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SURVEYING OFFSHORE CANADA LANDS
FOR
MINERAL RESOURCE DEVELOPMENT

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SURVEYING OFFSHORE CANADA LANDS for Mineral Resource Development

Third Edition

Based on the findings of government/industry workshops convened between 1970 and 1982 to study the technical and legal aspects of surveying for mineral resource development on offshore Canada Lands.

Edited by Harold E. Jones

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Department of Indian and Northern Affairs (IAND) (Oil and Gas Division)
Department of Transport (TC) (Canadian Coast Guard)
Department of Fisheries and Oceans (F&O) (Canadian Hydrographic Service)
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Foreword

The increasing demand for energy by all sectors of the Canadian economy has generated widespread searches for oil and gas. Extensive and urgent exploration in Canada's frontier regions has made the execution and regulation of offshore surveys increasingly important.

Since 1970, several government/industry workshops have been held to consider the regulations, techniques and procedures applicable to surveying for offshore resources. This government/industry cooperation has proven very valuable to all concerned and more workshops are anticipated. The most recent workshop met from March 15 to March 19, 1982 and recommended publication of this third edition of *Surveying Offshore Canada Lands for Mineral Resource Development.*

As Chairman of the interdepartmental Coordinating Committee on Offshore Surveys, I wish to thank all those who participated in the Workshop for their contributions, and in particular, the editorial committee for their fine work in preparing the report. I hope those who are involved in the offshore survey activity will find this report helpful in their understanding of the many technical procedures and the administrative and legal issues involved.

R.E. Moore

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Introduction

In the late 1960's, exploratory drilling for oil and gas began in earnest on the Canadian continental margins. Partly because the wells were being drilled far from shore and partly because the surveying systems and the regulations governing surveying had been designed for operations on land, those directly concerned with offshore mineral exploration realized that new approaches would be necessary to pinpoint the position of marine geophysical surveys and the location of offshore wells. These new approaches were particularly important off the East Coast, where some areas of the continental margin extend seaward for more than 1000 km.

In 1969, following initiatives by Shell Canada Limited and the Resource Management and Conservation Branch of the Department of Energy, Mines and Resources (EMR), meetings were arranged between industry and government under the auspices of the Surveyor General in EMR. The meetings were held to discuss the technical and administrative difficulties of surveying in the offshore, and to make arrangements whereby they might best be overcome. The arrangements included the establishment of the Interdepartmental Coordinating Committee on Offshore Surveys, under the chairmanship of the Director of EMR's Surveys and Mapping Branch; and, the formation of a six-week workshop, the Workshop on Offshore Surveys, composed of 20 members from various agencies in industry and government.

This first workshop was convened from January 12 to February 20, 1970, under the sponsorship of the Surveys and Mapping Branch. Its objectives were to study surveying systems and survey regulations and, to recommend feasible and acceptable surveying systems, procedures and amendments to the regulations appropriate to the development of offshore mineral resources. The Workshop decided to confine its terms of reference to three aspects: first, a study of present and potential capabilities of available positioning systems suitable for the Canadian continental margins; second, a consideration of the problem of monumentation or marking of offshore surveys; third, a review of existing survey regulations in light of these findings. The Workshop dealt with surveying as it pertained to oil and gas. The potential for other minerals, in the long term, was acknowledged but no exploration had been carried out for other seabed minerals in offshore Canada lands, and little if any elsewhere. The Workshop's main recommendations concerned improvements in coastal control, technical investigations and research of several surveying systems (including satellite navigation), amendments to existing survey regulations, and changes in the qualifications for Dominion Land Surveyors. The report of the Workshop formed the basis of the first edition of *Surveying Offshore Canada Lands for Mineral Resource Development*, published in 1970.

During the following few years, Workshop review groups met to assess developments in research, changing legislation, and new survey systems. Further recommendations were made. A second edition of *Surveying Offshore Canada Lands for Mineral Resource Development*, dated October 1975, was produced.

Since then there have been significant discoveries in the Arctic and on the east coast. The broadening of the qualifications for Dominion Land Surveyors, recommended by the first workshop, has been effected; the new syllabus for the Canada Lands Surveyor commission includes hydrographic surveying and other subjects required for offshore surveying. A new Canada Oil and Gas Act has been proclaimed. Offshore surveying techniques have changed considerably with the common place use of satellite-based survey systems. A new United Nations draft Convention on the Law of the Sea, which provides internationally accepted definitions of offshore jurisdictional limits, has been adopted. To review these developments and make further recommendations, a one-week workshop of 25 delegates from government and industry was held March 15-19, 1982 under the auspices of the Interdepartmental Coordinating Committee on Offshore Surveying. The Workshop recommended the production of this third edition of *Surveying Offshore Canada Lands for Mineral Resource Development*. It brings the second edition up to date with more emphasis on arctic aspects. There is a new section on the sequence of events leading to drilling for hydrocarbons in the offshore and there are additional chapters which emphasize positioning aspects of hydrographic surveying, geophysical surveying and sea ice.

Chapter 1

Offshore Mineral Resource Developments

Today, hundreds of companies are exploring the continental margins of over 100 countries, and almost 50 countries are producing or preparing to produce oil or gas from their offshore regions. Most of this offshore production began after the year 1970. Well over 30 000 offshore wells have been drilled to date. Exploration wells have now been drilled in 1486 m of water off the coast of Labrador, and a production platform in the U.S. Gulf Coast offshore is standing in 335 m of water. These are examples of current technology.

In the Canadian offshore, more wells are being drilled in deeper water and farther from shore. The deep water record for drilling was set in 1979 by the Texaco-Shell Blue H-28 well. In Arctic regions of Canada, artifical islands for drilling sites have been constructed in water up to 23 m in depth in the Beaufort Sea, while ice-reinforced drilling platforms have been utilized in water over 550 m in depth between the Arctic Islands.

About 28 million km^2 of the world's offshore areas lie in water depths of less than 300 m, which is still about the limit for offshore production. Of this total, 16 million km^2 have the potential for petroleum — a third of the world's total prospective area on land — but only a small fraction of this vast offshore area has been exploited thus far. Nonetheless, world offshore oil production is about 20 percent of the world's total output, and sub-sea oil reserves now comprise more than 20 percent of the world's total reserves. It has been predicted that by 1990, one-third of the world's total oil production will be obtained from the offshore. The National Petroleum Council, in March 1975, estimated that 55 to 70 percent of the world's offshore petroleum lay in a water depth of less than 200 m, and that 80 to 90 percent lay within the 200 nautical-mile limit.

Exploratory well locations are selected using geological and geophysical methods as well as information derived from any previous wells in the region. These selection methods involve a large component of data interpretation and extrapolation. Thus, the success of an exploratory well location is based on possibilities and only a small percentage of all exploratory wells are successful.

Furthermore, for most of these successful wells, only small reserves are discovered. For the remaining wells, increasingly large oil and gas fields are discovered, but with decreasing probability. Factors such as reservoir size, water depth, distance from shore, weather, sea states and ice conditions all affect the economics of drilling for, producing and transporting oil and gas from offshore fields. Moreover, what could be a viable field on land may be uneconomic in the offshore.

Figures 1,2, and 3 illustrate the location of Canadian offshore drilling operations, the expenditures involved and the cumulative number of wells drilled to 1981.

Offshore Drilling Techniques

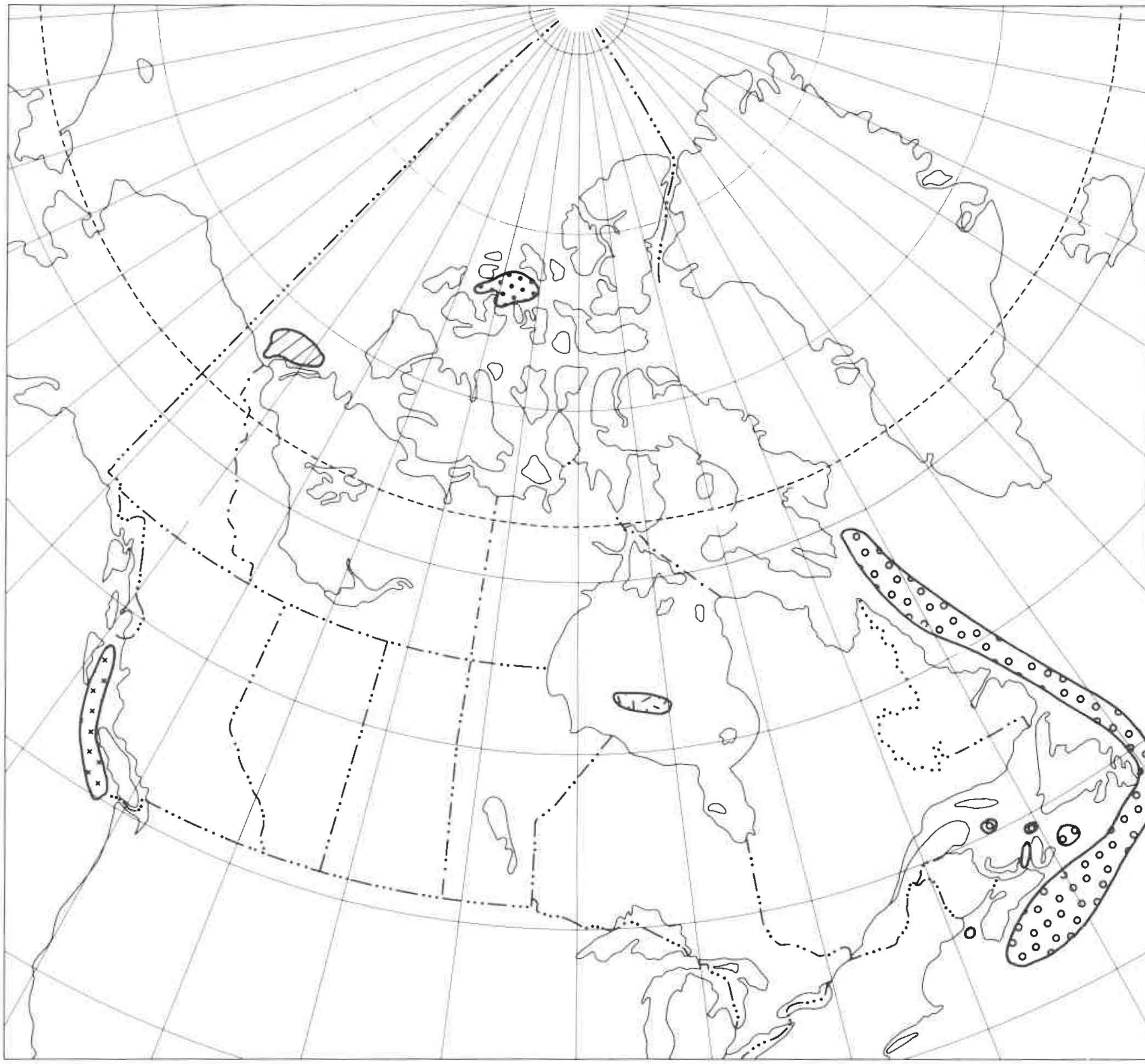
Around the world, offshore mineral resource development activities are moving to unexplored new and deeper waters. Advanced techniques and equipment for deepwater drilling, completion and production are being developed so that oil and gas accumulations at water depths greater than 400 m can be economically exploited. The trend to deeper waters with a generally more hostile environment,such as that encountered in the Canadian offshore, has given impetus to the construction of larger, heavier, semi-submersible types of drilling units with displacements at drilling draft in the range up to 25 000 tonnes. Figure 4 shows one of the types of semi-submersible drilling units. Other types are triangular or pentagonal in plan. The semi-submersible units which have predominated in recent design trends have an operating capability in 175 to 275 m of water; and one or two modified designs, using anchor cables rather than anchor chains, can drill in water up to 1000 m deep. Some of the newer units such as the Sedco 709 can be dynamically-positioned. For severe sea states, the semi-submersible unit is the most stable type of floating, drilling platform in service. There are also ship-shaped drilling units (drillships) such as the Canmar Explorer shown on the cover of this publication.

Off the west coast, no wells have been drilled since 1969 when the semi-submersible Sedco 135-F drilled 14 wells.

Off the east coast, many semi-submersible units have been used including the Sedco H, I, J. Sedco 706, 707, 709, Zapata Ugland and the Bow Drill I. Several drillships have been used on the Labrador coast including the Pelerin, Sedco 445, Pelican, Glomar Atlantic, Ben Ocean Lancer and the dynamically-positioned Discoverer Seven Seas which drilled in the world record depth of 1486 m. In the Gulf of St. Lawrence and off Sable Island, jack-ups have been used including the Salenergy II, Rowan Juneau, Gulflide, Zapata Scotian.

In Hudson Bay the semi-submersibles Pentagone 82 and Wodeco II drilled in 1974.

In the Beaufort Sea four drillships have been used: the Canmar Explorer I, II, III, and IV.



WELLS DRILLED

- WEST COAST - 14 WELLS FROM MOBILE DRILLING UNITS
- BEAUFORT SEA - 23 WELLS FROM MOBILE DRILLING UNITS
- BEAUFORT SEA - 20 WELLS FROM MAN-MADE ISLANDS
- ARCTIC ISLANDS - 20 WELLS FROM ICE ISLANDS
- HUDSON BAY -3 WELLS FROM MOBILE DRILLING UNITS
- EAST COAST - 152 WELLS FROM MOBILE DRILLING UNITS

Figure 1

Distribution of Canadian Offshore Wells Drilled to 1981

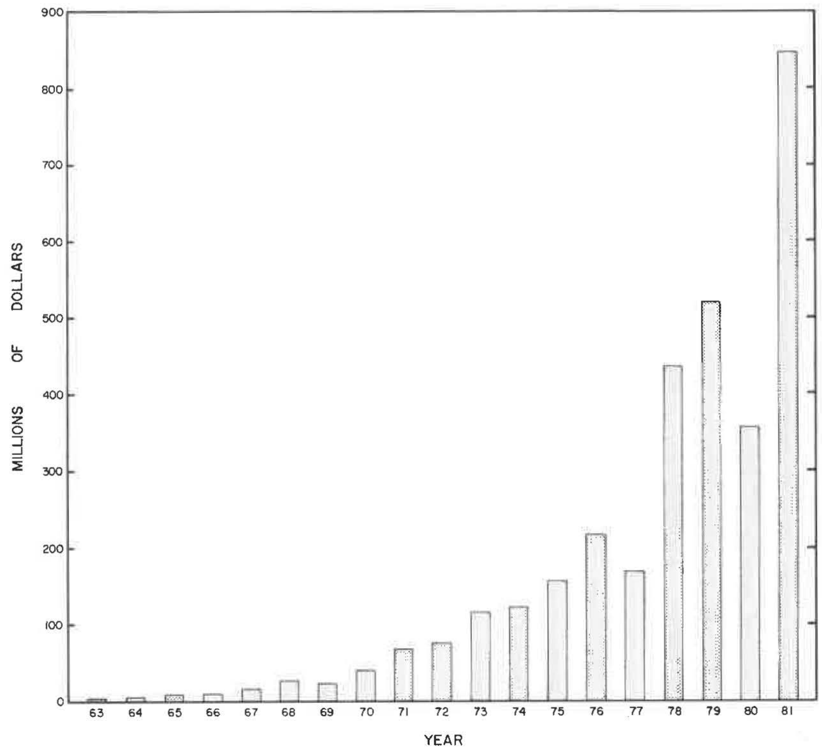


Figure 2

Approximate Annual Expenditures by Industry in the Search for Oil and Gas in the Canadian Offshore 1963-1981

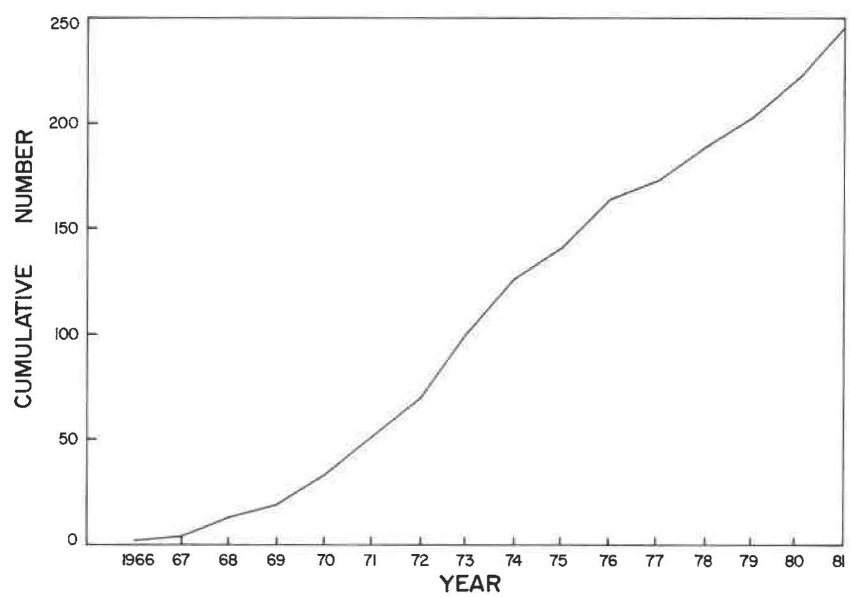


Figure 3

Number of Wells Drilled Offshore 1966-1981

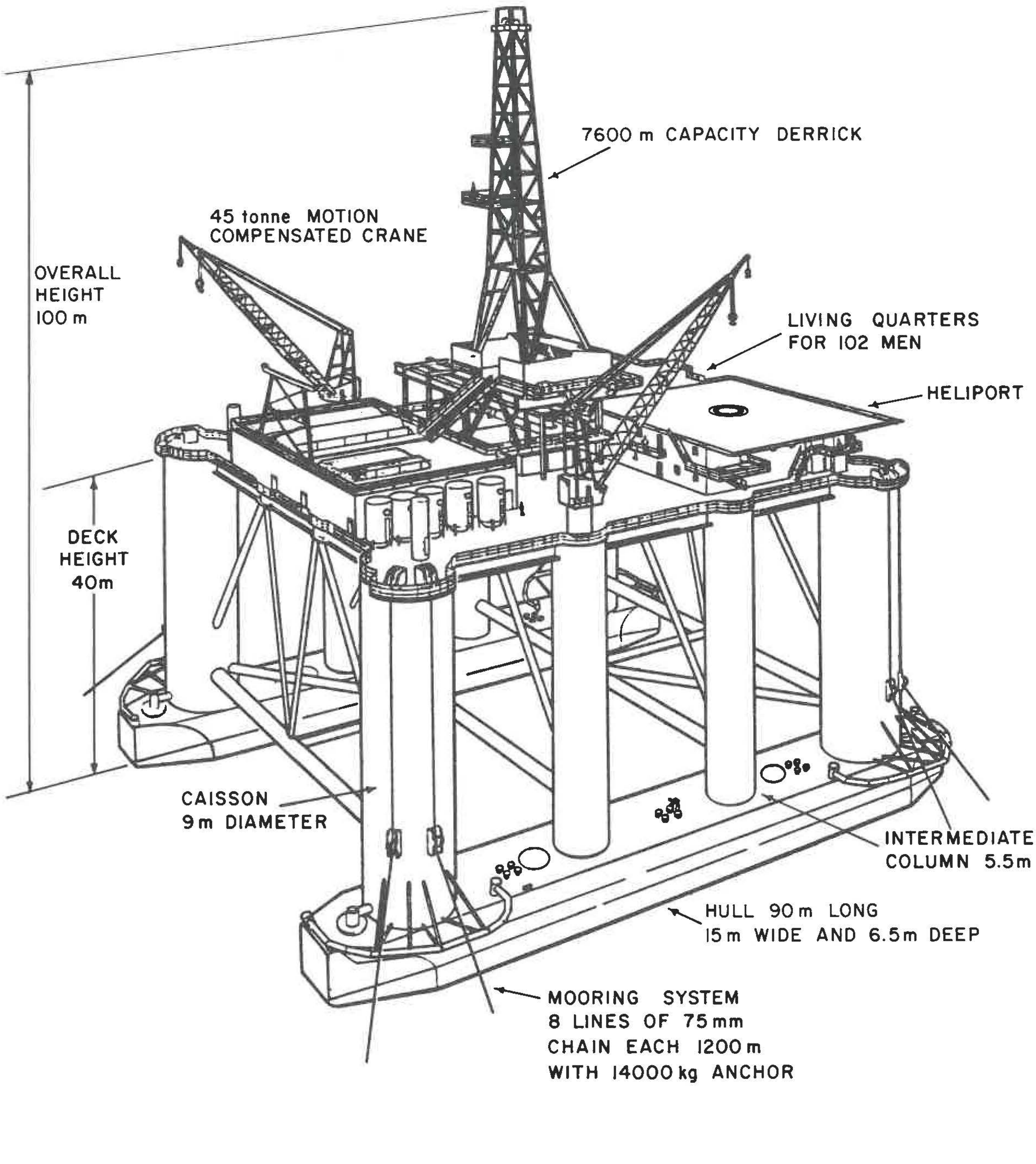


Figure 4

Typical Semi-submersible Offshore Drilling Unit (Sedneth 701) Built for Nederlandse Zeeboormaatschappij (Sea Drilling Netherlands) B.V.

Underwater Completions

The movement of exploratory activity to deeper waters or more hostile environments, plus the increasing costs of fixed-production platforms as water depths increase, has accelerated the development of underwater completion and production systems (Figure 5 and 14). These subsea systems, such as the one developed in Canada by Lockheed (Figure 5), permit men to work in a shirt-sleeve environment; in air at atmospheric pressure in capsules on the seafloor; and to use standard oil-field techniques to complete each well and to link it to subsea manifolding and production facilities. Two or three other such systems under development are becoming available commercially. They may also be used in more shallow waters, where ice is a threat, where there are shipping lanes or where warranted for other reasons.

