do not want to discuss their desired accuracies.

(b) Simulated Network Design. A basic simulated network design by using the modern instrumentation is necessary as this is the "back-bone" of the entire operation. For such design one has to consider primarily, the users' requirements, the configuration criteria, and how best a hybrid system can be used.

The important advantage of ocean-bottom transponder net over satellites is that satellites can track for a limited time when they are above a particular station, while ocean-bottom transponders can either track continuously or can be activated on command. This is very important for tsunami warning system.

The network design can be conducted in three stages: (1) Unit Array: Configuration and number of transponders necessary in one array; the type of observations needed; type of instrumentation in each array and/or at each transponder to make it a multi-purpose station; (2) Regional Net: Configuration of transponder arrays in areas of scientific interest and in practical problems areas, like boundary determination; (3) Global Net: Eventually to plan and design a global net based upon scientific regional nets mentioned in (2) above.

The network design in each of the three stages should be connected to a geodetic datum.

(c) Master Plan for Ocean-bottom Network. Looking at various publications, it becomes clear that many users and research institutions have their "own" transponder nets on the ocean bottom. It will be worthwhile at least to plan a global network, using the existing scattered transponder nets, if possible.

A master plan should be prepared which should provide information about the transponder types, their locations and working frequencies, obtained data and type of data.

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