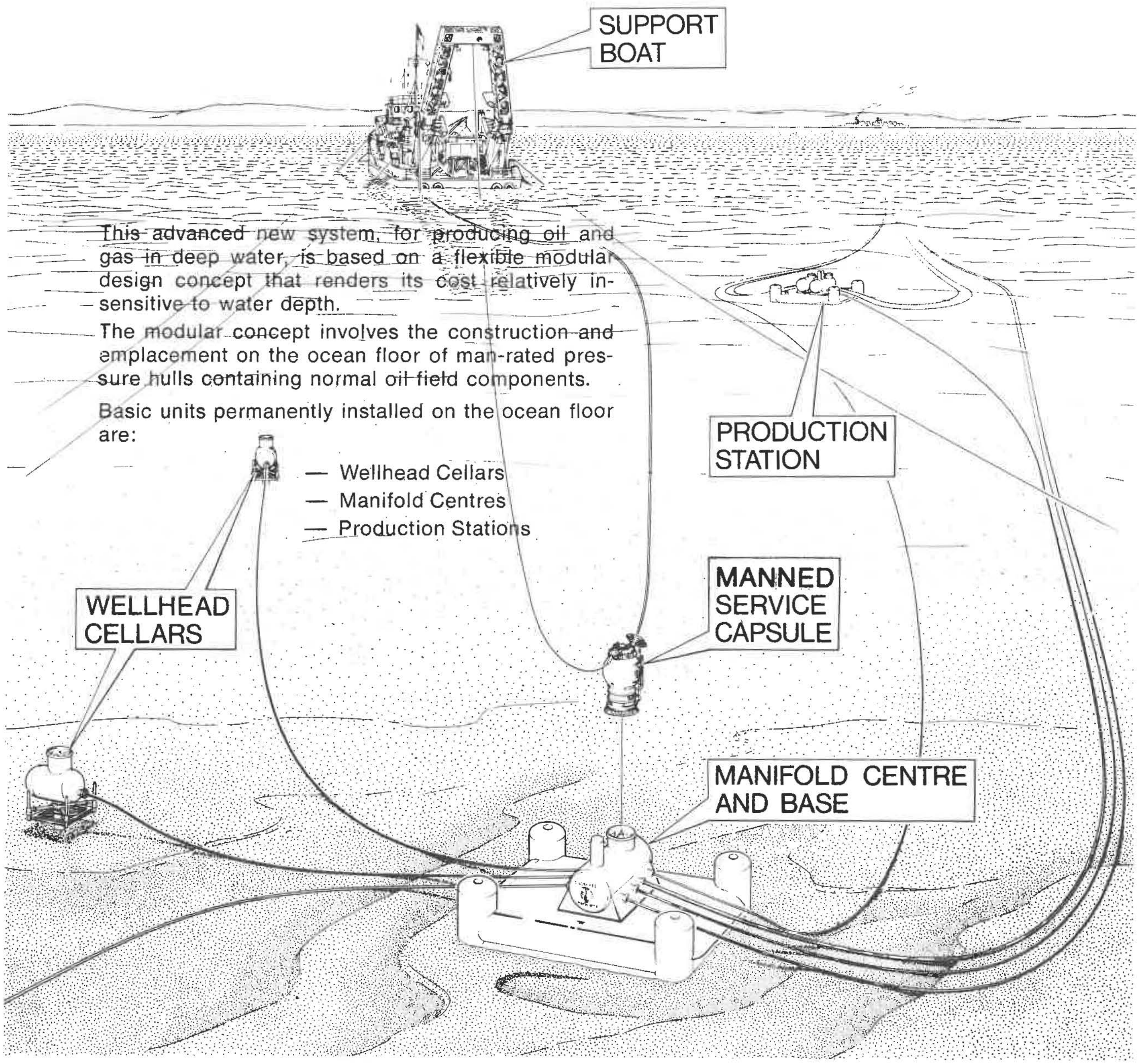


Figure 5

An Underwater Completion System Developed in Canada by Lockheed Offshore Petroleum Service

Manned submersibles of advanced designs are being constructed and used for geological exploration of the seafloor, subsea wellhead connections, pipeline inspection, rescue, and recovery tasks in hydrospace. They could also be used successfully in open Arctic waters to gather bathymetric and shallow seismic data; but in far northern waters the endurance, speed, under-ice position fixing and logistics pose many technical problems yet to be solved.

For underwater tasks that need no human eyes, the remotely-controlled submersible is normally used. Compared to manned submersibles, the unmanned submersibles are safer, less costly, smaller and simpler in design. They have working arms or manipulators and a variety of machine tools that can be attached. They are equipped with underwater camera, television, and acoustic devices, and some of the newest models are now being designed for useful work in depths from 3000 to 7000 metres.

For oil production purposes, enormous underwater oil storage systems constructed of steel or concrete are now used in the offshore at Dubai in the Persian Gulf and at the Ekofisk, Beryl, and other fields in the North Sea. These massive structures, weighing in the order of 200 000 tonnes, rest on the seafloor and are held in place by their own weight; and, since part of the structures are above water, they constitute man-made islands.

Canada's Continental Margin

Canada's continental margin (Figure 6), the part of the Canadian continental land mass which extends offshore beneath the sea, is the second largest in the world, exceeded only by that of the U.S.S.R. Extending seaward, the physical components of the margin include the continental shelf, the slope and the rise (Figure 7).

The Canadian margin, including Hudson Bay, covers over 6.5 million km^2, an area equivalent to over 60 percent of Canada's total onshore area. In some regions of the eastern margin, for example southeast of Newfoundland, it extends more than 1000 km from the coast. The geographical distribution of the Canadian margin is as follows: 2.5 million km^2 off the east coast, 1 million km^2 in Hudson Bay and Hudson Strait, 150 000 km^2 off the west coast, and the remaining 3 million km^2 in the Beaufort Sea, Arctic Archipelago and the Baffin Bay-Davis Strait region.

The physical continental shelf is that submerged portion of a continent that extends seaward with an average descending gradient of less than one degree, to a point where it merges into the continental slope. The world average water depth at the edge of the shelf is about 130 m, but the Canadian shelf is generally deeper. This is particularly so off the east coast where the shelf ends beneath a water depth of 400 to 500 m for the whole extent of the shelf north of the Grand Banks, and in the high Arctic, where the shelf off the Arctic Archipelago ends at about the 650 m depth. This phenomenon is thought to be due to the incompleted rebound resulting from the removal of the weight of Pleistocene ice cover.

The slope off Canada for the most part dips at angles averaging three to four degrees, to water depths varying from 2000 to 4000 m. The continental rise slopes more gently away from the base of the continental slope to the 3000 to 5000 m abyssal depths of the ocean floor.

Law of the Sea

Prior to the recently concluded Third Conference on the Law of the Sea, the 1958 Geneva Convention on the Continental Shelf expressed international law regarding seabed resources pertaining to a coastal state. Canada ratified the Convention in 1970.

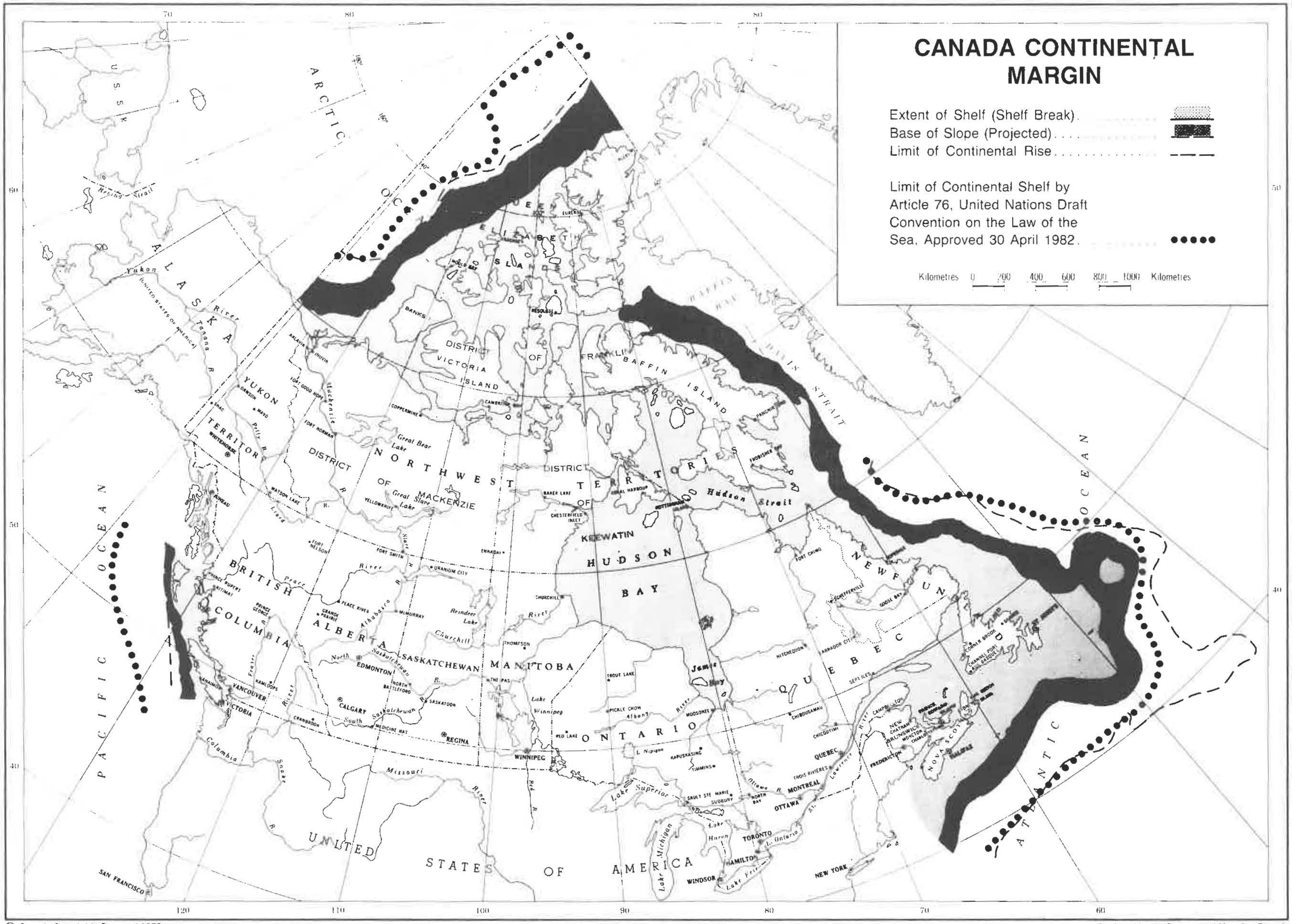
The Geneva Convention on the Continental Shelf provided that the coastal state "...exercises over the continental shelf sovereign rights for the purpose of exploring it and exploiting its natural resources." The Convention defined the continental shelf as extending "...to a depth of 200 m or, beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources...." The Convention further provided that the sovereign rights referred to are "exclusive" and "do not depend on occupation, effective or national, or on any express proclamation." The limits of national jurisdiction over seabed resources, under the Convention, were therefore dependent upon world-wide technological developments.

Canada's jurisdictional claims to minerals of the juridical continental shelf have been asserted by the issuance and administration of Canada oil and gas permits covering extensive areas of the continental shelf and slope and portions of the rise; by the supervision and regulatory control of all mineral resource activities in this region (Figure 8); as well as by declarations in Parliament, at the United Nations, and in other forums. These claims are supported by the 1969 decision of the International Court of Justice in the North Sea Cases, and by State practice.

The fact that Canada issued permits covering extensive offshore areas did not, by itself, maintain the nation's jurisdictional claims to the seabed resources of these areas. Unilateral action by a state does not in itself create or even necessarily lead to international law. It is the acceptance of this practice and the adoption of similar practices by other states that normally lead to the formulation of international law.

National limits of jurisdiction over seabed resources became an issue of major importance in the United Nations, with the introduction of a resolution by Malta in 1967. This resolution called for "Examination of the question of the reservation exclusively for peaceful purposes of the seabed and ocean floor and the subsoil thereof underlying the high seas beyond the limits of present national jurisdiction and the use of their resources in the interest of mankind." The United Nations Seabed Committee, and after 1973, the Third United Nations Conference on the Law of the Sea, experienced great difficulty in resolving the problem of where to draw the line between undersea resources to be covered by national jurisdiction, and undersea resources to be developed under an international regime for the benefit of all. Canada has been very active in attempting to resolve this issue.

Since 1967, Canada presented her position on the rights and responsibilities of coastal states before the representatives of all States. Canada's approach has been that coastal States should exercise sovereign rights to explore and exploit seabed



Produced by the Surveys and Mapping Branch, Department of Energy, Mines and Resources.

Figure 6

Canada's Continental Margin

resources out to the limit of their adjacent submerged continental margins.

Partly due to Canada's influence, wide shelf approaches were put forward by an increasing number of state members of the United Nations Seabed Committee, and later, in the many sessions of the Third Law of the Sea Conference held first at Caracas, then New York and Geneva. These were, to some extent, linked with the creation of an economic zone measuring 200 nautical miles from the shore, and within which a coastal state might exercise its jurisdiction over a range of resources and activities. However, the wide shelf concept did not achieve universal support, and compromises were necessary to incorporate an appropriate formula into the Draft Treaty. This was ultimately passed by vote in the final session of the Conference held in New York in April, 1982. Part VI of the draft convention (which is reproduced in Appendix C), deals with the Continental Shelf. It consists of articles 76 to 84.

The basis of Article 76 of the Draft Treaty, which describes the manner in which a coastal state may define the outer limits of its sovereign rights over seabed resources, was originally conceived by Ireland in collaboration with Canada. Simply stated, it recognizes these rights to at least 200 nautical miles out from the coast, and beyond this distance to the outer limit of the margin, where the latter can be demonstrated as extending beyond 200 nautical miles. The outer limit of the margin is defined by geomorphic and geological principles, and delimited by straight baselines, connecting points which are either: 1) no more than 60 nautical miles beyond the base of the continental slope, or 2) where the thickness of sedimentary rock beneath the continental rise is no less than one percent of the distance beyond the base of the continental slope.

The above limits are further restricted to a distance of no greater than 350 nautical miles from the coast, or a water depth of 2500 metres plus 100 km, whichever is greater. The compromise required to obtain broad support for the wide margin formula was an undertaking to share, with the international community, the revenues from mineral resource production from the continental margin beyond 200 miles, on the basis of up to seven percent of the value at the wellhead or minesite. The Law of the Sea Treaty is not yet codified as international law, the next step being the signing of the Treaty in Caracas in December 1982, after which it will be open to ratification by individual countries.

Article 76 requires each coastal state to establish the outer edge of its sovereign rights according to the specified definitions and instructions, wherever the margin extends beyond 200 nautical miles. The approximate position of this limit is shown in Figure 6.

In addition to the general international issue of the outer limits of national jurisdiction over seabed resources, as required by Article 76, Canada must make specific bilateral agreements with neighbouring countries. These agreements will be concerned primarily with the delineation of offshore boundaries for mineral and other resource purposes between Canada and the United States, in the vicinities of the Gulf of Maine, Strait of Juan de Fuca, Dixon Entrance and Beaufort Sea. There are also similar unsettled offshore dividing lines relating to the French islands of St. Pierre and Miquelon. The offshore dividing line between the Danish territory of Greenland and Canada in the Davis Strait and Baffin Bay (Figure 8) was determined by bilateral agreement in 1973. Agreements must still be negotiated for the section north of 82° 13' latitude.

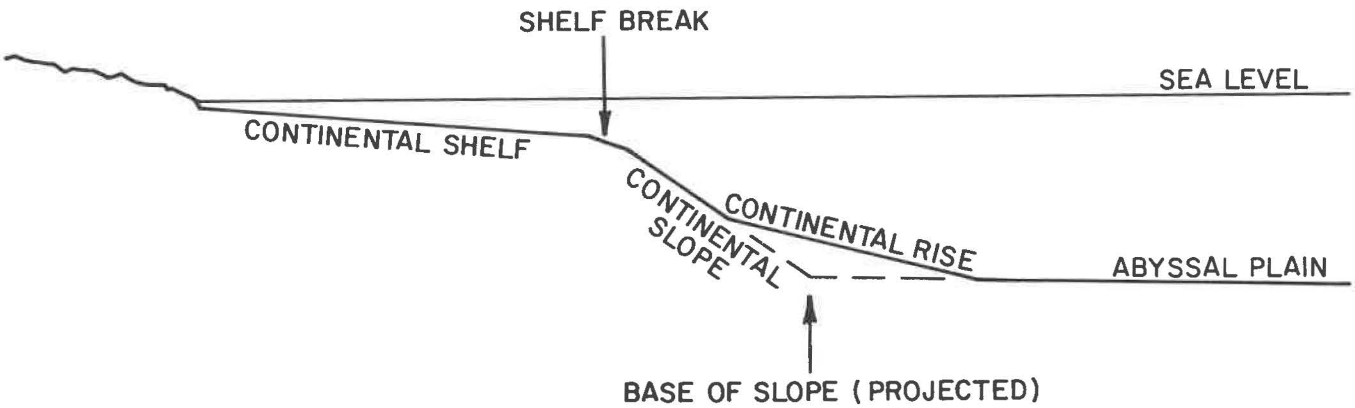
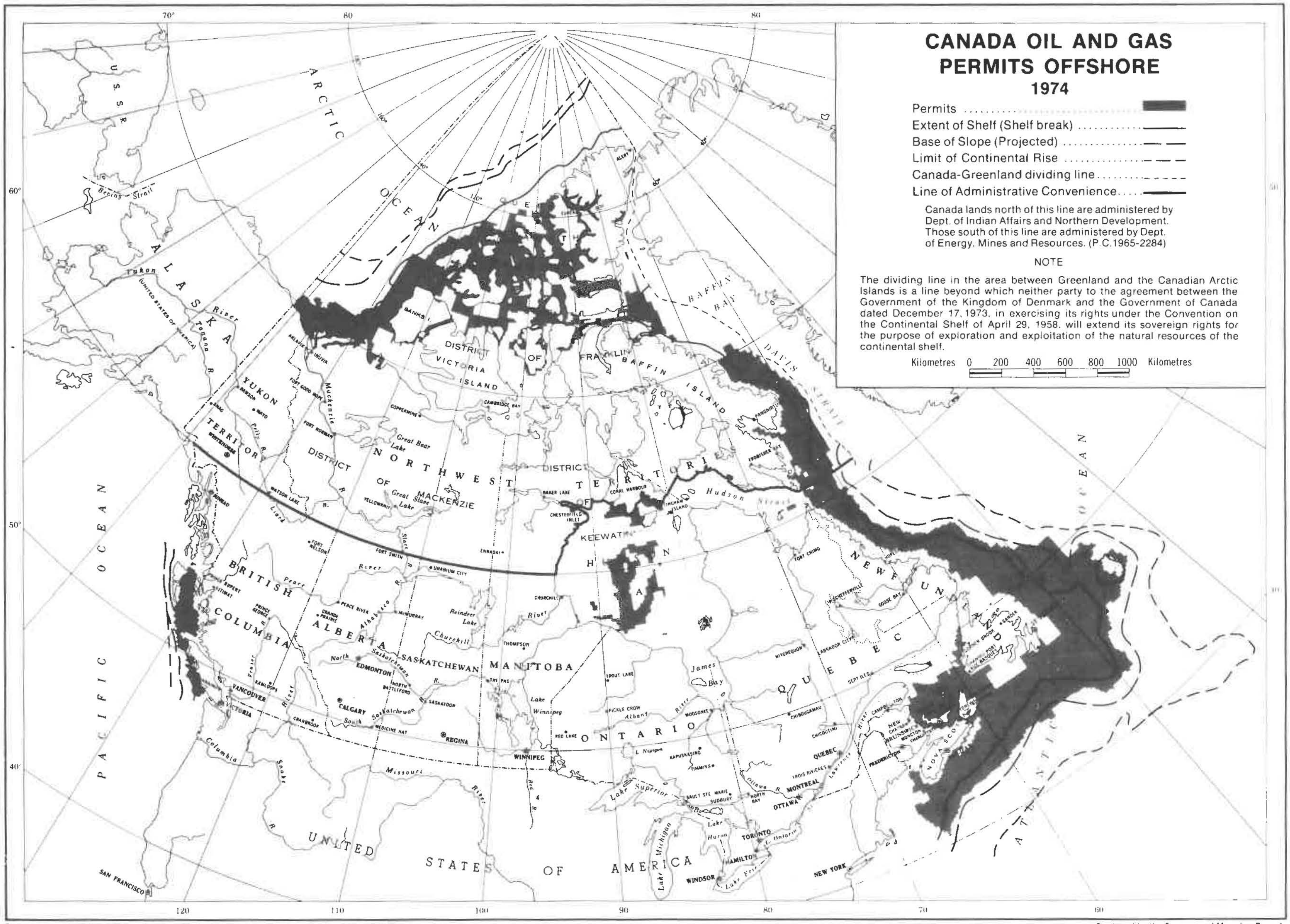


Figure 7

Schematic Profile of Continental Margin



Produced by the Surveys and Mapping Branch, Department of Energy, Mines and Resources.

Figure 8

Canada Oil and Gas Permits Offshore, 1974

The Sequence of Events Leading to Drilling

Exploration for oil and natural gas in Canada's Offshore depends upon a continuous knowledge of geographic position. Exploration on land also requires this information. The difference lies in the total lack of local stationary reference marks at sea and the complete reliance upon electronic hardware to produce a numeric coordinate (position fix) which relates the observer's position to a consistent reference frame. Section 9 of the Canada Oil and Gas Land Regulations specifies that this reference frame should be the 1927 North American Datum (NAD27).

Successive position fixes, commonly called events, are bound together by time interval measurements and ship velocity components. In the early stages of exploration, no positional reference marks are established.

The activities leading to the production of hydrocarbons from offshore regions generally exhibit a pattern in the following stages.

- Regional Reconnaissance — Deep Seismic Survey Ship Operation

  In this preliminary examination of sub-marine sediments, the purpose is, to look for leads, i.e., something that might indicate the presence of structural or depositional features. The geometric layout for such a program will depend on many factors including budget, and existing knowledge of the area. The line spacing might be between 5-10 km, and by arranging the spacing of the hydrophones on the streamers in an appropriate relation to speed of travel, a "pop" interval is arrived at. The "pop" interval is commonly about 25 metres throughout the whole program. In a moderate size job, some 10 000 shot-points may be activated and each one of these must have a discrete and consistent position determination.

- Semi-detailed Seismic Study — Deep Seismic Survey Ship Operation

  This is a follow-up to the reconnaisance survey and it provides a closer look at the anomalies which were detected at that time. They are measured and plotted so that the geologist can estimate the entrapment possibilities for hydrocarbons.

  To achieve a better appreciation of the reservoir size, the line spacing must be reduced considerably. An appropriate line spacing could be 500 m without changing the streamer configuration. Here again a large number of shot-points will be recorded and since the purpose is to find likely spots to drill for oil and gas, it will at some time be necessary to return to certain shot-point positions which are identified as optimum drilling positions. This points up the importance of survey system accuracy. The subsequent positioning of the drilling unit will be done using a different survey system. There must be no systematic error in either system which would prevent an accurate correlation of positions.

- Sea bottom Study — Shallow Seismic Survey Ship Operation

  Having mapped the outline of a prospective geological feature, the next logical step is to drill an exploratory or wildcat well but such a step must be preceded by a thorough study of the sea bottom around the proposed well site in order to anticipate subsurface hazards, anchoring problems, and other factors.

  Section 89 (3) of the Canada Oil and Gas Drilling Regulations requires a prognosis that provides information with respect to the oceanographic conditions, and the topography and composition of the sea floor. Appendix E of Section 89 (3) outlines in some detail the specific bathymetric, morphologic, sedimentary, biotic and hazardous conditions to be investigated and reported on prior to actual drilling.

  The garnering of this information generally requires the employment of a survey ship equipped with echo-sounder, sub-bottom profilers, sidescan sonar, under-water camera and light, and an energy source such as sparker or airgun. This ship is commonly smaller than that used for deep seismic operations. The process involves running a series of lines at approximately 400 metres. A minimum area of 2 km × 2 km around the wellsite must be studied but in practice the area could be much larger to accommodate the drilling of several holes.

- Exploratory or Development Well Location — the Positioning of a Drilling Vessel

  Objectives

  A drill-rig positioning survey should accomplish two principal objectives: 1) re-occupy the shot-point chosen as a result of the geophysical surveys as the optimal place to drill and 2), satisfy the legal requirements set down in the Canada Oil and Gas Land Regulations (COGLR).

  These objectives require the expertise of a survey engineer who understands the inherent accuracies, error sources, and types of blunders that occur in the positioning equipment used for dynamic and static surveys. Such expertise is to be found within the ranks of the new CLS Commission holders.

  Section 18 of COGLR calls for a tentative plan to be prepared which illustrates the position of the proposed hole. It should describe the proposed method of survey and the source of its control. Sections 19 and 20 of COGLR deal with *actual* well surveys. Section 19 (1) and 19 (4) require the survey plan to denote the surveyed position of a suspended or abandoned well with reference to the control system on shore. A description of the assumed parameters of the survey system and the shore station markings used must be provided. Should oil or gas be discovered in quantities of commercial signifiance and a decision made to "complete" the well with a view to production, Section 20 then requires that a plan of legal survey, approved by the Surveyor General, be submitted to the administrator of COGLA. This plan must show the legally definitive location of the well with reference to the unit and section boundaries within the appropriate grid area.

  The word "completed", with respect to a well, has a particular connotation in these Regulations. It does not signify merely the finishing of work required but rather the preparation of the well casing so that production could be maintained either immediately or at some future date. It is more specifically defined in Section 2(2)b of COGLR. Exploratory wells are rarely completed. Once a commercially viable field has been discovered and delineated, wells designed specifically for production are drilled. These are termed Development Wells. Section 21 then requires a plan of legal survey.

Procedures

Drilling rigs are constructed in various shapes and sizes. They can be self-propelled, dynamically-positioned or completely dependent upon work-boats for their propulsion. They can be ship-shaped, triangular, rectangular, pentagonal or otherwise. They may stand on the sea floor (jack-ups and submersibles) or float (semi-submersibles and drill ships).

Rig positioning is a complicated, costly and highly developed technique. It depends, for its success, not only upon a thorough knowledge of positioning systems but also upon a clear understanding of the functions and responsibilities of various personnel involved, (tow-master, surveyor, tool-pusher, the company drilling supervisor, etc.) and upon adequate comprehension of the sea-state and weather conditions. The approach plan needs careful preparation but should remain flexible to accommodate possible changes in weather, light conditions and other factors. Because rig operation at sea can cost upwards of $1 000 000 per week, any delay on the part of the surveyor must be fully justifiable. The geologist prescribes to the surveyor a target area within which the rig is to be positioned.

In ordinary cases, the survey vessel references the drilling position by anchoring a pattern of buoys surrounding the approximate site. The drilling vessel moves over the site, the anchors are placed and a static survey is begun. Usually some adjustment to the position will be required and this is performed by anchor-chain tension manipulation, thruster activation or work-boat tugging action.

The electrical centres of rig-mounted survey hardware, such as satellite-receiver and radio navigation antennae (e.g., Loran C), are seldom positioned exactly above the well bore. It is necessary to relate the well bore's position to the electrical centre by measurement of the distance and azimuth of the line joining them. Knowledge of this azimuth is gained by observing its relationship to the rig heading. Rig heading must also be determined by the surveyor to conform to the operator's pre-assigned favoured direction. This is done to facilitate helicopter landings and work-boat cargo transfer.

- Delineation Wells and 3D Seismic Study

If the exploration well has found oil or gas, the operator will then assess the extent of the reservoir. At this stage, a three dimensional (3D) seismic program is initiated to survey the anomaly; this time at a much greater density. A 3D seismic program generates a closely related volume of data and this is processed in a variety of ways to develop an understanding of reservoir size and characteristics. Line spacing is close (75 m is common) and for that reason survey precision must be high. If evaluation of the 3Ddata indicates that the reservoir may be viable, delineation wells may be drilled to prove its size and content.

- Engineering Surveys Required for Artificial Islands in the Beaufort Sea

To ensure stable platforms for drilling that are safe from moving ice floes, tides and current action, artificial islands are commonly being built in the Beaufort Sea. The design of artifical islands is an evolving technology. Hard and fast rules do not exist. Standards for maximum water depth and minimum island dimensions have not been established. Two main types of artificial islands have been used:

— Sand Only
  This involves the dredging, transport, and dumping into place of large volumes of sand in up to 20 m of water, resulting in a cross-section as shown in Figure 9.

— Caisson on Sand Berm
  A second technique involves the use of sand-supported steel or concrete caissons. These reduce the quantities of sand required and the time needed for construction. Various caisson designs are being employed but generally a cross-section such as shown in Figure 10 is used.

For some aspects of this work the primary requirements for a positioning system are good repeatability and convenience. For example the dredge must be able to return to the same spot efficiently and the dredged material deposited without delay in limited areas. For other aspects, where positions which may derive from different systems must be correlated, the prime requirement is accuracy. For example, different systems might be used for picking the site for drilling, locating suitable fill material, studying subsequent island erosion, surveying for pipeline routes ice movement, and location of pingos. The surveyor must be aware of the capabilities and limitations of various positioning systems.

- Pipeline Surveys

Draft regulations designed to control the laying and the operation of pipelines in the offshore are being developed but have not been proclaimed as yet. They have been revised by several government and industry groups. Those portions of the regulations which relate to surveys govern primarily the approval and engineering aspects of pipelines and do not address legal survey requirements.

Positioning capability is essential at every stage of offshore pipeline development. Reconnaissance, route selection, pipe lay-down, servicing, twinning and product-accessing all require the ability to return to the same point. Positional information must be referred to in public documents and accurately plotted on hydrographic charts. It is important to relate the position of a pipeline to other facilities and to hazardous features either natural or man-made.

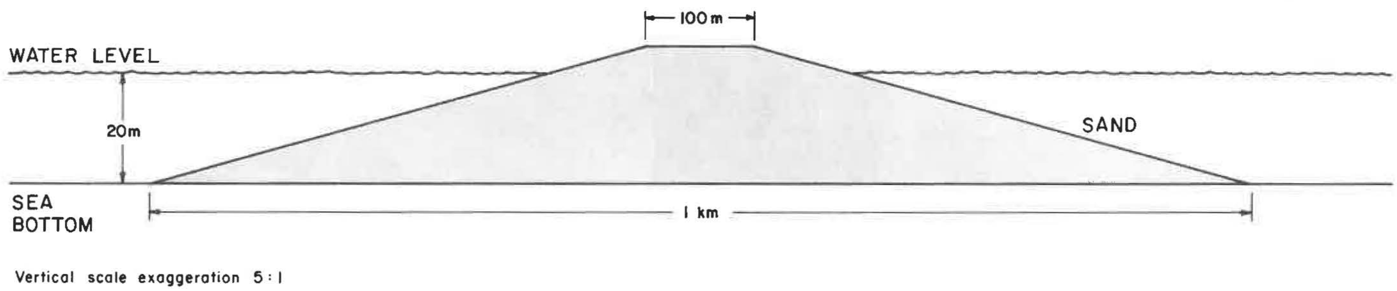


Figure 9

Profile of a Typical Artificial Island Built of Sand only

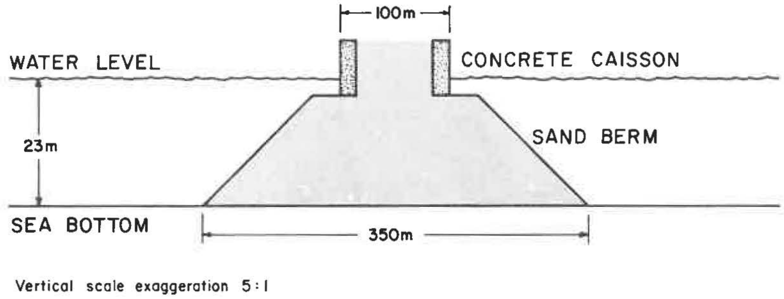


Figure 10

Profile of a Typical Artificial Island Consisting of a Caisson on Sand Berm

It is the practice to protect onshore pipeline installations with an easement, title in fee simple, lease or other legal disposition which is based upon a unique and surveyed strip of land or right-of-way. Problems exist in granting this kind of protection over offshore land beyond the limit of the Territorial Sea. The Law of the Sea agreements will dictate the nature of protection that can be granted for rights-of-way.

Chapter 2

Resource Management of the Canadian Offshore

The responsibility for the management of non-renewable resources in Canada's offshore areas is shared by the Minister of Energy, Mines and Resources and the Minister of Indian and Northern Affairs under two common parliamentary Acts (*The Canada Oil and Gas Act* and the *Oil and Gas Production and Conservation Act*) and their associated Regulations (The Canada Oil and Gas Land Regulations, The Canada Oil and Gas Drilling Regulations, the draft Canada Oil and Gas Production Regulations, and the draft Canada Oil and Gas Pipeline Regulations). The areas of ministerial jurisdiction are defined by a line of administrative convenience (Figure 8). In order to achieve a uniform and even-handed administration of the offshore rights, the Ministers have created the Canada Oil and Gas Lands Administration (COGLA). That administration is responsible to each of the two Ministers for the administration of the non-renewable resources within the individual jurisdictions, including the disposition of rights.

The recently adopted *Canada Oil and Gas Act* provides a management regime for oil and gas rights in the offshore areas. The primary document is an Exploration Agreement which provides the exploration rights to a specific surficial area and the exclusive right to apply for a Production Licence. The Production Licence provides the exclusive rights to produce and sell oil and gas under a specific surficial area. Figure 8 shows the areas of exploratory interest during 1974 when rights were administered under permits issued under the previous regulations. As a result of the new Act, all these rights are now being renegotiated. There will be changes in the exact areas held but the general areas of interest remain as in 1974.

Exploration for oil and gas may be conducted under an Operating Licence issued under the *Oil and Gas Production and Conservation Act*; however, as no exclusive benefits are derived from the exploration, it is not widely used by industry. The *Oil and Gas Production and Conservation Act* provides the basic industrial regulation in operational activities.

Minerals, other than oil and gas, are administered by the two Ministers under the Canada Mining Regulations made pursuant to the *Territorial Lands Acts and the Public Land Grants Act*. The minerals within the jurisdiction of Indian and Northern Affairs are managed by the Mining Division within the Northern Affairs Program, while COGLA provides management of minerals for the Minister of Energy, Mines and Resources.

Exploration Operations

Since 1966 a total of 242 wells have been drilled offshore; 14 off the West Coast, 3 in Hudson Bay, 6 in the Gulf of St. Lawrence, 1 in the Bay of Fundy, 155 off the East Coast, 41 in the Beaufort Sea (19 from drill ships, 22 from artificial islands) and 23 from ice platforms in the Arctic Islands.

The technology of producing oil and gas in ice-covered or ice-congested waters, and in waters where icebergs are a threat, is still at the research and development stage in the oil and gas industry.

The following is a chronological summary of drilling in the Canadian Offshore:

1966: Two wells by Pan Am-Imperial on Grand Banks.

1967: Mobil Oil Canada's first Sable Island well and Shell Canada's first wells off the west coast.

1968: Shell's continuous drilling program off the west coast.

1969: Shell's drilling off the west and east coasts. Drilling by Aquitaine in Hudson Bay.

1970: Shell's continuous drilling on the Scotian Shelf. Two wells by Hudson's Bay Oil and Gas in the Gulf of St. Lawrence.

1971: Drilling on the Scotian Shelf continued by Shell and commenced by Mobil. Continuous drilling commenced by Amoco-Imperial on the Grand Banks. Well by Tennoco et al on the Labrador Shelf and by Elf Oil on the Grand Banks.

1972: Drilling off the east coast continued by Shell, Amoco-Imperial and Mobil.

1973: Drilling off the east coast continued by Shell Amoco-Imperial-Skelly and Mobil-Gulf. Wells drilled by Eastcan et al on the Labrador Shelf. One well commenced by Elf Oil off the east coast. The first well Immerk B-45 was drilled from an artificial island, in 3 m of water in the Beaufort Sea.

1974: Continued drilling by Shell, Amoco et al and Mobil et al off the east coast. Wells by Union and Texaco on the Scotian Shelf, by Eastcan et al and by BP Canada et al in the Labrador Sea, and by Aquitaine et al in Hudson Bay. Panarctic drills first well from reinforced ice platform off Melville Island.

1975: Continued drilling by Mobil et al off the east coast. Resumption of drilling by Eastcan et al and by BP et al in the Labrador Sea. Setting of silos by Dome Petroleum for 1976 drilling in the Beaufort Sea.

1976: Dome commences drilling with drillships in the Beaufort Sea.

1978: First sub-sea completion in the Arctic Islands, Drake F-76.

1979: Whitefish, Venture Hibernia and Koponar all discovered. Blue H-28 drilled in world record water depth of 1 486 m by Discoverer Seven Seas.

1980: Tarsiut, Char, Balaena and Hekja all discovered. Year round drilling on the Grand Banks.

1981: First caisson retained island in the Beaufort Sea. Cisco, Skate and Maclean discovered in the Arctic Islands.

Control of Oil and Gas Operations

Comprehensive control over all oil and gas operations in the Canadian offshore including safety of personnel, the conservation of resources, and the prevention of waste and pollution is provided for under the *Oil and Gas Production and Conservation Act*. The Act's broad authority covers exploration, drilling, production, conservation, storage, transmission, distribution, measurement, processing and other handling of oil and gas. The Act applies to all areas of the Canadian offshore as well as the land areas of the Yukon and Northwest Territories. Section 3 of the Act reads:

> "3. This Act applies in respect of oil and gas in any of the following areas, namely:
> a) the Yukon Territory or the Northwest Territories;
> b) Those submarine areas adjacent to the coast of Canada to a water depth of two hundred metres or beyond that limit to where the depth of the superjacent waters admits of the exploitation of the natural resources of the seabed and subsoil thereof; and
> c) any lands that belong to Her Majesty in right of Canada or in respect of which Her Majesty in right of Canada has the right to dispose of or exploit the minerals therein; but does not apply in respect of oil and gas in any such area if the area is within the geographical limits of, or if the administration of the oil and gas resources in the area has been transferred by law to any of the ten provinces of Canada."

Regulations relating to drilling, the Canada Oil and Gas Drilling Regulations, have been enacted under Section 12 of the *Oil and Gas Production and Conservation Act*. Sections 87 and 104 concern offshore surveying, including the submission by operators of tentative and final well survey plans, and the requirements for legal surveys for development wells and for certain other wells. Section 10 of the Canada Oil and Gas Land Regulations, which were enacted under Section 54 of the *Canada Oil and Gas Act*, provides for access to offshore drilling and production locations as well as and assistance from operators for surveyors on the job.

Chapter 3

Administration of Offshore Surveys

The management and regulatory control of oil and gas exploration and development operations by a number of companies, for varying periods over many extensive areas of the Canadian continental margins, require a system which clearly defines unique locations and boundaries. Such a system for the offshore must provide the same services as a land system; that is, it must facilitate the issuance and maintenance of the mineral rights granted for a specific area, be designed to prevent disputes between adjacent holders of rights, and provide a means of reconciling any disputes that might occur.

For the Yukon Territory, the Northwest Territories, and the Canadian Continental margins, the same geographically defined grid system is used to delineate rights relating to oil and gas exploration or development. The system is defined in Sections 4 to 9 of the Canada Oil and Gas Land Regulations. For exploratory rights the basic unit is a grid area which extends ten minutes (approximately 19 km) in latitude and either 15' or 30' in longitude depending on the latitude. For assigning development rights the grid areas are subdivided into approximately square sections extending one minute (approximately 2 km) in latitude.

Other countries which have offshore petroleum developments also delineate development rights by geographically defined grids. Regulations relating to surveys are generally minimal and operators have commonly cooperated amongst themselves and with the host country to provide more or less integrated survey systems. Appendix A is a review of regulations for the North Sea developments and a representative sample of other areas; offshore from Gabon, Tunisia, the United Arab Emirates, Brazil, and China.

A geographic grid is also used to delineate exploratory rights for hard minerals in the Northwest Territories but it is not the same grid as used for oil and gas. It is defined in sections 29 and 2 of the Canada Mining Regulations and is based on the NTS (National Topographic System) of 1: 50 000 map sheets. This grid could be extended offshore if a need arises. However, for administering mining rights under the Canada Mining Regulations, a geographical grid is not used; the basic unit is a claim, the boundaries of which must be marked on the ground by stakes or monuments. For claims near shore, submerged staking procedures can be used but they are unsuitable for defining rights more than a few hundred metres offshore. The 1970 Workshop on Offshore Surveys recommended that a geographically defined grid system be established for defining terminable grants for mining rights on the Canadian shelf. It is anticipated that if economically viable hard mineral deposits are discovered offshore, a geographical system will be established.

Boundaries and Monuments

On land, boundaries are generally defined by physical monuments placed in the ground, and their positions and descriptions are recorded. However, oil and gas grid areas and their subdivisions are not monumented but are defined in terms of geographic coordinates. To establish the position of the geographic grid, measurements must be made from local control survey markers; the descriptions and positions (coordinates) are available from the Geodetic Survey of Canada, EMR or from provincial authorities. In cases where grid boundaries are monumented, the boundary monuments would govern; in the absence of boundary monuments, the calculated distances from the nearest control monuments define the position of the boundaries.

The feasibility of establishing a system of offshore control monuments for resource administration on the Canadian shelf was a major concern of the first Workshop in 1970. The three basic requirements for survey monuments are permanance, clear definition and accessibility. These three requirements are essential to confirm the position of a boundary or to extend a survey network as may be necessary to define the position of other nearby boundaries. In the Offshore there are also significant economic and national security aspects to providing monumentation. Many means of monumentation, including towers, buoys, transponders, reflectors, abandoned wells, submarine cables, wrecks, seafloor topography, and gravimetric and magnetic field anomalies were considered by the Workshop and deemed inadequate. Only survey monuments established on fixed development platforms (figure 13) satisfy the three basic criteria of permanence, clear definition, and accessibility. Corrosion, disturbance by fishing gear, and inordinate cost preclude the establishment of permanently-monumented control on the continental margin prior to the establishment of development structures. The detailed findings of the first Workshop on offshore monumentation are reprinted in Appendix G.

At sea, as on land, there is no need to monument the boundaries of oil and gas rights granted by permit, lease, or agreement. The survey requirement is that the position of the theoretical grid boundary be known relative to any well and to the limits of the field. Providing that all surveys are based on the same reference frame and that their accuracy is adequate, the boundaries of rights can be determined and production procedures regulated without reference to boundary monuments.

Offshore surveying becomes more difficult with increasing distance from shore, largely because of the absence of local control monuments. The configuration of the coast line, the depth of water, and the presence of ice add serious difficulties for offshore surveyors. Other sections in this report provide information on how to deal with these difficulties.

The absence of monumentation or other devices to make a grid boundary visible does not inhibit the development of an oil and gas field, whether on land or offshore. In the event of a prospect being discovered by geophysical means, in the neighbourhood of a boundary between different operators, arrangements for exploratory drilling are usually made on a cost-sharing basis. At the development stage, wells are normally positioned to provide for optimum production of the field.

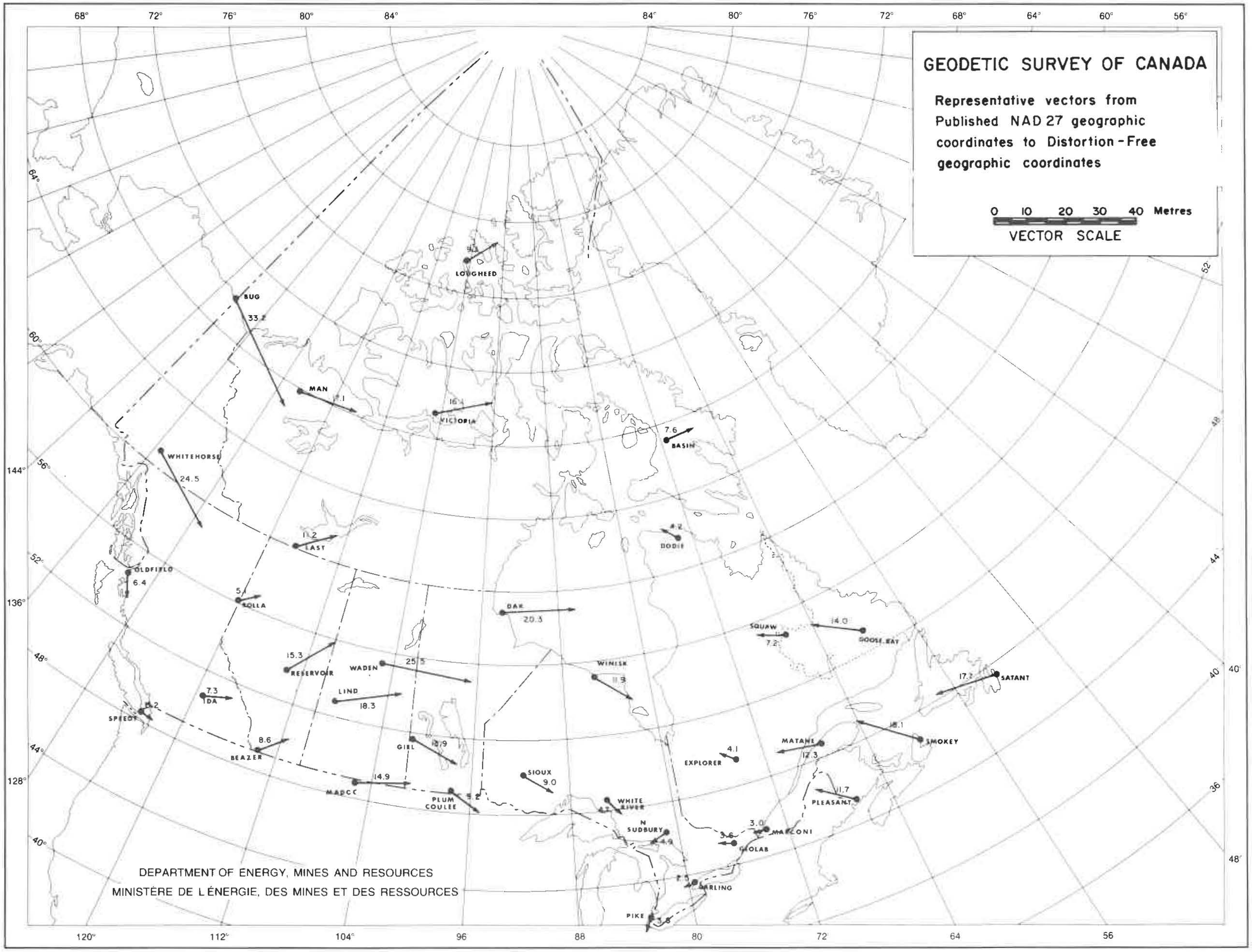


Figure 11

Distortion in the 1927 Datum

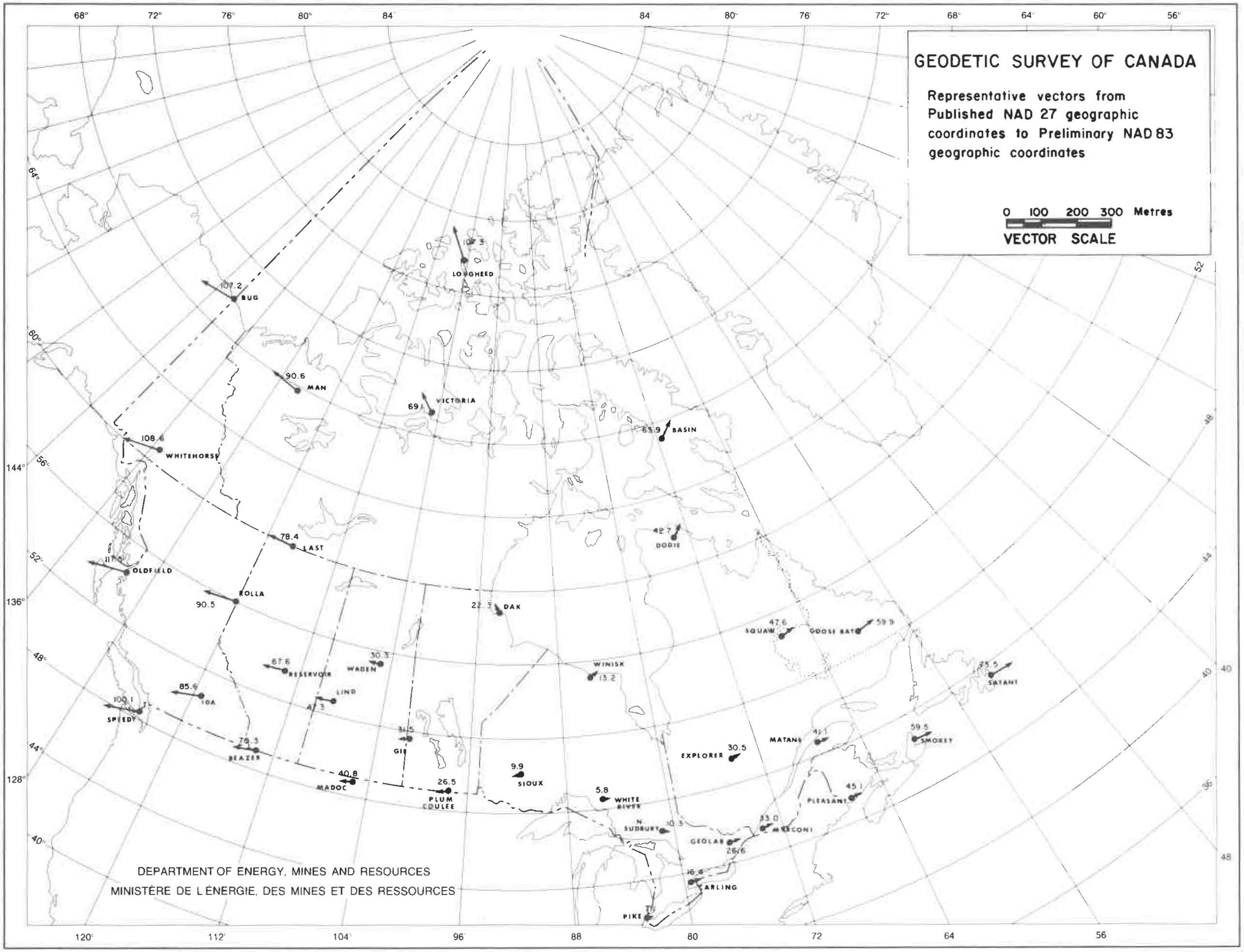


Figure 12

Shift in Position from the NAD27 Geographic Grid to the NAD83 Geographic Grid

The well position relative to a grid boundary is important because it allows the operator to relate the position of the prospective reservoir to the permit boundaries. This information, along with information on geological structures and properties, is necessary in the developmental stage to negotiate agreements on an equitable assignment of mineral rights, royalties and field costs among the operators. The geological factors are generally less accurately known than the boundary positions.

Monuments and Datum Considerations

Although a geographically defined grid is used to delimit rights so as to provide a theoretically perfect system, there is in practice, more than one geographic grid with significant differences. A particular reference system must be specified. In Canada and USA, the established reference system consists of lists of coordinates for control monuments referred to as "1927 NAD" or "NAD27" coordinates and published by the Geodetic Survey of Canada. For onshore surveys, the positions of the grid lines could be established by measuring appropriate distances from the nearby monuments. However, in the offshore, ties to nearby stations may not be feasible, and the nearest monuments may be hundreds of kilometres away from the survey area. Offshore positions may be determined by satellite based or hydrographic survey systems, usually based on a reference system different from the published 1927 NAD coordinates. There are significant differences, up to about 100 metres, between the coordinates of the same point with respect to these datums. Methods of transforming positions on one datum to positions on another datum are discussed in other chapters.

Because there are significant distortions in the 1927 datum that are clearly evident using the regular survey methods, a new datum termed "NAD83" is being developed. It will be based on a new reference figure which is a better world fit than the one used for NAD27. Because of this change in the reference figure, there will be larger changes in coordinates from NAD27 to NAD83 than would have resulted from a readjustment based on the original reference figure. Although the initial adjustment of the primary framework is expected to be completed in 1984 or 1985, the lower order networks will not be completely integrated into the primary control nor will comprehensive coordinate lists become available until approximately 1987. However, estimates of the changes in coordinates can now be made for stations in the primary networks. These estimates can give an accurate assessment of relative errors of stations within a limited region but there remains an uncertainty of a fairly uniform shift of up to about 12 metres which is yet to be resolved. Figure 11 shows the distortions in the NAD27 and Figure 12 gives the difference between the published NAD27 coordinates and the anticipated NAD83 coordinates for primary control monuments across Canada. Administrative procedures have yet to be devised to adopt the new datum, maintain the old datum and handle the boundary discordances between new rights and rights previously granted.

Positioning Systems

In general, early offshore oil and gas fields were found relatively close to shore and, as in the Gulf of Mexico, some are seaward extensions of known fields onshore. Such developments allowed the use of the same accurate, short-range survey systems as used on land. In the Canadian offshore, however, some areas of promise lie beyond the range of land survey systems; consequently,the less precise hydrographic survey systems have had to be used. Early Canadian explorations depended solely upon navigational facilities of a very low order of accuracy.

Even now, some geophysical surveys use marine navigation systems which were not designed to provide high absolute accuracy. Such systems, during their establishment in a locality, can provide a reliable means of returning to a position or of relating positions within a limited survey area. These systems are said to have good repeatability. However, the positions relative to the reference frame may not be adequately determined, in which case the system is said to have poor accuracy. A system with good repeatability but not necessarily good accuracy may be adequate if the essential requirement is the ability to return to a point while using the same system. If there is a possibility of returning to a point using a different survey system or relating a survey to a grid boundary, then a system with good accuracy is necessary.

Defining a Well Location

The Canada Oil and Gas Land Regulations require the position of every well drilled on Canada lands, onshore or offshore, to be determined by a survey. A well is defined in the regulations as being an opening in the ground. For a well drilled on land the definition presents no particular difficulty and, even after the well has been plugged and abandoned, a permanent marker remaining at the site can be used by the surveyor. In the offshore, a more practical point for positioning is the drill string at the elevation of the drilling platform or, more specifically, the Kelly-bushing.

If the well is drilled from a fixed platform or a bottom-supported jack-up unit, any horizontal offset between the position of the Kelly-bushing and the position of the well at the seafloor must be supplied by the drilling engineer. For a floating drilling unit, the surface position of the Kelly-bushing, relative to its position over the wellhead on the seafloor, is continually monitored and adjusted to the vertical.

Furthermore, when an offshore well has been plugged and abandoned, no trace of its previous existence is normally visible, and as a rule, no equipment is left on the seafloor to obstruct other legitimate users of the sea. The positioning survey for an offshore exploratory well must be undertaken before abandonment and in practice will be started immediately following spudding in.

Downhole Surveys

Section 21 (b) of the *Canada Oil and Gas Land Regulations* requires that the locus of the drill hole with respect to the unit and section boundaries be shown on the survey plan. The measurement of the displacement of the drill bit from the wellhead position is the responsibility of the drilling engineer. If multiple hole drilling platforms (Figures 13 and 14) are used for development wells, the accuracy and reliability of the downhole surveys are of critical concern. Inclinometers and magnetic or gyro compasses are commonly used for this purpose. With the decreased accuracy of gyroscopic and magnetic techniques in the high Arctic, knowledge of the drill bit position becomes less accurate. This problem may require research in the development of alternate methods for downhole surveys. Scott and MacDonald (1979) and Wolf and DeWardt (1980) have done studies relating to the uncertainty of downhole surveys.

Monuments and Underwater Completions

Oil or gas production from the Canadian offshore has not yet begun; however, if an offshore oil or gas field is developed using underwater completion and production techniques (Figures 5 and 14), the underwater structure could provide a base for a survey monument. A point on the structure could be marked or described as the survey monument. To make a survey tie to such a monument, the position of a surface vessel relative

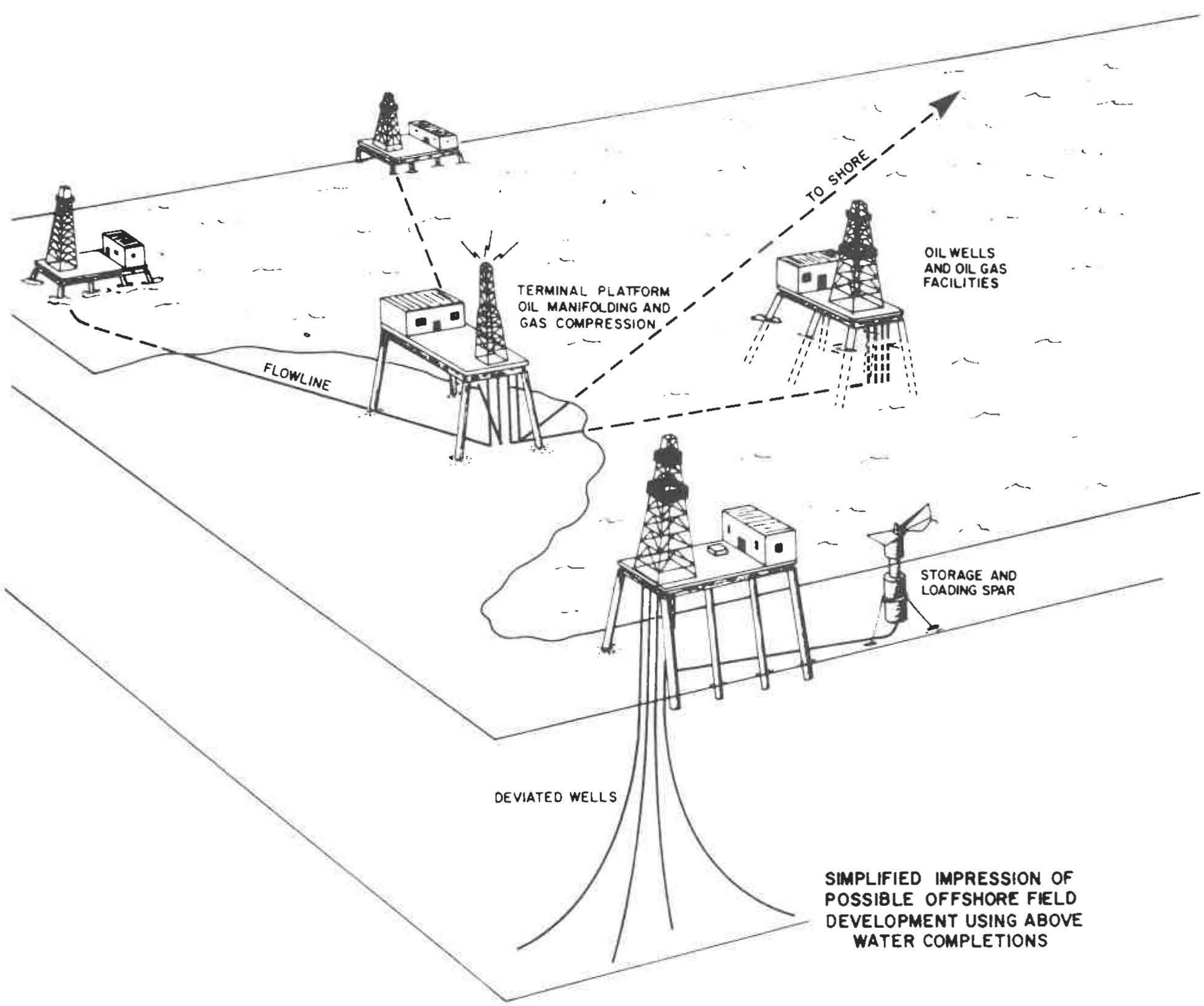


Figure 13

Field Development Using an Above-Water Completion Arrangement

to that of the monument would have to be determined. The offshore oil industry has developed a variety of techniques to accomplish this accurately, while a floating drilling unit is over a well.

If control were to be extended from the monument after the drilling unit has departed, a system of adequate accuracy would have to be devised to relate the monument's position to that of a survey vessel substituting for the drilling unit. This would undoubtedly involve the same techniques used by industry to locate and return to the subsurface structure. The surveyor must become familiar with the principles and mechanics of these techniques, in order to assess the various sources of error and the relative accuracy of the system. Considerable research is necessary before the survey problems associated with subsurface completions can be resolved.

Positioning Reports for Exploratory Wells

The three essential purposes of the regulations relating to positional surveys for an exploratory well are: to ensure that reliable methods are employed to determine the geographic position of the well; to enable an operator to relocate and return to a well where operations have been suspended, should the need arise; and to enable a relief well to be drilled from another rig in order to intersect the geological formation at the point where a well may be blowing out of control.

For these reasons, the operator must supply, to the regulatory agency, a survey plan and a full report of the position fixing systems used. The survey methods used must allow for the positioning to be assessed and repeated, and all shore stations used to fix the well position must be permanently marked and described in the survey plan. Specifications for the positioning

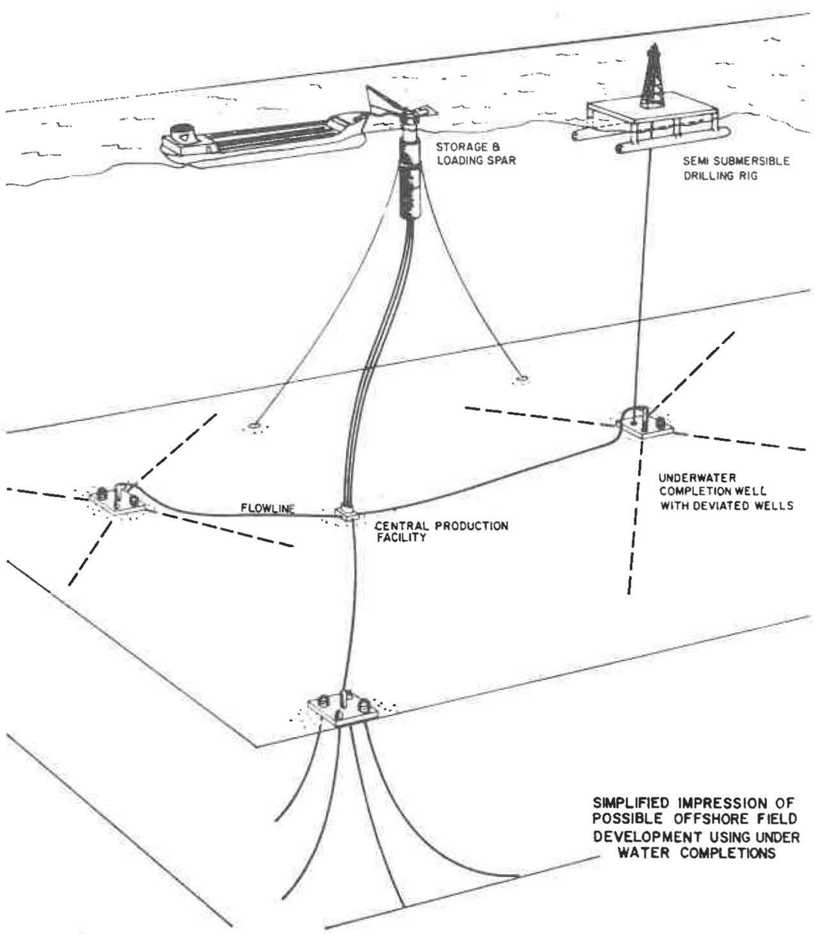


Figure 14

Field Development Using an Underwater Completion Arrangement

reports of exploratory wells are given in Appendix E. The plan and report are to be submitted to the Canada Oil and Gas Lands Administration in Ottawa. These plans and reports are then forwarded to the Surveyor General for his review and for filing in the Canada Lands Surveys Records.

These positioning reports (and plans) for exploratory wells do not carry the status of Legal Surveys and are subject to revision if more accurate or reliable surveys are subsequently made. The positions of the boundaries of the grid area or its subdivisions, in relation to the well, are not fixed by the survey.

Canada Lands Surveyor Qualifications

Recommendations arising out of the 1970 Workshop on Offshore Surveys were instrumental in the formation of a Committee on Dominion Land Surveyor qualifications, chaired by C.H. Weir under the aegis of the National Advisory Committee on Control Surveys and Mapping (NACCSM). The purpose of the committee was to seek out procedures to restructure the profession in its federal aspects in view of technological advances and a requirement to revise the Canada Lands Surveys Act, thus providing for a new commission replacing the DLS and DTS. The Committee recommended a broadening of the qualifications to include a knowledge of the principles of surveying in the offshore.

As a result, the Act was revised in 1979 and the previous DLS commission was changed to a Canada Lands Surveyor commission which now covers a broader range of expertise including geodesy, hydrography and photogrammetry. The Surveyor General's *Manual of Instructions for the Survey of Canada Lands*, has been modified to include specific sections on offshore surveys. The initial process of commissioning surveyors from other fields, through the Grandfathering clause, has now been completed. There are now many Canada Lands Surveyors who have the required skills to do offshore legal surveys.

Legal Surveys

Positioning reports for development wells must take the form of a legal survey which is normally carried out as soon as is practical after a drilling structure is on location. A legal survey may occasionally be required for wells other than development wells. (Sections 12 and 20 COGLR) The essence of a Legal Survey is that it provides monumentation and is legally definitive. It provides legally definitive coordinates to monuments (or wells) and is regulated by the Surveyor General of Canada. The purpose of a Legal Survey is to identify conclusively the position of boundaries relative to local monuments and to wells, regardless of any survey imperfection. Within a grid area cell boundaries are defined by the theoretical distances from the initial well in that area.

Legal coordinates are unchangeable even if future or more accurate surveys indicate that a more accurate position could be derived; this is fundamental. In effect, the monuments become witness monuments to the boundaries and the legal coordinates correspond to call distances. For scientific purposes or to provide control for a grid area outside the one in which the monument is situated, the Dominion Geodesist or Surveyor General may assign coordinates different from those that are legally definitive within the grid area.

During the production stage, there must be a permanent structure at the wellhead. A point on the structure which can be clearly and easily defined can be chosen and classed as a survey monument. This will provide a reference point by which other wells in the same grid area can be accurately and effectively related to the first well and to lease boundaries. If underwater completion structures are used (Figure 14), measurements from the underwater monuments could be made, but they would be more difficult than those made from a structure above water (Figure 13).

Part E of the Surveyor General's *Manual of Instructions for the Survey of Canada Lands* deals with offshore legal surveys under the Canada Oil and Gas Land Regulations.

International Boundaries and Dividing Lines

Canada's international boundary with the United States is marked by many types of land monuments. For offshore extensions of the boundary it has not been possible to erect monuments in the conventional manner. By the treaty of 1908, the International Boundary Commission required that parts of the international boundary on the coasts between the territorial waters of Canada and the United States be demarcated by the permanent range marks established on land. Two such offshore boundaries pass through Passamaquoddy Bay to the Atlantic Ocean and through Georgia, Haro and Juan de Fuca Straits to the Pacific Ocean. Within the bays and straits, the reference points were marked by large triangular concrete pyramids which serve as range marks or cross-range marks for the courses of the boundaries. Tall, steel range towers have been built on Point Roberts which allow the line to be determined in Boundary Bay and in the Strait of Georgia.

Boundary turning points farther from shore are referenced to monuments, range beacons or lighthouses to define the boundary for some distance from land. Some of the lighthouses used have frame structures, consequently their destruction and/or replacement may occur. To recover their exact location, witness marks have been established and their distances and directions from the lighthouses accurately determined.

Canada's continental shelf adjoins that of the United States in four separate locations — the Gulf of Maine, seaward of Juan de Fuca Strait, seaward of Dixon Entrance and in the Beaufort Sea. As yet, no agreement has been reached between the United States and Canada regarding the extension of defined boundaries across the continental margin in these areas, for the purpose of exploration and exploitation of mineral resources. And, no agreement has yet been reached between France and Canada regarding the mineral rights around the islands of St. Pierre and Miquelon.

In an agreement dated December 17, 1973, the governments of Canada and Denmark agreed on a dividing line between Greenland and the Canadian Arctic Islands beyond which neither country will extend its sovereign rights for the purpose of exploration and exploitation of the natural resources of the continental shelf (Figure 5). The dividing line is defined by lines joining turning points which have assigned geographic coordinates. The agreement does not extend north of 82° 13' latitude.

In accordance with the Territorial Sea and Fishing Zones Act of 1964, Canada has issued, from time to time, coordinates of points based on NAD27 from which straight baselines have been constructed. The straight baselines, in effect, provide a simplified artificial coastline by closing off bays and other indentations while following the general trend of the coast. The waters enclosed by straight baselines are considered internal waters of Canada. The outer limit of Canada's territorial sea is drawn 12 nautical miles seaward from the ordinary low water mark, from straight baselines or from certain lands which become dry at low tide and which lie within 12 miles of the coast. Straight baselines are in effect along the coasts of Labrador, Newfoundland, Nova Scotia, Vancouver Island, and the Queen Charlotte Islands.

Norman L. Nicholson (1979) provides further information on the acts and regulations pertaining to the boundaries of Canada, its provinces and territories. A comprehensive list of maps and charts depicting offshore international boundaries, territorial seas and fishing zones is included in Appendix F.

Chapter 4

Survey Control

Coastal Control

To make economic and effective use of any ranging survey system in order to provide positions of offshore points of the required accuracy, shore stations must be tied to coastal control of at least third-order accuracy. Locations of shore stations must be based on careful and detailed consideration of local topography, and they must be located in such a way as to give satisfactory angles of intersection (cut-angles) between measured lines. It is unlikely that monumented control stations in any particular area will be situated in appropriate locations for shore stations of offshore positioning systems. Control monument accuracy and spacing requirements have been met on nearly all the coastal regions of Canada with the exception of the Southern shores of Hudson Bay and James Bay, where Aerodist and Doppler control exists at 100 km spacing; and, the west coasts of Vancouver Island and the Queen Charlotte Islands, where coastal control is of fourth-order accuracy or lower.

Along much of the mainland coast of northern Canada, third-order control was established prior to the adjacent first-order framework. Some of these third-order surveys have not been subsequently adjusted into the first-order control. Such existing coastal control could be upgraded appreciably by ties and readjustments, if the requirement should arise in some specific area.

Because errors in shore control may be greatly magnified when used to extend control hundreds of miles offshore, it is preferable that the shore control for offshore surveys be of second-order accuracy.

National Geodetic Data Base (NGDB)

Since 1971, the Geodetic Survey of Canada has been developing a computerized storage and retrieval system for geodetic control information. The computerized data file stores coordinates (with their order), elevations, marker data, station data, agency data, identification photography and the text of descriptions. This constitutes most of the control survey information normally requested from the Geodetic Survey of Canada.

The data records for each point are organized by station number and accessed by a "System 2000" database management system. This scheme permits relatively rapid retrieval of records by numerous methods, for example, point number between specified geographic limits or within a given radius of a specified position. The output may be printed in several formats; however,the modular nature of the system allows for easy addition of new formats. The principal difficulties and costs occur in the assembling, coding and validating of the data to be filed. By 1982, data on 126 000 points had been put into the system. It is anticipated that following further development and refinement, the public will be able to have direct access to the file for needed information.

To use the NGDB, a participating agency requires a computer terminal, financial code number, and an access code. Costs would include changes for the communication line and for the computer. In addition to retrieving the basic data supplied by the Geodetic Survey of Canada, an agency may also choose to store its own information in the NGDB, in which case there would be a cost charged for the storage of the disc. Codes may be used to limit access to or to modify specific data.

Scientific Adjustments of Survey Networks

Several large, regional and Canada-wide adjustments of the primary control nets of Canada have been made by the Geodetic Survey of Canada using different reference surfaces or with different types and degrees of constraint. The coordinates of these adjustments are useful for studies of survey systems or datums. Figure 13 is derived from such an adjustment. It should be noted that even if these coordinates are based on the same reference surface as was used for the original NAD27 adjustment, they are not classed as NAD27 values. In order to reduce confusion, they are not released to the general public by the Geodetic Survey of Canada except for specific, limited purposes.

Accuracy Specifications

The orders of control specified in this report are those presented in *Specifications and Recommendations for Control Surveys and Survey Markers 1978*, published by the Surveys and Mapping Branch, Department of Energy, Mines and Resources, 1978 (see Table II). The classification is based on the maximum dimension of the 95 percent confidence region (ellipse) between any two points in the network (after adjustment). The formula for the maximum dimension is:

$$r = C\,(d + 0.2) \qquad (1)$$

where:

r = the maximum dimension (semi-major axis) in cm,
C = a constant depending on the order,
d = the distance in km between the points under consideration.

TABLE I

Relative Accuracy of Published NAD27 Coordinates and Spacing of Monuments Along the Canadian Sea Coast in 1982

	FRAMEWORK CONTROL		SHORE STATIONS		
AREA	Spacing (km)	Semi-major axis of 95% conf. region (ppm)	Spacing (km)	Semi-major axis of 95% conf. region (ppm)	REMARKS
Nova Scotia, S.E., Shore	30	20	15	230	
S. & E. of Nfld.	15-150	100	10-15	230	
Gulf of St. Lawrence	30	60			Some third-order breakdown in southern part. Local datum for PEI, NS, NB is not NAD27.
Labrador Coast	200	60	10	230	
Hudson St.-Ungava	40	20	10	230	Some coastal control not adjusted into the subsequent high-order geodetic triangulation.
Hudson Bay-North	50	20	10-15	230	Coastal stations not adjusted into the subsequent high-order geodetic triangulation. The NAD27 is too narrow by about 30 m across the North end of Hudson Bay.
Hudson Bay-South (inc. James Bay)	100	40			Aerodist and Doppler
Arctic Islands	75	20	10-15	150	
Beaufort Sea	0	25	10-15	150	Coastal control is being upgraded by readjustment and additional field work in 1982.
Pacific Inshore	50	50	1-5	1250	The basic control is distorted by about 50 ppm near Prince Rupert. Additional field work was done in 1975.
Pacific Offshore	250	50	8	1250	Some new work was done on the Queen Charlotte Islands in 1975.

NOTE: The tabulated accuracy figures for the framework control are derived mainly from an assessment of the discrepancies indicated when position differences, derived from published coordinates, are compared with measurements made by more accurate techniques, and reflect net distortions caused by forced closures. They are an attempt to evaluate absolute accuracy of distances between either adjacent points on a net or points separated by a few hundred kilometres.

TABLE II
Accuracy Standards for Horizontal Control Surveys

		Semi-major axis of 95% confidence region, r = C (d + 0.2)											
	Constant	d = 0.1 km			d = 3.0 km			d = 30 km			d = 300 km		
Order	(C)	cm	ppm	ratio	cm	ppm	ratio	m	ppm	ratio	m	ppm	ratio
1	2	0.6	60	1/16700	6.4	21	1/47000	0.6	20	1/50000	6	20	1/50000
2	5	1.5	150	1/6700	16.0	53	1/19000	1.5	50	1/20000	15	50	1/20000
3	12	3.6	360	1/2800	38.4	128	1/7800	3.6	121	1/8300	36	120	1/8300
4	30	9.0	900	1/1100	96.0	320	1/3100	9.1	302	1/3300	90	300	1/3300

Chapter 5

Geodetic Reference Systems

For the purpose of determining coordinates of points on the earth, various coordinate systems have been defined, or more precisely, have evolved. Traditionally, the location of a point has been described by two "horizontal" coordinates (latitude and longitude) and one "vertical" coordinate (elevation above sea-level). The classical methods of determining these coordinates are triangulation (for latitude and longitude) and levelling (for elevations). Therefore a separate treatment of "horizontal" and "vertical" networks was natural. This separate treatment gave rise to defining two *reference surfaces* or *datums*: the ellipsoidal (or horizontal) datum, to which the latitudes and longitudes refer, and the geoidal (or vertical) datum to which the elevations refer.

More modern methods, such as satellite positioning, are now in use which give three dimensional (3D) Cartesian coordinates. In this case,definition of a datum (reference surface) is not necessary. It is, however, necessary to determine the relation of the satellite (3D) coordinate system to the classical horizontal (ellipsoidal) and vertical (geoidal) reference surfaces.

The basic reference systems, their definition and relationships are described in this section.

The Conventional Terrestrial (C.T.) System

The C.T. system is a three-dimensional Cartesian system with its origin at the geocentre (centre of mass of Earth). The Z-axis is taken as the average position of the earth's rotational axis during the years 1900 to 1905. The X-axis is parallel to the Mean Greenwich Astronomic Meridian Plane. The Y-axis is chosen to form a right handed system. This system is sometimes called the "Average Terrestrial System" but this name implies that the Z-axis is the average rotational axis over all time, which is not, of course, the case. With the advent of modern techniques such as Doppler satellite we are able to compute 3D coordinates of points in the C.T. system.

Astronomic Latitude and Longitude and Height Above the Geoid

These three coordinates constitute one of the most fundamental of coordinate systems. The astronomic latitude (Φ) and longitude (Λ) are determined from observations of stars and time. Their relation to the C.T. system, when they are properly corrected for the misalignment of the earth's instantaneous rotational axis and the C.T. Z-axis, is shown in Figure 15.

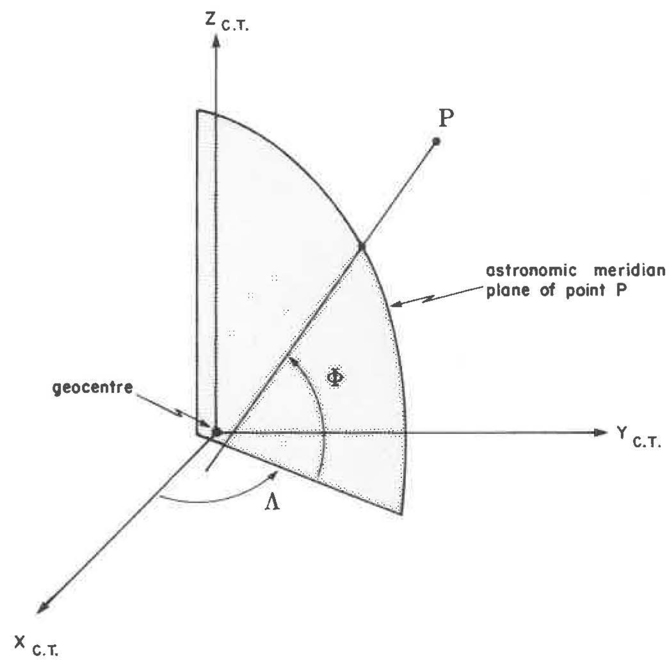


Figure 15

Relationship between the Conventional Terrestrial System and the Astronomical Latitude and Longitude

The geoid is defined as that equipotential surface of the earth which would coincide with the surface of the "undisturbed" oceans, where "undisturbed" refers to the effects on the ocean surface which result from tides, currents and nonhomogenities of temperature, salinity etc. Heights of the geoid above the Clarke 1866 Spheroid (NAD27) are given in Table D4. It is possible to estimate the location of the geoid at the sea-coast by observing the fluctuating water height over time, and making corrections for the phenomena mentioned above, using the best information available. Usually, the mean level of the water height as measured at tide gauges over many years (corrected only for the tidal cycles) is used as the approximate location of the geoid. This "mean sea level" at various tide gauges is used as a reference for defining the heights "above mean sea level" of all stations across Canada by using height differences measured by spirit levelling. This method has served well for many years but uncorrected ocean disturbances and systematic levelling errors are causing increasing concern. Much effort is now being made to better understand various systematic effects on both the coastal geoid determination and the levelling process itself. The geodetic level net of Canada is now under intensive study in anticipation of a readjustment entitled North American Vertical Datum 1987. This new datum should have a negligible effect on offshore surveys.

Ellipsoidal Systems

Since the earth very nearly takes the shape of an ellipsoid of rotation, this figure makes a convenient choice as a mathematical surface on which computations may be performed. The ellipsoid is also a convenient model for purposes of modelling the earth's gravity field.

The general relationship of the ellipsoidal system to the C.T. system is shown in Figure 16, where ϕ, λ, h denote ellipsoidal latitude, longitude and height respectively. Note that, in general, the geometric centre of the reference ellipsoid (i.e. the origin of the X_E, Y_E, Z_E Cartesian system) is offset from the geocentre. This "offset" can be described by three translations X_o,Y_o,Z_o (referred to the C.T. System). Also, the X_E, Y_E, Z_E axes may not be parallel to the $X_{C.T.}$, $Y_{C.T.}$, $Z_{C.T.}$ axes which can be expressed by three small rotation angles ω_X, ω_Y and ω_Z as indicated in the figure. In practice however these rotations are usually defined to be zero and in this case the mathematical relationship between ϕ, λ, h and $X_{C.T.}$, $Y_{C.T.}$ and $Z_{C.T.}$ is given by:

$$X_{C.T.} = X_o + (\nu + h) \cos \phi \cos \lambda \qquad (2)$$
$$Y_{C.T.} = Y_o + (\nu + h) \cos \phi \sin \lambda \qquad (3)$$
$$Z_{C.T.} = Z_o + (\nu \cdot b^2/a^2 + h) \sin \phi \qquad (4)$$

where a and b are the major and minor semi-axes of the ellipsoid respectively and ν is the radius of curvature of the ellipsoid in the prime vertical, given by:

$$\nu = a(1 - e^2 \sin^2\phi)^{-½} \qquad (5)$$

where $e^2 = (a^2 - b^2)/a^2$

The transformation from $X_{C.T.}$, $Y_{C.T.}$, $Z_{C.T.}$ to ϕ, λ, h is as follows: First the C.T. coordinates are transformed to X_E, Y_E, Z_E by;

$$X_E = X_{C.T.} - X_o \qquad (6)$$
$$Y_E = Y_{C.T.} - Y_o \qquad (7)$$
$$Z_E = Z_{C.T.} - Z_o \qquad (8)$$

Then, with $\epsilon^2 = (a^2 - b^2)/b^2$,

$p = (X_E^2 + Y_E^2)^{½}$

and $u = \arctan ((Z_E.a)/(p.b))$

we have,

$$\phi = \arctan \frac{Z_E + \epsilon^2 b \sin^3 u}{p - e^2 a \cos^3 u} \qquad (9)$$

$$\lambda = \arctan (Y_E/X_E) \qquad (10)$$

$$h = Z_E/\sin \phi - \nu \cdot b^2/a^2 \qquad (11)$$

Realization of the Various Reference Systems

The term "realization" is used to mean locating, to the best of our ability, the reference system with respect to the physical earth. Any such realization is based on observations. For example, to realize the geoid in coastal areas, mean sea level observations are made at tide gauges. The observations at each tide gauge can be corrected by out best estimate of the departure of mean sea level from the geoid, at that locality, and heights of nearby bench marks can thus be derived. These heights indicate the location of the geoid reference surface relative to bench marks on the physical earth.

In the classical approach to the realization of ellipsoidal systems, we define three more quantities: N, ξ, and η to show the relationship of the astronomic latitude and longitude to the ellipsoidal system. For simplicity, consider a geocentric reference ellipsoid as shown in Figure 17.

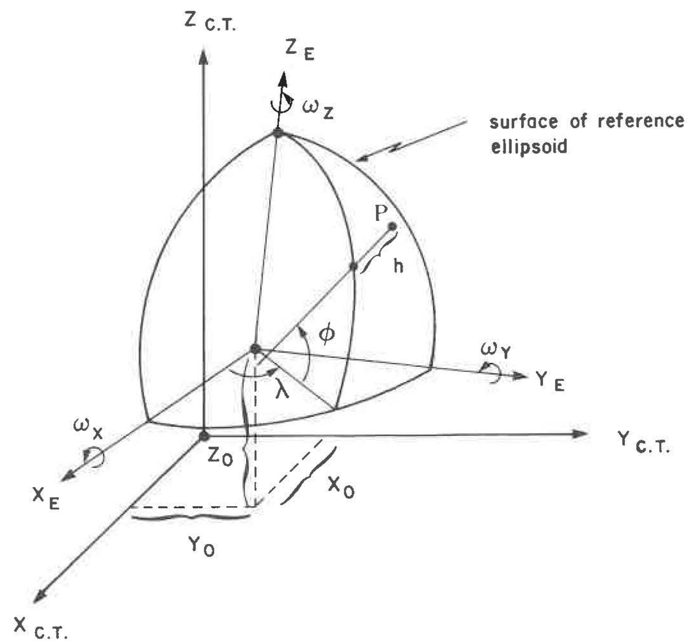


Figure 16

Relationship between the Conventional Terrestrial and Ellipsoidal Reference Systems

The geoidal height N is the height of the geoid above the ellipsoid and the deflection of the vertical θ is the angle between the zenith and the normal to the ellipsoid which can more usefully be represented by its north-south component ξ and its east-west component η. We can see that the ellipsoidal height h is given to a very high degree of accuracy by:

$$h = H + N, \qquad (12)$$

where H is the height of the point P above the geoid measured along the plumbline through P. The relationship between the ellipsoidal coordinates ϕ, λ, and their astronomic counterparts Φ, Λ, *when the axes of the ellipsoidal system are assumed parallel to those of the C.T. system,* can be given in terms of the deflections of the vertical as;

$$\xi = \Phi - \phi \qquad (13)$$
$$\eta = (\Lambda - \lambda) \cos \phi \qquad (14)$$

The astronomic azimuth A and geodetic azimuth α are related as follows, *again assuming that the axes of the ellipsoidal system are parallel to those of the C.T. system,*

$$A - \alpha = \eta \tan \phi + (\xi \sin \alpha - \eta \cos \alpha) \cot Z \qquad (15)$$

where Z is the zenithal angle between the zenith and the target. Equation (15) is called Laplace's equation; it is sometimes used in its truncated form, since Z is usually close to 90°.

$$A - \alpha = \eta \tan \phi = (\Lambda - \lambda) \sin \phi \qquad (16)$$

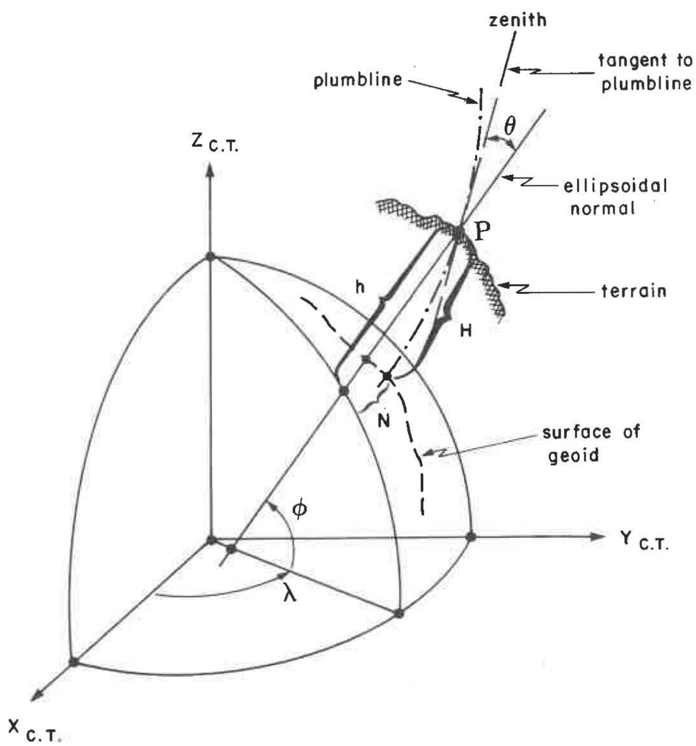


Figure 17

Relationship of the Geoid to the Ellipsoidal System

The derivation of equations (13), (14), (15) and (16) is implicitly based on the ellipsoidal and C.T. axes being parallel. When these equations are used in computations of geodetic networks the parallelism of these two systems is enforced within the limits of observational and systematic errors.

The definition and positioning of a reference ellipsoid with respect to the earth can be accomplished in two different ways. Both methods define the size and shape of the reference ellipsoid by adopting values for the semi-axes a and b (or equivalently a and the flattening $f = (a-b)/a$, or a and the eccentricity e). In the classical approach one of the stations in the geodetic network is chosen as the "initial point". The position of the ellipsoidal system can be defined by adopting equations (13) to (15) and specifying values for ϕ_o, λ_o, and N_o at the initial point. The observed astronomic latitudes, longitudes and azimuths at many network points, through the use of the Laplace equation, effectively sets the three rotational constants to be zero. The selection of ϕ_o and λ_o is made so as to keep the values of deflections small at all network points where astronomic latitudes and longitudes have been observed. This was the process used to position the Clarke 1866 ellipsoid (a = 6 378 206.4 m, b = 6 356 583.8 m) for use as the 1927 North American Datum (NAD27).

The more modern method of positioning a reference ellipsoid is to specify three translation components X_o, Y_o, Z_o and the three rotational angles ω_X, ω_Y, ω_Z. This is now feasible since satellite techniques now provide three-dimensional Cartesian coordinates for survey stations in the Naval Weapons Laboratory (NWL) reference systems, such as the NWL 9D, which are very close approximations to the C.T. system. With small corrections, these coordinates are brought into the C.T. system. In 1979, in Canberra, the International Union of Geodesy and Geophysics (IUGG) adopted an ellipsoid, which best fits the world and can serve both as a gravity model and as a horizontal datum for all nations. It makes sense to adopt the size and shape of this ellipsoid (a = 6 378 137.000 m, b = 6 356 752.314 m) and to set the translations X_o, Y_o, Z_o and rotations ω_X, ω_Y, ω_Z all to zero to define a new reference surface for geodetic networks.

Within the next few years a rigorous readjustment of the North American geodetic networks will take place referred to a geocentric ellipsoid termed NAD83. The positioning of this ellipsoid will probably be accomplished by setting X_o, Y_o, Z_o, ω_X, ω_Y to zero and allowing the observed astronomic azimuths and longitudes to define the longitudinal origin. The Laplace equation will not be used explicitly; a new mathematical model which implicitly carries the Laplace equation in a more general way will be used in the adjustment.

Datum Transformations

It is often necessary to transform ellipsoidal coordinates referred to one datum to the corresponding ellipsoidal coordinates referred to a another datum (i.e., a different reference ellipsoid with different defining constants). For the case in which the ω_X, ω_Y, ω_Z rotations are zero for both datums, a general method of performing this transformation is described below.

Suppose the coordinates ϕ_1, λ_1, and h_1, of a point referred to datum 1 whose defining parameters are a_1, b_1, (semi-axes) and $X_{0.1}$, $Y_{0.1}$, $Z_{0.1}$ (translations) are to be transformed to the corresponding coordinates ϕ_2, λ_2, h_2 of that point referred to datum 2 whose defining parameters are a_2, b_2 and $X_{0.2}$, $Y_{0.2}$, $Z_{0.2}$.

The first step is to transform ϕ_1, λ_1, h_1, to C.T. coordinates using equations (2), (3) and (4) i.e.;

$$X_{C.T.} = X_{o.1} + (\nu_1 + h_1) \cos\phi_1 \cos\lambda_1$$
$$Y_{C.T.} = Y_{o.1} + (\nu_1 + h_1) \cos\phi_1 \sin\lambda_1$$
$$Z_{C.T.} = Z_{o.1} + (\nu_1 \cdot b_1^2/a_1^2 + h_1) \sin\phi_1$$

where

$$\nu_1 = a_1 (1 - e_1^2 \sin^2\phi_1)^{-1/2}$$

and $$e_1^2 = (a_1^2 - b_1^2)/a_1^2$$

Then, using these C.T. coordinates in equations (6), (7) and (8) we can compute Cartesian coordinates X_{E2}, Y_{E2}, Z_{E2} (referred to datum 2) i.e.;

$$X_{E2} = X_{C.T.} - X_{0.2}$$
$$Y_{E2} = Y_{C.T.} - Y_{0.2}$$
$$Z_{E2} = Z_{C.T.} - Z_{0.2}$$

Finally, using these coordinates, along with the semi-axes a_2, b_2 of datum 2, we can compute ϕ_2, λ_2, h_2 (referred to datum 2) using equations (9), (10) and (11), ie;

$$\phi_2 = \arctan \frac{Z_{E2} + \epsilon_2^2 b_2 \sin^3 U_2}{P_2 - e_2^2 a_2 \cos^3 U_2}$$

$$\lambda_2 = \arctan (Y_{E2}/X_{E2})$$

$$h = Z_{E2}/\sin \phi_2 - \nu_2 \cdot b_2^2/a_2^2$$

where,

$$\epsilon_2^2 = (a_2^2 - b_2^2)/b_2^2$$

$$P_2 = (X_{E2}^2 + Y_{E2}^2)^{1/2}$$

$$U_2 = \arctan ((Z_{E2} \cdot a_2)/(P_2 \cdot b_2))$$

and

$$\nu_2 = a_2 (1 - e_2^2 \sin^2 \phi_2)^{-1/2}$$

1927 North American Datum (NAD27)

As mentioned earlier the 1927 North American Datum (NAD27) has been defined by the classical method as a Clarke 1866 ellipsoid positioned at an arbitrary initial point and with axes oriented parallel to the C.T. system by the adoption of equations 13 to 16, (e.g. see Mitchell 1948, Bomford 1971). Station MEADES RANCH in Kansas U.S.A. was chosen as the initial point with coordinates ϕ_0, λ_0. The geoid height was assumed to be zero. The eight definitive constants necessary to specify the shape and position of the reference ellipsoid and the orientation of its axes are:

$$a = 6\ 378\ 206.4 \text{ m}$$
$$b = 6\ 356\ 583.8 \text{ m}$$
$$\omega_X = 0$$
$$\omega_Y = 0$$
$$\omega_Z = 0$$
$$\phi_0 = 39° \ 13' \ 26.686'' \text{ North}$$
$$\lambda_0 = 98° \ 32' \ 30.506'' \text{ West}$$
$$N_0 = 0$$

Between 1927 and 1932, the existing first order geodetic networks in Canada and the United States, along with a few second order networks were adjusted. The adjustment, based on the above-defined reference system, produced a system of coordinates which has since then been held fixed for control purposes. There were only a few networks in Canada that could be incorporated at that time. These consisted of triangulation networks in southern Quebec and Ontario and along the southern boundary of the western provinces. Subsequently, first order trangulation networks were extended northwards from stations in the original networks and were adjusted, based on the same reference system, holding the coordinates of the original networks fixed. The determined coordinates for the new nets were termed "NAD27 values" or sometimes "on the 1927 NAD" and were in turn held fixed when further extensions were made from them.

As Canada developed, requirements for control increased faster than the first order network could be extended. Second and third order nets and traverses were extended hundreds and thousands of kilometres north from the first order networks. The coordinates established were designated NAD27 values if the net was connected to, and thus based on, the system of coordinates derived by the original adjustments. These surveys were and are subject to revision as they are densified and/or are tied to more accurate framework control.

With the advent of EDM equipment, electronic computers and doppler-satellite survey techniques, substantial distortions have been found in the first order survey networks. Since there has been a requirement for stability, it is only in areas where distortion has greatly exceeded the inherent accuracies of the surveys that the Geodetic Survey of Canada has derived new revised coordinates, also designated NAD27. Where this has happened the new adjustment has been fitted into the surrounding network.

The published lists of coordinates which are being held fixed are being used as a datum, in the general sense of an assumed reference, by those who need a stable reference system of coordinates. For practical purposes the *published lists* are considered by many surveyors and scientists *to be* the NAD27 (e.g., National Academy of Sciences, 1971). The term is understood in this sense by the Geodetic Survey of Canada when dealing with requests for NAD27 control coordinates.

The NAD83 Adjustment Project

The 1983 North American Datum (NAD83) project is an international co-operative project to adjust all North American geodetic horizontal control networks together, using a new geocentric ellipsoid as a reference surface. The project involves Canada, United States, Mexico, Greenland and several Central American countries.

In the late 1960's and early 1970's several areas of distortion in the Canadian primary network became evident and it was apparent that, because of distortions in the Canadian primary network, a comprehensive adjustment was needed to improve accuracy to meet modern requirements. In 1972, the Geodetic Survey of Canada began a systematic evaluation of the primary framework. The distortions are shown in Figure 13. As a result, the framework has been strengthened by additional scale control and Laplace azimith control and has been further constrained and complemented by a network of 170 basic Doppler satellite stations.

Present plans call for the NAD83 adjustment to be computed on the world best fitting ellipsoid as adopted by the International Association of Geodesy and Geophysics at Canberra in 1979, and oriented by the Laplace azimuth observations, with the Final datum orientation parameters being derived in the continental adjustment.

The continental adjustment is scheduled for completion in 1985 with the integration of secondary networks to follow immediately. It is expected that comprehensive lists of coordinates of primary and secondary control will not be completed before 1987; however it is possible to estimate the differences which will exist.

For the framework points, absolute coordinate differences between existing published values, termed NAD27, and new values derived by the NAD83 adjustment will range up to about 100 metres on the west coast and up to 70 metres on the east coast (an apparent expansion of NAD83 compared to NAD27). Differences will be small in Ontario. Figure 12 shows the differences as vectors. For secondary points, the coordinate differences have not been analyzed and could differ significantly from those predicted for the framework stations.

Local Datum Shifts

For any point with known NAD27 latitude, ϕ_{NAD27}, longitude, λ_{NAD27}, and elevation above the ellipsoid, h, it is possible to derive the 3D Cartesian coordinates relative to the centre of the reference ellipsoid.

$$X_E = (\nu + h) \cos \phi_{NAD27} \cos \lambda_{NAD27}$$
$$Y_E = (\nu + h) \cos \phi_{NAD27} \sin \lambda_{NAD27}$$
$$Z_E = (\nu \cdot b^2/a^2 + h) \sin \phi_{NAD27}$$

At that station we may also observe, by Doppler satellite, coordinates relative to the origin of the C.T. system ($X_{C.T.}$, $Y_{C.T.}$, $Z_{C.T.}$). It can be seen from equation (2) to (4) that the differences between the corresponding coordinates will comprise the offset (X_o, Y_o, Z_o) to the centre of the reference ellipsoid from the origin of the C.T. system. When derived in this manner they are termed the Local Datum Shift.

$$X_o = X_{C.T.} - X_E$$
$$Y_o = Y_{C.T.} - Y_E$$
$$X_o = Z_{C.T.} - Z_E$$

If there were no distortions in the 1927NAD network (and the Doppler satellite position was perfect), the offsets or Local Datum Shifts for all NAD27 points would be the same. Because of the distortions, variations of some tens of metres have been found for determinations at different localities across Canada. Rough mean values for this datum shift are:

$$X_o = -15 \text{ m}$$
$$Y_o = 165 \text{ m}$$
$$Z_o = 175 \text{ m}$$

The Geodetic Survey of Canada has derived and tabulated predicted Local Datum Shifts for a selection of points across Canada. Tables and graphs are given in Appendix D. These tables can be useful in computing geographic coordinates from Doppler satellite observations, which will be consistent (within about 10 metres) with the local published NAD27 system of coordinates. Mean values of X_o, Y_o, and Z_o from the nearest station are used in equations (6) to (8). Where higher accuracies are required a simultaneously observed Local Datum Shift must be used as described in the following sample computations.

Techniques have been developed (Lachapelle and Mainville, 1981) to model in two dimensions the distortion between two coordinate systems. This technique could be used to derive NAD27 coordinates from a Doppler satellite position, given the relationship between known Doppler satellite and NAD27 position values at a surrounding network of points.

Sample Computations

The following computations of a local datum shift and position difference survey illustrate the use of these formulae.

From the geodetic data bank, the NAD27 coordinates and elevation above sea level for geodetic station "House" near Fort McMurray, Alberta are:

$$\phi_1 = 55° \, 55' \, 00.48330'' \text{ North}$$
$$\lambda_1 = 112° \, 04' \, 48.00740'' \text{ West}$$
$$H_1 = 695.879 \text{ m}$$

The height of the geoid (sea level) above the NAD27 reference ellipsoid, scaled from Figure D4, is 7.1 m, and the measured height of the electrical centre of a Doppler receiver antenna above the monument was 2.007 m. The sum of these, 704.977 m, is the ellipsoidal height of the electrical centre. (Note that, while the scaled geoid height is not precise, derived position differences will be only slightly affected if consistent geoid heights are used for a local area). The derived NAD27 Cartesian coordinates for House are:

$$X_{E1} = -\ 1\,346\,869.377 \text{ m}$$
$$Y_{E1} = -\ 3\,320\,263.362 \text{ m}$$
$$Z_{E1} = +\ 5\,259\,639.012 \text{ m}$$

Doppler satellite observations at House yielded Cartesian coordinates in the C.T. system for the electrical centre of the antenna:

$$X_{CT1} = -\ 1\,346\,891.72 \text{ m}$$
$$Y_{CT1} = -\ 3\,320\,096.40 \text{ m}$$
$$Z_{CT1} = +\ 5\,259\,814.26 \text{ m}$$

Thus the local datum shift, derived by subtracting the NAD27 coordinates from the corresponding C.T. coordinates, was

$$X_o = -\ 22.44 \text{ m}$$
$$Y_o = +\ 166.96 \text{ m}$$
$$Z_o = +\ 175.25 \text{ m}$$

At a second station nearby, where NAD27 coordinates were required, Doppler observations were taken simultaneously. The solution of the Doppler equations which yielded the above C.T. coordinates for House incorporated the observations at both stations (termed a translocation) and also yielded C.T. coordinates for the second station:

$$X_{CT2} = -\ 1\,346\,534.95 \text{ m}$$
$$Y_{CT2} = -\ 3\,321\,000.33 \text{ m}$$
$$Z_{CT2} = +\ 5\,259\,820.68 \text{ m}$$

These can be converted to NAD27 Cartesian coordinates by subtracting the local datum shift derived above yielding:

$$X_{E2} = -\ 1\,346\,512.51 \text{ m}$$
$$Y_{E2} = -\ 3\,321\,167.29 \text{ m}$$
$$Z_{E2} = +5\,259\,645.43 \text{ m}$$

These Cartesian coordinates may be converted using equations (9) to (11) to yield NAD27 geographic coordinates for the second station:

$$\phi_2 = 55° \, 45' \, 41.763''$$
$$\lambda_2 = -112° \, 04' \, 09.417''$$
$$h_2 = 1104.586 \text{ m}$$

If the local geoid height is subtracted from the derived h we have the height above sea level of the electrical centre of the antenna at the second station.

Chapter 6

Offshore Positioning

Positions on the continental margins must be related to the currently recognized datum as defined by the nearest coastal control. At the time of writing, this is defined in the COGLAR to be the 1927 North American Datum (NAD27).

Zones

Line-Of-Sight Zone

This zone is the continental shelf area extending from shore to the limit of unobstructed direct radio or optical-signal transmission, within which positions can be determined using many commonly used microwave or optical survey systems. Second-order or even first-order accuracy can be achieved in positioning fixed or floating platforms, by a surveyed connection to coastal control. The common on-land survey techniques using electronic distance measuring equipment and theodolites can also be used to position a ship or drilling rig close to shore.

Over-The-Horizon Zone

This zone is the continental shelf area extending beyond the limit of unobstructed direct radio wave propagation, where certain microwave systems continue to provide reliable measurements because of enhanced signal processing, 'ducting' of the radio waves or increased power. Signal quality usually decreases as distances extend past the line-of-sight-zone.

Remote Zone

This zone is the continental shelf and margin area beyond the line-of-sight zone. The less accurate, longer wave radio surveying and navigation systems must generally be used in this zone. Off Canada's east coast, on the Tail of the Bank and the Flemish Cap, it is particularly difficult to achieve adequate accuracy using the common radio systems.

Accuracy and Repeatability

The absolute (geographic) accuracy of a position fix is a measure of the ability to relate the position of the fix to any other point on the earth's surface. The repeatability of a fix is the ability to relate position fixes over a limited distance, or to return to the point fixed. Repeatability is important in making closely spaced observations, determining the shape of seabed features and measuring the ship's course and speed. Absolute accuracy is important for mapping related to coastal features or when it is necessary to know a position relative to a geographically defined point or grid. It is also important in cases where a survey overlaps work positioned by a different system, or in cases when the surveyor is positioning by two or more systems integrated together.

To achieve absolute accuracy, systematic biases such as pattern-zeroing errors and uncertainty of propagation velocity must be eliminated. For repeatability, constant systematic errors can be tolerated, but when these errors vary slowly with time, the ability to return to a position is lost. Since it is impossible to eliminate entirely systematic errors, repeatability is always better than absolute accuracy; although with some systems such as microwave and Doppler satellite positioning, systematic errors are small and absolute accuracy and repeatability are practically equivalent.

Survey accuracy is expressed relative to a datum or to fixed survey control monuments which define a datum locally. Offshore surveys of Canada Lands can be classified according to specifications of the Department of Energy, Mines and Resources (1978).

Measurement Accuracy

The usual method of assessing the accuracy of survey measurements is to repeat them many times under widely differing circumstances, to eliminate systematic errors, and then calculate the standard deviation of the measurements. A fundamental difference between land and sea surveying is that at sea it is difficult to repeat an observation because of ship movement.

At sea, accuracy can be expressed as a standard deviation of repeated measurements only at bottom-mounted or stabilized drilling platforms where movement is minimal. Accuracy estimates are normally obtained by: estimating magnitudes of all known error sources; combining the estimated errors; and checking the result, when possible, by comparison with simultaneous measurements made with an independent system having different types of error sources. It is important to realize that most error estimates for radio-positioning systems are very much in the ball park variety; the time and money required to make an accurate assessment are rarely available. Error estimates tend to be biased toward the best interests of the estimator.

A common model used to analyze the accuracy of length measurements is to divide error sources into two independent groups: those causing errors independent of length, and those causing errors directly proportional to length. The standard deviation, σ_R of a measured range, is then given by:

$$\sigma_R = \sqrt{r^2 + (fR)^2} \tag{17}$$

r = the standard deviation of the combined factors which are independent of length (expressed in length units),

f = the standard deviation of the combined factors which are dependent on the length (expressed as a ratio).

R = the length of the range.

Where measurements are being made onshore or to stable platforms in the line-of-sight zone, using on-land type survey systems, both r and f add significantly to the value of σ_R. This is also true for two-range hydrographic systems when an arbitrary, uniform signal velocity is selected. In these circumstances, a value for f = 1/10 000 has been accepted as a reasonable estimate for the standard deviation of the combined error sources depending on the range. But if corrections are applied, taking into account the measured properties of the air and water along the range, the proportional part is not a significant part of the overall accuracy of the systems now used.

There are many ways of expressing accuracy of measurements. The standard deviation is a measure of the dispersion of observations and is based on the Gaussian or normal distribution of errors (see Table III). For repeated measurements of a quantity, it is the square root of the sum of the squares of the residuals from the mean, divided by one less than the number of measurements.

Despite the fact that measuring systems do not produce measurements exactly in conformity with the theoretical distribution of errors, the theory provides a close enough approximation to reality to be a useful tool in error analysis. In particular, radio-positioning or EDM systems tend to give a slightly higher proportion of large errors than the theory predicts. There is, theoretically, a 33 percent probability of a measurement having an error greater than the standard deviation (one σ level); but there is only a five percent probability of the error exceeding the two σ level. This level is commonly used as an expression of the accuracy of hydrographic survey systems, because it corresponds more closely to the popular feeling that the accuracy is the maximum error one could expect.

Positional Accuracy

The positional accuracy attained with respect to shore control by various survey or navigation systems depends mainly on the type of system. The three main types are:

a) Those by which a position is derived from a pair of ranges to two shore stations: such systems are known as range-range if the signal is transmitted from the master on board the ship, and is re-transmitted from the slave shore stations to the master; or rho-rho if the signal is transmitted one way from the shore stations to a shipborne receiver.

b) Those by which a position is derived from a pair of range (or phase) differences between signals received from the ends of two baselines between shore points; known as hyperbolic systems.

c) Those which are basically designed to provide position differences derived indirectly from non-linear measurements, e.g., Doppler shift of known frequencies or accelerations.

TABLE III

Gaussian (Normal) Distribution of Errors

Accuracy Expression	Error Level	*(%)	Remarks
Two Sigma	2σ	95	Only a few errors are larger
One Sigma, Std. Deviation, RMS	1σ	67	Sometimes a deceptive method of expressing accuracy
Average Error	0.80σ	58	Most errors are smaller than the average
Probable Error	0.67σ	50	As likely as not to be exceeded

*Probability of a Measurement with an Error less than the Error Level

Most hydrographic systems can be operated as either type A or B. For these systems, the positional accuracy attained depends not only on the accuracy of the range or range difference but largely on the geometry of the fix. The United States Navy Navigational Satellite System (NNSS, commonly called the Doppler satellite system, Navsat or Satnav), and inertial-navigation systems are examples of type C. For the latter systems particularly, the positional accuracy attained depends on the techniques and procedures used.

The accuracy of a position fix for most systems is generally different in different directions. For example, for most of the area covered using a two-range system (range-range or rho-rho), there is a minimum uncertainty in the direction towards the pair of shore stations, and a maximum uncertainty in a direction perpendicular to the minimum (see Figure 18). To express the fix accuracy, the standard deviations in the maximum and minimum directions are taken to be the semi-major and semi-minor axes of an ellipse. The ellipse is known as a standard-error ellipse. For a two-range system a fair approximation of the semi-major axis a of the standard-error ellipse is given by:

$$a = \operatorname{cosec} \beta \sqrt{\sigma_1^2 + \sigma_2^2} \qquad (18)$$

where:

σ_1 and σ_2 are the standard deviations of the two ranges, and β is the angle of intersection of the ranges.

if $\sigma_1 = \sigma_2 = \sigma$, this becomes:

$$a = \sqrt{2} \cdot \sigma \operatorname{cosec} \beta \qquad (19)$$

Using this model, Figure 18 illustrates the deterioration, as the length of the ranges increases, of the fix accuracy of a typical two-range hydrographic survey system for different base lengths and cut angles.

The standard-error ellipse describes an area around the computed, most probable fix position, within which there is a 39 percent probability of the true position being situated; the assumption being that the standard deviations of the measurements are valid descriptions of the differences between measurements and true values. If the dimensions of the axes are multiplied by 2.45, this probability increases to 95 percent. This level is used to classify survey accuracy in EMR's *Specifications and Recommendations for Control Surveys and Survey Markers* (1978). Table IV illustrates the variation in probability of a fix being within ellipses for other multiples of the standard-error ellipse axes.

Some survey adjustment programs such as GALS (McLellan, 1970) have a design mode which will produce standard-error ellipse dimensions, given estimated measurement accuracies and the design of the network. This may provide a more rigorous and descriptive method than using equations (17) or (18) to analyze or classify a survey tie, because the shape and orientation of the error figures are given. But it should be realized that both these methods depend on estimated measurement accuracy and the extent of correlation between the measurements.

TABLE IV

Probabilities for Various Error Ellipses

Multiple of a standard-error ellipse dimension	Probability of a fix being within the derived-error ellipse (percent)
2.4	95
2.00	86
1.00	39
0.80	28
0.67	20

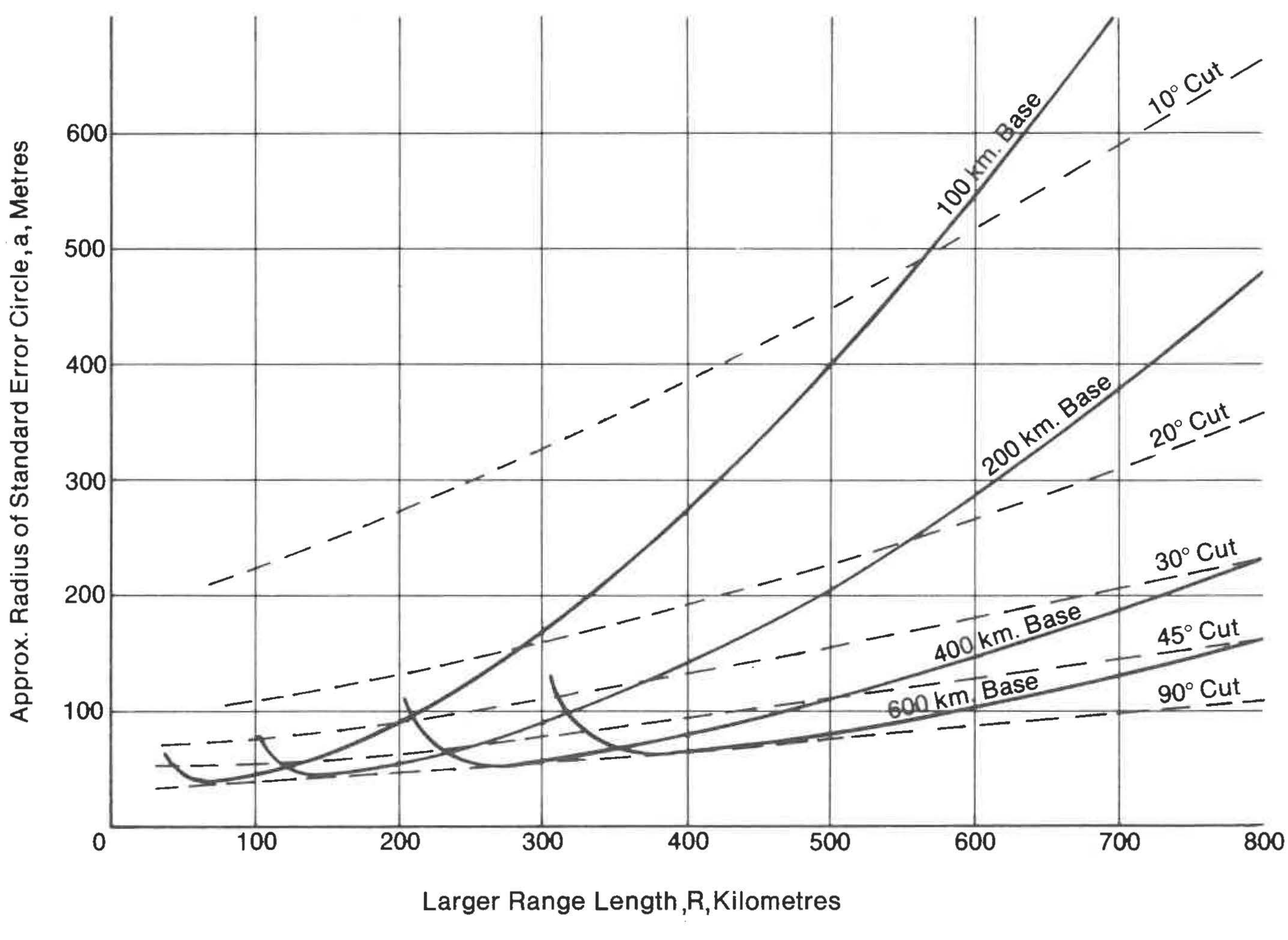


Figure 18

Fix Accuracy of a Typical Two-Range Survey System

Chapter 7

Ground-Based Radio Positioning Systems

Classification

Radio navigation systems are allotted narrow bands within the frequency spectrum as shown in Figure 19. The systems are grouped according to their transmitted frequency: super high frequency (microwave), medium frequency (MF), low frequency (LF) and very low frequency (VLF); since frequency determines the range, accuracy, and size of the shore transmitter and, hence, the cost of logistics. From Table V it can be seen that, as a ship moves farther from shore, a lower frequency system must be used to obtain the required range; consequently, accuracy deteriorates and larger, more powerful transmitters are required.

Within a group of systems, the difference in the performance of systems constructed by various manufacturers is generally slight. System prices, suppliers, and optional features change each year as new design concepts emerge. An extensive listing of these details is given by C.B. Jeffery, and A.G. Andrews in "The Position Finder" (1971) or by R. Adm. R.C. Munson in "Positioning Systems" (1977).

Accuracy of the lower frequency systems decreases, partly because it is technically difficult to measure more accurately than about 1/100 of a wavelength, and partly because it is more difficult to estimate the mean propagation velocity of a radio wave over a long range. The system size and power increase for two reasons: the signal has to travel further, and a radio wave can only be propagated efficiently from an antenna which is at least one quarter wavelength long. Shorter antennas require additional power. A medium frequency system operating at 2 MHz has a wavelength of 150 m, thus a 10 m antenna (1/15 wavelength) is very inefficient. Table V shows typical values for the repeatability of range measurements at the two-standard deviation level, but does not indicate fix accuracy. The figures for fix accuracy are generally several times larger than those for range accuracy, depending on the intersection angle of the ranges and on the characteristics of the positioning system. The figures for range accuracy are larger than those for range repeatability, and depend on the care taken in calibration and on measuring factors which affect the signal's velocity of propagation.

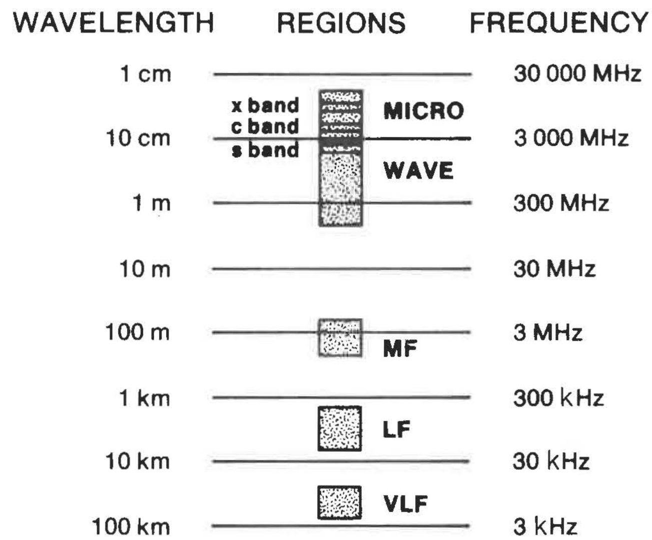


Figure 19

Regions of the Frequency Spectrum Used for Navigation

Modes of Operation

Range-Range

Signals from a shipborne transmitter are received at two or more transponders (or slave transmitters) on shore and retransmitted to a receiver on the vessel. The round-trip travel time of the radio wave is measured and converted to a distance, and two such distances define the ship's position as the intersection of two-range circles. This is the most accurate mode, due to the strong geometry of the pattern of intersecting circles. The number of vessels that can use the same shore stations simultaneously is limited to one for some systems, or, by time-sharing techniques, up to a maximum of four for others. Microwave systems are always used in the range-range mode; most MF and LF systems can also be used in this mode. The one weakness of range-range, from a rigorous point of view, is that the pattern cannot be monitored; whereas, for hyperbolic or rho-rho, the pattern can be monitored and thus changes in zero adjustments and other systematic errors can be detected.

Rho-Rho

The ship carries a receiver. The shore transmitters and the receiver on the ship are controlled by precise atomic-frequency standards. Once the frequency drift (differential clock rate) between the shore and shipborne frequency standards has been established and accounted for, the shipborne receiver shows no phase change until the ship moves. Any phase change indicating ship movement can be converted to a change in range and can be added to the initial range to the shore transmitter. The pattern geometry is the same as range-range, except that a one-cycle change in phase indicates a full wavelength change in range, instead of half a wavelength as in a two-way measurement of the range-range mode. Measurement accuracy is slightly inferior to range-range because of very small (a few parts in 10^{14}) differences in the frequency of the atomic standards. The advantage of the rho-rho operation is that no transmitter or large antenna is needed on the vessel, and the greater range of a larger, more efficient shore antenna can be fully exploited. In addition,

TABLE V

Offshore Positioning Methods

Representative Systems	Measurement	Range	Repeatability (2 σ Level)	Shore Station	Approximate Cost (1982)	Characteristics
MICROWAVE RADIO (LOCAL):						
Trisponder and Autotape	Pulse match phase comparison	50 km, given height to get line of sight	10 m 2 m	10 kg Transmitter 30 kg Battery 10 cm Antenna	$ 80 000 $120 000	Extremely accurate, minimal-calibration, easy to deploy and operate. Unambiguous
Syledis	Pulse match pulse comparison	300 km	5 m, line of sight, 30 m beyond	16 kg Beacon 47 kg Amplifier 30 kg Batteries Generator	$150 000	Limited testing in Canada, useful beyond line-of-sight.
MICROWAVE RADIO (GLOBAL):						
Doppler Satellite Navigation	Frequency comparison, range difference	Worldwide, intermittent fixing	240 m (see Doppler-System)		$ 50 000	Worldwide negligible systematic error. 2-hour intervals. Ship's velocity must be known.
GPS, Navstar	Time signals, pseudo ranges	Worldwide, continuous	10 m (being tested)			Under development, only partial satellite constallation available.
MEDIUM FREQUENCY RADIO:						
Hi-Fix	Phase comparison range or range difference	300 km (less at night)	10 m	100 kg Transmitter 100 kg Generator 10-30 m Antenna	$300 000	Very good relative accuracy. Considerable calibration required for geographic accuracy. Acute ambiguity problem.
Hi-Fix/6	Phase comparison range or range difference	300 km	10 m	50 kg Transmitter 10-30 m Antenna Generator	$300 000	Requires calibration, acute ambiguity problem.
Argo	Phase comparison range or range difference	400 km	5 m	30 kg Transmitter 30 m Antenna Generator	$300 000	Has some lane identification capability, requires calibration.

TABLE V (Cont'd.)

Offshore Positioning Methods

Representative Systems	Measurement	Range	Repeatability (2 σ Level)	Shore Station	Approximate Cost (1982)	Characteristics
LOW FREQUENCY RADIO:						
12f Survey Decca	Phase comparison range or range difference	650 km (less at night)	25 m	300 kg Transmitter 300 kg Generator 50 m Antenna	$300 000	Good relative accuracy. Very expensive to deploy, calibration req'd.
Main Chain Decca	Phase comparison range difference	350 km	40 m	Not supplied by user	Receivers Rented	Good relative accuracy. Calibration required Ambiguity problem.
Main Chain Loran-C	Pulse with phase comparison. Range or range diff.	2 000 km	50 m	Not supplied by user	$ 50 000 (rho-rho) $ 4 000 (hyperbolic)	Very long range. Marginally less accurate than Decca. Calibration req'd. Less ambiguous than Decca. Convenient.
Accufix	Pulse with phase comparison. Range or range diff.	700 km	50 m		$300 000	Low powered version of Loran-C
VERY LOW FREQUENCY RADIO:						
Omega	Phase comparison	10 000 km	500 m	Needs a shore monitor within 500 km to achieve this repeatability	$ 20 000 (2 receivers)	Worldwide, only stopgap survey technique.
ACOUSTIC						
Seabed Transponders	Pulsed: ranging	10 km	10 m	100 kg transponder (moored just above seabed)	50 000 (1975)	Very accurate. Used anywhere. Takes time to lay and recover transponders. Very short range.
Doppler-Sonar	Frequency comparison	200 m depth	—	—		Measures ship velocity.

the number of users is not limited. Loran-C, Decca Lambda, Toran and Omega are being used in the rho-rho mode, and there is no reason, in principle, why other systems should not use the same mode. The pattern can be monitored at an onshore stationary receiver.

Hyperbolic

The master transmitter is located onshore. Ideally, it should be placed roughly midway between the two slave transmitters so that the master-slave baselines form a shallow V concave to the service area. The shipborne receiver measures the difference in arrival time between the master signal and the responding signal that the master signal elicits from the slave transmitters. Different frequencies (Decca, Raydist, etc.) or time delays (Hi-Fix, Loran-C), are used to avoid confusion over the origin of each signal. The time differences are converted to range differences, which plot as hyperbolic lines of position (LOP). The pattern can be monitored at a stationary receiver onshore. The pattern geometry is weaker than rho-rho, but there is no limit to the number of users and the receiver is much less expensive. All MF, LF and VLF systems can be used in the hyperbolic mode.

Line of Position (LOP)

A line of position (LOP) is the locus of points on the earth's surface having a constant measurement by a radiopositioning system. It is either a range circle (as in range-range or rho-rho systems), range difference hyperbola, or a bearing. Two intersecting LOPs give a position fix.

Modes of Transmission

Continuous Wave (CW)

This mode provides continuous transmission on one frequency. The advantages of a CW positioning system are derived from the fact that the continuous information enables the most accurate cycle-match measurement. In cycle matching, the time interval is measured between the zero crossing of cycles received from master and slave transmitters. Many CW systems include a form of time-sharing in which the continuous broadcast of the measuring frequency is interrupted briefly to transmit a different frequency. This different frequency can be used for lane identification (Hydrodist, Decca, Omega).

Pulsed Transmission

This is a transmission made in short pulses or groups of pulses, with the transmitter silent most of the time. Measurement may be to the leading edge of the pulse (Pulse Match) or to a specific cycle within the pulse (Cycle Match). By this technique, ambiguity is eliminated at microwave frequencies and alleviated at low frequencies. As well, skywave interference problems are virtually eliminated at low frequencies (Loran-C).

Time-Shared Transmission

The transmitter is switched off at intervals to allow another transmitter to use the same frequency. This allows a hyperbolic or multi-user range-range chain to operate on one frequency, thereby saving on equipment cost, economizing in frequency spectrum and reducing susceptibility to interference (Hi-Fix, Omega).

Propagation of Radio Waves

Modes of Propagation

The various modes of signal transmission are illustrated in Figure 20. At microwave frequencies, there is almost no curvature of the signal path; if one cannot see the transmitter one cannot receive the signal. By signal enhancement, over-the-horizon transmissions are available with some systems. The direct wave provides the most accurate measurements. For lower frequency systems, which generally have the receiver below the horizon of the transmitter, the groundwave which follows the earth's surface (and is thus following approximately along a geodesic) is used for measurement. Skywaves and reflected waves are nuisance interference.

There is one radio positioning system which receives microwave signals at long ranges, much beyond the line of sight, because of the ducting of the signal between layers of the atmosphere. In this ducted mode, signal waves reflected from the sea interfere by either reinforcing or diminishing the amplitude of the ducted wave. Surveyors have reported dead zones where no signal could be received, presumably because of destructive interference. There are other microwave radio positioning systems that achieve over the horizon ranges by using signal enhancement techniques.

At medium and low frequencies, the groundwave follows the earth's surface, extending into the atmosphere to a height of about a wavelength. It also penetrates sea water about one metre and considerably deeper into low conductivity land. The signal travels to the receiver by skywave reflection from the ionosphere as well as by groundwave. This skywave is particularly strong at night, when an absorbing layer just below the ionosphere disappears. The strength of the skywave generally increases with distance from the transmitter, whereas the groundwave loses strength (Figure 21). When the skywave reaches a significant proportion of total signal strength, the interference as described in the subsection entitled "Radio Noise and Skywave" occurs. One way of getting around this problem is to transmit pulses, as is done with Loran. The groundwave, because it has the shorter path to travel, arrives first; if the measurement is made on the initial part of the pulse (before the arrival of the skywave), the measurement is free from skywave interference.

At very low frequencies (VLF), the signal of the Omega system travels through the duct formed between the earth's surface and the ionosphere with the duct acting as a waveguide. The width of the duct varies as the reflecting layer of the ionosphere moves diurnally up and down. Somewhat inaccurate skywave corrections must be applied. These may vary by as much as 5 km in an hour. A more accurate corrective measure is to monitor the changes at a stationary receiver, on shore nearby, and apply corresponding corrections to a receiver at sea. However, the best position-line accuracy of the Differential Omega technique is probably about ± 500 m.

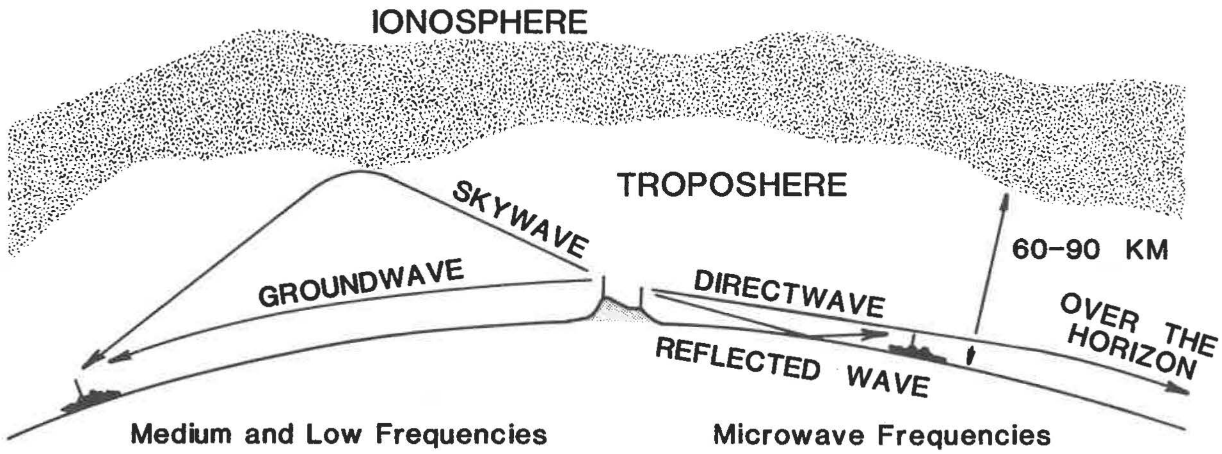


Figure 20

Radio Wave Propagation

Primary Phase Lags

All electronic positioning systems are dependent, in some way, on the time integration of the speed of propagation of electromagnetic radiation in the atmosphere. In September 1975, the International Union of Geodesy and Geophysics recommended that: the value of 299 792 548 m/s with a standard deviation of 1.2 m/s (Bulletin Géodésique, No. 118, Dec. 1975), be used whenever the most precise speed of propagation in a vacuum is required. For EDM calculations, the less precise, previously accepted value V_o = 299 792.5 km/s is generally used. The velocity of propagation in the atmosphere, V_e depends on the refraction index:

$$V_e = V_o / \eta$$

The index of refraction of the atmosphere is dependent on the air pressure, temperature, and the amount of various gases (water vapour, carbon dioxide, etc.) in the air. Normally, dry bulb and wet bulb temperatures and total air pressure are the only three parameters measured. Using a formula such as that given by Essen and Froome (1951), the index of refraction can be computed. The primary phase lag signal delay is dependent on the index of refraction, and is directly proportional to the distance. It should be noted that the correction is independent of the carrier frequency (see also, the section on computation of primary and secondary phase lag).

Secondary Phase Lags

For medium and low frequency radio waves travelling directly over the earth's surface, there is a second factor often called the secondary phase lag. It is dependent upon the electrical properties of the top portions of the surface material down to the signal penetration depth, and on the vertical rate of change of the index of refraction. The penetration depth of signals at Decca frequencies is less than a metre in seawater. The secondary phase lag over a distance is a non-linear function involving the distance, frequency, conductivity of the surface, permittivity of the air and surface, and the curvature of the radio wave; the first three factors being the most important in offshore surveying.

Formulas and procedures described by Johler (1956) are the accepted method to compute the secondary phase lag over a smooth surface of a homogeneous medium. Since the equations are complex and the computations extensive, it is usually advantageous to replace the rigorous formula with a polynomial approximation. P. Brunavs (1977) developed polynomials to replace the total phase lag computation for the Loran-C carrier frequency over sea water and land. The Canadian Hydrographic Service has extended the use of the polynomials to include Loran-C over fresh water and an Agro carrier frequency over sea water. The polynomial takes the form:

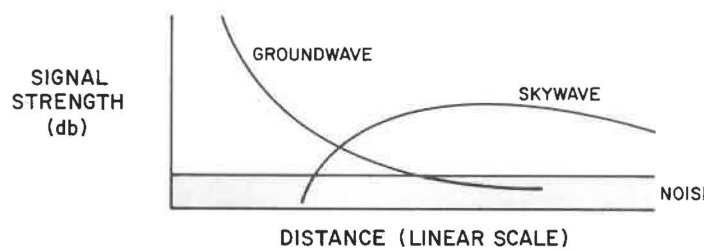


Figure 21

Strength of Signals as a Function of Distance

$$P = \frac{C_0}{S} + C_1 + C_2 \cdot S + (C_3 \cdot S + C_4)e^{(C5.S)} + \frac{C_6}{1 + C_7 \cdot S + C_8 \cdot S^4} \qquad (20)$$

where: P = Total Phase Lag (metres),

C_0, C_1, C_2 — C_8 are given in Tables VI and VII for specified frequencies, conductivities, and permittivities, and

S = Distance in metres / 100 000.

For Loran-C frequencies, the polynomials are valid for distances from 3 km to 4 000 km to an accuracy better than 2.5 metres with respect to the rigorous equations given by Johler (1956). For the Argo frequency polynomial,the accuracy is better than 1.3 metres and the applicable distances are from 2 km to 500 km. The use of the polynomials for other medium frequency systems operating elsewhere in the 1600 – 2000 kHz frequency band would incur an additional loss of accuracy up to one metre.

The assumed primary phase lag used in the polynomials is the index of refraction of 1.000 338. To change the index of refraction in the total phase lag polynominal, subtract 33.8 from C_2 and add $(\eta - 1) \times 100\,000$ where η is the desired index of refraction.

• Tests of Johler Model

The Canadian Hydrographic Service conducted several tests at different frequencies to determine the secondary phase lag. Sea trials off the Nova Scotia coast in 1973 showed an agreement of approximately 5 m between observed ranges measured by Hi-Fix and predicted ranges calculated from survey observations after corrections for secondary phase lag. The Johler model was thus confirmed for phase lags at 1700 to 2000 kHz over sea water off the Atlantic coast.

Extensive tests were made in the Gulf of St. Lawrence in 1969 to determine the accuracy of the Decca Lambda system when used in the range-range mode and with phase lag corrections applied (Brunavs and Wells 1971). These tests confirmed the Johler model for Decca Lambda frequencies (70 to 170 kHz) in commonly encountered east coast conditions.

The model has also been confirmed for open water conditions in the Arctic. During April and August 1973, the Canadian Hydrographic Service, in cooperation with the Geodetic Survey Division and the Polar Continental Shelf Project of the Department of Energy, Mines and Resources, carried out a comparison test using Decca frequencies to determine the phase lag in Amundsen Gulf for sea-ice conditions, by comparing it with the phase lag for open-water conditions. The August test was conducted over open sea water, the primary and secondary phase lag effects were computed and an effective velocity was derived. The result agreed with the observed velocity, thus confirming the Johler model for Arctic open water (Gray, 1975).

• Sea Surface Conductivity

The Marine Environmental Data Service (MEDS) of the Department of the Environment made a statistical study of 21 173 sea-surface conductivities measured on the Nova Scotia coast, Gulf of St. Lawrence, Grand Banks, and Labrador coast (Forester, 1973). The area was divided into blocks, usually 5° squares of latitude and longitude. Data was accumulated for each block for each calendar month. The statistics produced for each block, for each month, included the mean conductivity, standard deviation of the observations, maximum and minimun observed values, and a number of samples. Figure 22 gives five curves from this data which describe the average conditions off Canada's east coast.

Three of the curves are: the conductivity, the average of the mean conductivities for all blocks for each month, and the maximum and minimum mean conductivities for any block during that month. The maximum and minimum monthly mean values should be considered with caution because no extensive efforts were made to eliminate blunders from the large mass of data. Also given for each month are the lowest monthly mean values for any block in the study area minus three standard deviations for that block, and the highest monthly mean value for any block in the study area plus three standard deviations for that block. These last curves should indicate a better than 99 percent confidence band for the observations. Sea-surface conductivities of the water off the east coast should rarely be outside the limits shown by these two curves.

The MEDS study indicates that no appreciable variations exist with respect to different areas on the Atlantic coast. This indication may have resulted from the fact that block areas were delineated strictly by geographic coordinates. No attempt was made to relate block boundaries to shorelines or the boundaries of the Labrador current or the Gulf stream. Nevertheless, these curves are representative of sea-water conductivities in the areas adjoining the eastern Canadian coastline. Since the study was done in an area where there are large disturbing influences including the cold Labrador current, the warm Gulf stream, and the fresh water influx of the St. Lawrence River, it is reasonable to assume that surface conductivity in other areas may not be more variable.

A study of the total phase-lag polynomials indicates the magnitude of errors in range which would result from various errors in conductivity. If we assume a mean conductivity of 3.2 Siemen per metre (S/m), and the actual conductivity is within the range 2.0 to 5.5 S/m (the approximate outside limits of the 99 percent confidence region shown in Figure 22), the maximum errors for Loran-C would be:

at 10 km, 1.0 m or 100 ppm or 1/10 000
at 100 km, 3.0 m or 30 ppm or 1/33 000
at 1 000 km, 11.4 m or 11 ppm or 1/88 000.

Mean monthly values taken from Figure 22 would reduce the errors slightly. Conductivity measurements taken at the time

TABLE VI

Coefficients for Computing Groundwave Phase Lags
For Loran-C (100 kHz)

for: distances over 200 m,
permittivity of the atmosphere, E1 = 1.000 676
vertical lapse rate of the atmosphere, α = 0.75
datum velocity, c = 299 792.5 km/s
permittivity of the surface, E2 in e.s.u.

Surface Conductivity (Siemen/m)	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
SEA WATER (E2 = 81)									
5.5	2.277	-111.0	98.08	-13.75	112.8	-0.254	0.0	0.00	0.
5.0	2.277	-111.0	98.20	-13.51	112.8	-0.254	0.0	0.00	0.
4.5	2.277	-111.0	98.35	-13.23	112.8	-0.254	0.0	0.00	0.
4.0	2.277	-111.0	98.53	-12.90	112.9	-0.254	0.0	0.00	0.
3.5	2.277	-111.0	98.75	-12.50	112.8	-0.254	0.0	0.00	0.
3.0	2.277	-111.0	99.01	-12.00	112.8	-0.254	0.0	0.00	0.
2.5	2.277	-111.0	99.35	-11.36	112.8	-0.254	0.0	0.00	0.
2.0	2.277	-111.0	99.80	-10.50	112.8	-0.254	0.0	0.00	0.
LAND (E2 = 15)									
0.03000	2.277	1.9	126.77	43.7	36.9	-0.600	-30.3	13.64	310.
0.02500	2.277	15.4	129.63	43.9	29.2	-0.600	-35.2	14.08	310.
0.02000	2.277	31.0	133.49	45.1	18.4	-0.600	-40.0	14.30	310.
0.01750	2.277	42.1	135.98	45.7	11.0	-0.600	-43.9	14.47	310.
0.01500	2.277	55.7	139.05	46.6	2.1	-0.600	-48.1	14.42	290.
0.01250	2.277	73.6	142.94	47.0	-8.9	-0.600	-54.3	14.13	270.
0.01000	2.277	98.0	148.11	47.0	-24.0	-0.600	-60.8	14.00	245.
0.00750	2.277	133.7	155.47	49.0	-47.0	-0.600	-72.5	13.20	226.
0.00600	2.277	166.0	161.67	49.2	-66.7	-0.600	-83.3	12.67	167.
0.00500	2.277	195.5	167.04	48.9	-83.9	-0.598	-94.3	12.26	151.
0.00400	2.277	236.2	173.89	47.5	-105.9	-0.587	-108.7	10.76	96.
0.00300	2.277	297.1	182.95	48.3	-143.1	-0.556	-127.7	10.42	74.
0.00250	2.277	341.3	188.62	47.5	-163.8	-0.534	-146.4	9.16	56.
0.00200	2.277	402.7	195.13	48.8	-195.3	-0.508	-169.3	8.29	31.
0.00175	2.277	442.6	198.63	51.4	-218.0	-0.496	-183.5	8.02	28.
0.00150	2.277	492.2	202.13	54.3	-236.5	-0.457	-208.2	7.16	21.
0.00140	2.277	515.5	203.43	55.3	-241.1	-0.433	-223.2	6.62	17.
0.00130	2.277	541.1	204.70	57.6	-249.7	-0.415	-237.4	6.36	14.
0.00120	2.277	569.1	205.82	61.6	-263.1	-0.406	-249.3	6.25	13.
0.00110	2.277	599.8	206.75	67.3	-280.2	-0.402	-259.7	6.22	13.
0.00100	2.277	633.3	207.42	75.0	-299.4	-0.400	-271.4	6.30	13.
0.00090	2.277	669.3	207.73	85.3	-319.7	-0.399	-285.7	6.48	13.
0.00080	2.277	707.5	207.58	98.9	-339.9	-0.401	-302.3	6.74	14.
0.00070	2.277	746.5	206.87	118.2	-361.1	-0.409	-316.9	6.97	16.
0.00060	2.277	785.1	205.45	145.8	-382.5	-0.426	-328.0	7.31	20.
0.00050	2.277	819.4	203.26	182.6	-392.5	-0.450	-347.2	7.78	25.
0.00040	2.277	845.8	200.16	216.5	-357.8	-0.473	-401.6	7.58	16.
0.00030	2.277	855.7	196.04	219.5	-217.3	-0.488	-523.4	5.64	7.
0.00020	2.277	832.2	190.58	190.3	-8.7	-0.498	-685.7	5.23	6.
0.00010	2.277	717.7	183.06	164.2	132.0	-0.510	-690.6	7.25	19.
0.00005	2.277	573.3	178.07	158.7	165.4	-0.516	-568.4	9.61	55.
0.00001	2.277	393.6	173.46	155.7	186.4	-0.522	-402.8	11.29	111.

TABLE VII

Coefficients for Computing Groundwave Phase Lags For Hi Fix and Argo (1702 kHz) Over Water

for: distance over 200 m,
permittivity of the atmosphere, E1 = 1.000 676
vertical lapse rate of the atmosphere, α = 0.75
datum velocity, c = 299 792.5 km/s
permittivity of the surface, E2 is e.s.u.

Surface Conduc-tivity (Siemen/m)	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
				SEA WATER (E2 = 81)					
5.0	0.00773	0.1	46.5497	-2.2933	4.6154	-0.5	-4.0968	6.0	0.
4.0	0.00776	2.2	46.7871	-2.7977	3.1919	-0.5	-4.6779	6.0	0.
3.0	0.00766	2.9	47.4754	-2.5022	3.4076	-0.5	-5.5516	6.0	0.
2.0	0.00744	3.1	48.7884	-1.3986	4.5915	-0.5	-6.6647	6.0	0.
1.0	0.00711	6.0	50.8178	-0.5671	4.4715	-0.5	-9.1115	6.0	0.
				BRACKISH WATER (E2 = 80)					
0.75	0.00694	9.4	52.2567	-0.3049	3.5038	-0.5	-11.2025	6.0	0.
0.50	0.00655	12.5	54.1506	0.7259	3.3363	-0.5	-13.7614	6.0	0.
0.25	0.00593	18.0	57.9187	4.2427	4.4423	-0.5	-19.5047	6.0	0.
0.10	0.00461	23.7	62.0038	14.7811	2.0696	-0.5	-31.1729	6.0	0.

of the range measurement would give the most accurate results.

Additional Secondary Factor (ASF)

- Overland Path

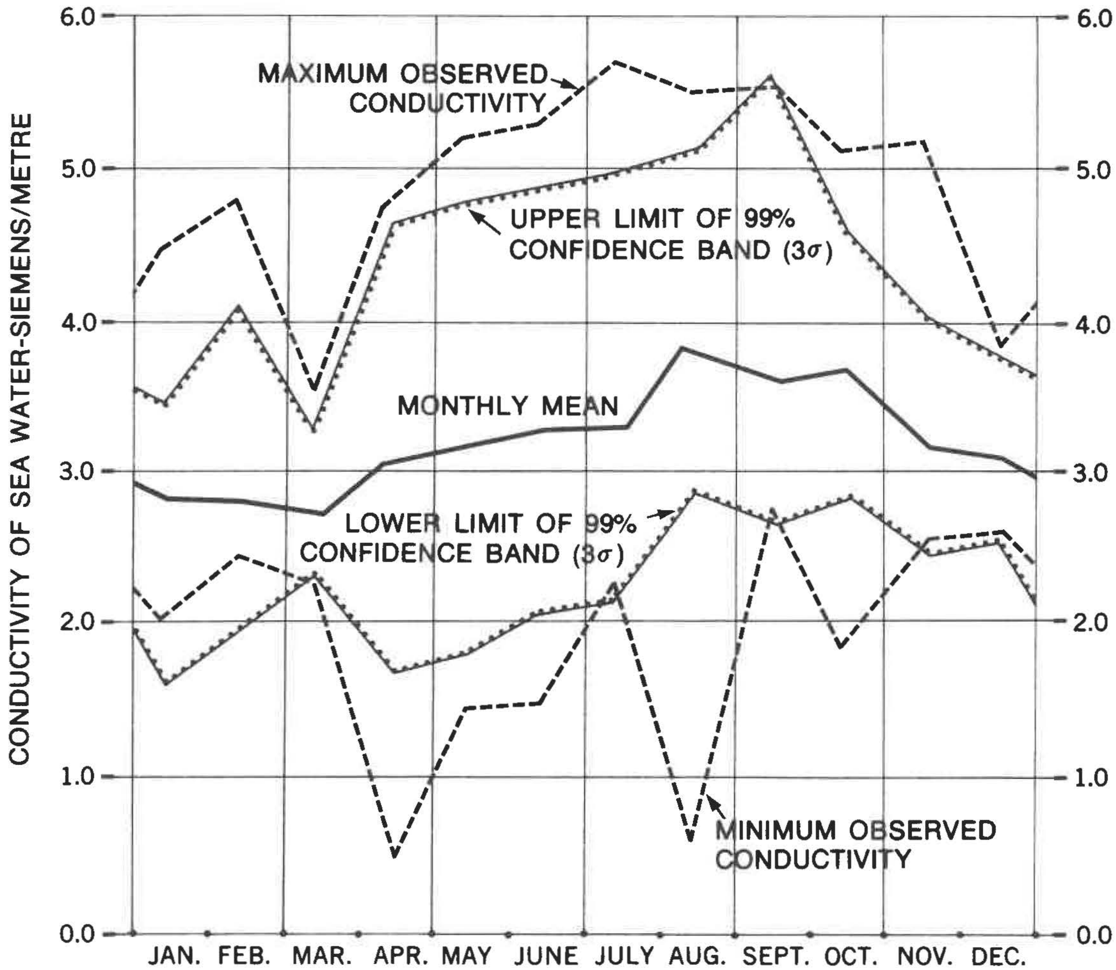
In conditions where medium and low frequency transmissions have overland paths between the transmitter and receiver, there is a substantial change in the secondary phase lag from what it would be with total sea-water conditions. This change is caused by the very different electrical properties of the land as opposed to those of the sea. There are significant changes with regard to different types of land, i.e., rocky, wooded, cultivated, or swampy, and fresh-water lakes present their own electrical properties. Seasonal changes caused very pronounced variations in the electrical properties. Under these conditions, the Johler (1956) model is quite unsatisfactory for estimating secondary phase lag. To avoid overland paths, most transmitters for offshore surveys have been situated close to the coast.

Loran-C is a long-range positioning system capable of being used at ranges up to 2000 km. Consequently, the area of good geometric coverage is quite large and it is inevitable that some overland path must exist. The trend in the past few years has been to establish more Loran-C stations inland, so that the chain can be used for both marine and air navigation.

However, the inland locations involve long overland paths from the transmitter which may range from a dry plateau to a rain forest. Extensive testing of the overland path characteristics of the secondary phase lag would have to be carried out in order to predict the secondary phase lag accurately enough for surveying purposes.

If the overland correction was constant over the survey area, the correction would be relatively simple to measure. One method is to compare a Loran-C fix with a more accurate fix, but in some cases the correction varies rapidly; for example, the Canadian Hydrographic Service found that when steaming around Scaterie Island (east point of Cape Breton Island), the correction to the Loran-C range measured to Nantucket changed by 2.4 microsec (700 m) in 46 km (25 nautical miles), as the overland path increased.

For navigational purposes, the disadvantages of overland paths are minimal when compared to the advantages obtained by good geometry; however Loran-C chains will also be used for surveying; when so used the effect of secondary phase lag due to overland transmission will have to be considered.



For January the mean conductivity is 2.82, the observed range of conductivities is 2.07 to 4.46, and there is a 99% probability that the conductivity is within the range from 1.59 to 3.44 siemens/metre.

Figure 22

Variation in Sea-Water Conductivity off Canada's East Coast

The modified Millington's method (Bigelow, 1965) of determining the secondary phase lag correction of composite paths is not precise enough for most survey work, but can provide a rough estimate of the ASF or, if used in connection with observed ASFs, the method can provide an improved estimate of the ASF in the area of the observations. A sample computation for the line shown in Figure 23 is given in Table VIII.

- Over Sea Ice Path

Early experience with Decca indicated that its accuracy was significantly reduced if the area of operation was ice covered. During April and August 1973, the Canadian Hydrographic Service, in cooperation with the Geodetic Survey Division and Polar Continental Shelf Project of the Department of Energy, Mines and Resources, carried out tests using Decca equipment to determine the characteristics of the secondary phase lag over sea ice in comparison with those over open water. The tests showed (Gray, 1975) that by assuming a uniform velocity of propagation and accepting a linear relationship between secondary phase lag and distance, the velocity observed over sea ice in April was 2.9951 x 10^8 m/s, and the velocity observed over open water in August was 2.9961 x 10^8 m/s, a difference of 1 part in 3000.

The observed velocity over open water confirmed the theoretically determined primary and secondary phase-lag computations, using observed meteorological and oceanographic properties.

Gray's (1975) report confirmed that at Decca frequencies (84 to 130 kHz), the effect of even 2 m of sea ice, on one range, was significant (of the order 1:3000). It showed that the magnitude of the effect would be very dependent on the thickness and conductivity of the ice, and indicated that the thickness and conductivity of the ice could be variable within an operational area. There was not enough data to establish a model adequate enough to estimate an ASF for sea-ice conditions.

Several surveys have been made using Hi-Fix frequencies (1700 to 2000 kHz) over different types of sea ice in the Canadian Arctic; the maximum operating range was reduced,

TABLE VIII

Sample Millington's Method Computation for Loran-C

Distance from Transmitter km	Conductivity at Siemen/m	Total Phase Lag at Start of Section m	Total Phase Lag at End of Section m	Total Phase Difference m
Forward				
0				
	.001	1499.0	679.2	-819.8
100				
	4.	67.3	219.9	152.6
300				
	.002	978.1	1183.8	205.7
400				
	3.5	307.3	584.9	277.6
700				
			TOTAL	-183.9
Reverse				
0				
	3.5	1499.0	221.2	-1277.8
300				
	.002	978.1	1183.8	205.7
400				
	4.	305.8	488.3	182.5
600				
	.001	1891.8	2099.3	207.5
700				
			TOTAL	-682.1
			MEAN	-433.0

Total Phase Lag over Sea-water of Conductivity 5 Siemen/m = 579.8 – 1499.0 = -919.2 m

Additional Secondary Factor = -433.0 – (-919.2) = 486.2 m

= 1.62 microsec.

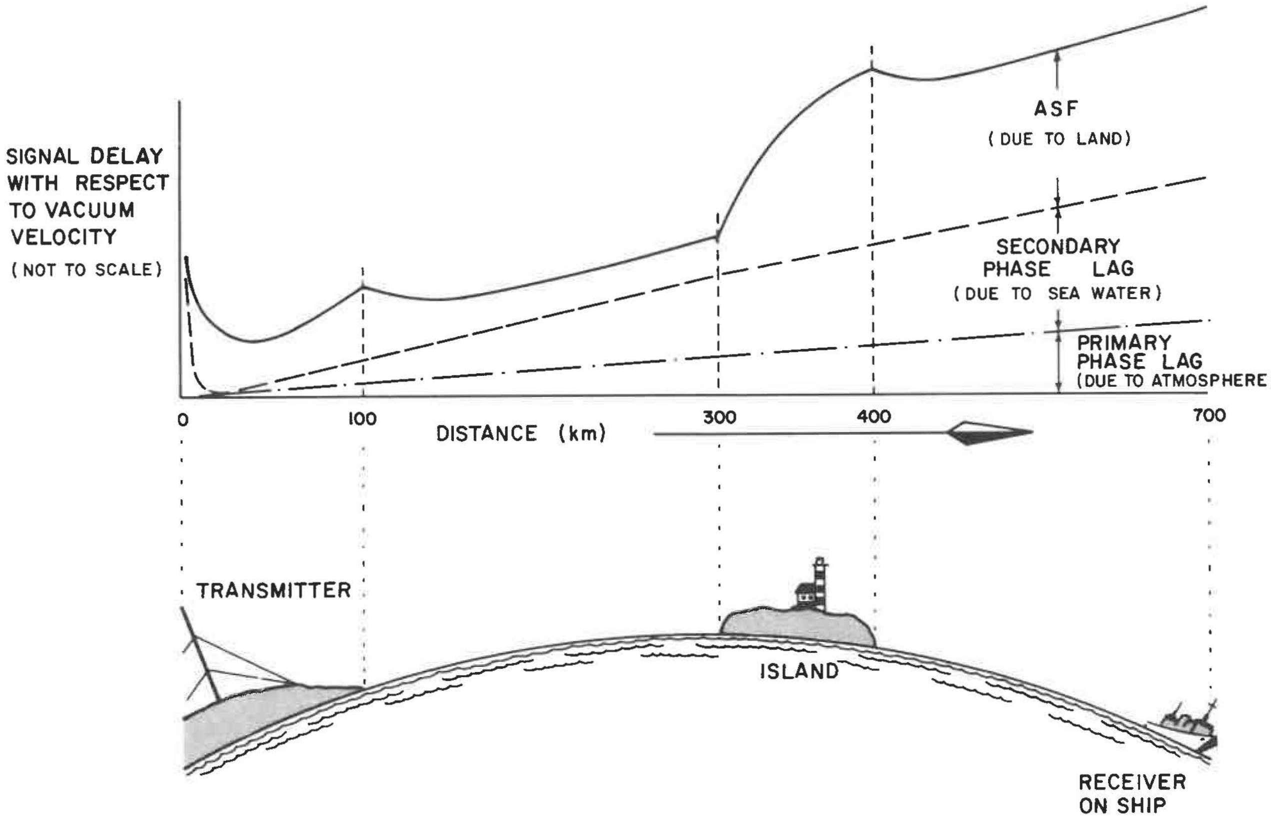


Figure 23

Phase Lag Components

and in some cases there was a complete loss of signal well within the normal range of the system. In addition, the propagation velocity varied considerably depending on the thickness and age of the ice. With even a small amount of rapidly melting ice in Northumberland Strait, the Canadian Hydrographic Service observed a change of one part in 3300 in the effective velocity. Sea ice has a much greater effect on propagation velocity at Hi-Fix frequencies than at Decca frequencies.

Computation of Primary and Secondary Phase Lags

The atmospheric index of refraction at the ship and shore stations can be readily measured using barometers and wet and dry thermometers, but the value may not represent conditions in the intervening distance. Depending on the accuracy required, it may be necessary to sample or estimate conditions along the intervening distances. For microwave systems, the nomograms supplied for tellurometers are convenient for deriving η_{obs} from measured temperatures and pressure.

The primary phase lag incorporated in the total phase lag polynomials was derived using a nominal index of refraction, η_{nom} = 1.000 338:

$$\text{Primary Phase Lag} = (\eta_{nom} - 1)d \qquad (21)$$

For an observed value η_{obs}, the C_2 term of the polynomial must be corrected:

$$C_2\ (\text{corrected}) = C_2\ (\text{nom}) + 100\ 000\ (\eta_{obs} - \eta_{nom}) \qquad (22)$$

Locking Constant

For a range-range system, giving readings in lanes, the general expression for the computation of distance from observed lane readings is:

$$d = (n_{obs} - n_L)\cdot\frac{\lambda}{2} \qquad (23)$$

where:

n_{obs} = observed lane reading,
n_L = locking constant,
λ = wavelength for the effective velocity V_e and comparison frequency f_c, ($\lambda = V_e/f_c$).

Using phase-lag values, the expresion is:

$$d = (n_{obs} - n_L)\cdot\frac{\lambda_o}{2} - P_d \qquad (24)$$

where:

λ_o = wavelength for vacuum velocity ($\lambda_o = V_o/f_c$),
P_d = the total phase lag value for distance d.

In determining the locking constant we have to compute the correct lane number for a known distance d.
Using phase-lag values, we have:

$$n = \frac{2}{\lambda_o}(d + P_d), \qquad (25)$$

and $$n_L = n_{obs} - n. \qquad (26)$$

Effective Phase Velocity

When using the total phase lag polynomials it is useful to consider how the tabulated values can be related to an effective radio-wave propagation velocity (correctly known as phase velocity). If, at a distance d, the phase of the actual signal lags by P_d behind what it would be if the signal has travelled at the velocity in a vacuum V_o, the corresponding effective phase velocity V_e is:

$$V_e = V_o\left(1 - \frac{P_d}{d}\right) \qquad (27)$$

Assuming a signal path derived from the total phase lag polynomial completely over sea water, the values are a reasonable approximation to P_d. For example, for a Loran-C signal travelling through air with an index of refraction 1.000 338 over sea water with conductivity 3.2 S/m, the computed total phase lag is 307.5 m for a distance of 400 km. The corresponding effective velocity is:

$$V_e = 299\ 792.5\left(1 - \frac{307.5}{400\ 000}\right) = 299\ 562.0 \text{ km/s}$$

A fictitious wave travelling with a constant velocity of 299 562.0 km/s would arrive at the 400 km mark at the same time as the actual wave travelling with a velocity which varies depending on location along the path.

Inspection of sample phase lag computations would show that the phase lag increases steadily outside the range of the induction field, but the corresponding effective velocities are relatively constant, decreasing only slightly with increasing range.

Because the effective velocity is relatively constant for each frequency range, an approximate value can be chosen to derive ranges if the accuracy required does not warrant the use of the phase lag polynomial.

Changing of Reference Velocity

The tabulated phase lags are all referenced to the vacuum velocity. The use of the vacuum velocity is a convention, and the main advantage is that the phase lags are always positive. There is, however, the drawback that numerically, the phase lag corrections are quite large, therefore in certain cases it is more convenient to use some other reference velocity.

The conversion can be made as follows:

$$p^1 = p - \frac{V_o - V_1}{V_o}\,d \qquad (28)$$

where

p^1 = phase lag, referenced to velocity $V^1{}_o$,
p = tabulated phase lag, referenced to vacuum velocity V_o = 299 792.5 km/s,
d = distance, to which p^1 and p refer.

Example:

For Hi-Fix, Conductivity 3.2 S/m, and d = 100 km, the phase lag from polynominal is 49.7 m,

For the velocity, $V^1{}_o$ = 299 650 km/s.

$$p^1 = 49.7 - \frac{299\ 792.5 - 299\ 650}{299\ 792.5} \times 100\ 000 = 2.2 \text{ m.}$$

If the selected new reference velocity were lower than 299 650 km/s, more of the derived phase lags would have a negative sign, indicating that at these particular distances there is a phase advance with respect to the nominal value. It is fully appropriate to use phase lags as positive and negative values provided no mistake is made when they are inserted in the required formulae. In case of doubt, a check using effective velocity may also be made since the latter does not vary with a change in reference velocity.

The velocity of 299 650 km/s has special significance because it has been widely used as an approximation for average phase velocity over sea water. If the phase lags are converted to this velocity as a reference, it is found that, for an average sea-water conductivity of approximately 4 S/m, this velocity is quite suitable for Hi-Fix frequencies, but is somewhat too high for the Decca frequency band of 70 to 170 kHz. At these lower frequencies the effective velocity varies between 299 500 and 299 610 km/s; thus, the adoption of a single best-fitting velocity is less suitable at low frequencies.

It is evident that the phase lag data could be used to derive a best-fitting constant velocity for different system frequencies and expected ranges from the transmitters.

When automatic computers are used, the main criterion is that the phase lag function is accurate and simple for computing, therefore it is convenient to use the vacuum velocity V_o.

Numerical Examples

For the different systems there are different simple equations (30) and (31) for deriving a nominal range from the instrument readings supplied. For all systems, where the accuracy requirements warrant, this nominal range can be corrected using equation:

$$d = d_n - (P_d + \eta_{obs} - \eta_{nom})\, d_n \qquad (29)$$

where:

d = corrected range;
d_n = nominal range (derived differently for different systems);
P_d = Total Phase Lag as computed for the range by the polynominal, for the appropriate frequency, conductivity and permittivity;
η_{obs} = observed index of refraction;
η_{nom} = nominal index of refraction of the phase lag polynominals

Hi-Fix

In this system, the readings are expressed in lanes. Since the signal makes a two-way trip, the effective lane width is one half the signal wavelength. The nominal range is given by:

$$d_n = (n_{obs} - n_L)\frac{\lambda_o}{2} \qquad (30)$$

where:

n_{obs} = observed lane reading;
n_L = locking constant;
λ_o = nominal wavelength, for vacuum velocity ($\lambda_o = V_o/f_c$);
V_o = vacuum velocity of electromagnetic waves;
f_c = comparison frequency.

Field Data:

range 1, n_{obs1} = 1500.0 lanes (locking constant, n_L = 0),
range 2, n_{obs2} = 2000.0 lanes (locking constant, n_L = 0).

Accepted Constants:

vacuum velocity V_o: 299 792.5 km/s.
sea surface conductivity: 3.0 S/m.
comparison frequency f_c: 1702 kHz.
index of refraction n: 1.000 338 (correction to computed total phase lags from polyminals = 0).

Computations:

nominal lane width $\lambda_o/2 = V_o/2f_c$ = 88.0707 m

From equation (30):

nominal range d_{n1} = (1500-0) 88.0707
= 132 105.0
nominal range d_{n2} = (2000-0) 88.0707
= 176.141.3

From equation (15):

range d_1 = 132 106.0 + 65.1 = 132 171.1 m.
range d_2 = 176 141.3 + 85.4 = 176 226.7 m.

Loran-C (Rho-Rho)

In this system, the readings are given in microseconds of travelling time. Since the signal travels only one way, the nominal range is given by:

$$d_n = (L - E)V_o, \qquad (31)$$

where:

L = Loran-C reading;
E = emission delay = coding delay + baseline travel time;
V_o = vacuum velocity of electromagnetic waves.

Field Data:

Loran-C reading for Cape Race	L_R	= 50 201.50 us.
Loran-C reading Angissoq	L_A	= 3 598.42 us.
Emission delay for Cape Race	E_R	= 18 212.24 us.
Emission delay for Angissoq	E_A	= 0.00 us.

Accepted Constants:

vacuum velocity V_o: 299 792.5 km/s;
sea surface conductivity: 4.0 S/m;
signal frequency f: 100kHz
index of refraction n: 1.000 338 (Correction to tabulated phase lags = 0).

Computations:

from equation (31):
nominal range to Cape Race,
d_{nR} = (0.050 201 50 – 0.048 212 24)299 792 500
= 596 365.2;

nominal range to Angissoq,
d_{nA} = (0.003 598 42 – 0.000 000 00)299 792 500
= 1 078 779.3.

From equation (29):

range to Cape Race, d_R = 596 365.2 – 484.9
= 595 880 m
range to Angissoq, d_A = 1078 779.3 – 950.6
= 1077 829 m.

Phase Lags in Hyperbolic Systems

In hyperbolic systems, the introduction of specific phase lag corrections is a rather cumbersome process and the additional accuracy obtained is seldom warranted. It is usually satisfactory to use a reasonable estimate of the average velocity for the particular conditions.

Accuracy of Radio Positioning

The positioning accuracy of any radio positioning system depends on two factors:

- The accuracy of an individual measurement, which depends on instrumental accuracy, knowledge of the propagation velocity, care taken in calibration, etc.
- The Fix Geometry Factor, or Geometric Dilution of Position (GDOP), that is, the ratio of the position error to the measuring error. It depends on the angle at which the LOPs intersect, and it includes the lane expansion or error magnification of

hyperbolic systems (see Figure 24). At point P, the GDOP is the same as the ratio of the long diagonal of the diamond formed by the intersecting LOPs at P, to the width of the lanes at the baselines between shore stations. The geometric pattern set up by the intersecting LOPs depends on how the transmitting stations are located relative to the survey area, therefore the geometric pattern is, to some extent, under the control of the surveyor. The error in position, resulting from a given measurement error, depends critically on the location within the pattern.

From an examination of the diamond-shaped figures formed by the lattice of LOPs, one can see the error in position which would result from a measurement error of one lane. For a hyperbolic system (Figure 24), the long axis of each diamond is the positional error which would be a result of each hyperbolic measurement being too large by one lane. For a range-range system (Figure 25) in localities distant from the shore stations, the short axis of the diamond is the positional error which would result from range measurements that are too large by one lane for each range. Clearly, the same ratios of measurement error to position error are valid for smaller measurement errors in the same general vicinity.

The lattice pattern indicates that in most areas, there exists a "worst" direction for fix accuracy. Within the area of coverage of a range-range system, this "worst" direction is normal to the baseline in the part close to the baseline, and parallel to the baseline in the part far from the baseline. When using a hyperbolic system far out in the area of coverage, the "worst" direction is towards the master.

In a hyperbolic system, the average errors in measuring the phase difference at a point P, between the signals received from the master and slave transmitters, is a small fraction of a cycle of each of the transmitted frequencies. Each of these fractions of a cycle can be expressed in length units, by multiplying the fractions by the wavelength of the appropriate transmitted signal. The average errors, expressed in metres, for each of the slave frequencies, are not generally the same. However, they are close enough in magnitude to characterize a system.

If, in a given system, the error of both red and green phase differences is e_m metres, the error in the red position-line measurement for a point on the baseline between the master and red slave is e_m metres. Similarly, the error in the green position-line measurement for a point on the green baseline is e_m metres. But, for an arbitrary point P within the area covered by the system, the errors, expressed in metres, in each of the position-line measurements are not in general e_m metres; it is only along the baseline that the wave-length of the transmitted signal is equal to the distance between position lines of the lattice. In general, the position-line errors, in metres, corresponding to phase-difference errors of e_m in both the red and green measurements are given by:

$$e_R = e_m \operatorname{cosec} \rho/2 \text{ (metres)}, \quad (32)$$
$$e_G = e_m \operatorname{cosec} \gamma/2 \text{ (metres)}, \quad (33)$$

where:

e_R is the error in the red-position line,
e_G is the error in the green-position line,
ρ is the angle subtended by the baseline between the master and red slave.
γ is the angle subtended by the baseline between the master and green slave.

If the errors in the measurement of the red and green position lines at a point P (Figure 18) are e_R and e_G respectively, and the angle between the position lines at P is θ, the resultant error in the position fix d_{LA} is given by:

$$d_{LA} = \operatorname{cosec} \theta \sqrt{e_R^2 + e_G^2 + 2e_Re_G\cos \theta} \quad (34)$$

note that by the properties of a hyperbola:

$$\theta = (\rho + \gamma)/2. \quad (35)$$

Combining equations (32), (33) and (34) we have:

$$d_{LA} = e_m \operatorname{cosec} \theta \left(\operatorname{cosec}^2 \rho/2 + \operatorname{cosec}^2 \gamma/2 + 2 \operatorname{cosec} (\rho/2) \operatorname{cosec} (\gamma/2) \cos \theta\right)^{1/2} \quad (36)$$

Equations (34) and (36) are valid only if the errors in the red and green position-line (or phase difference) measurements

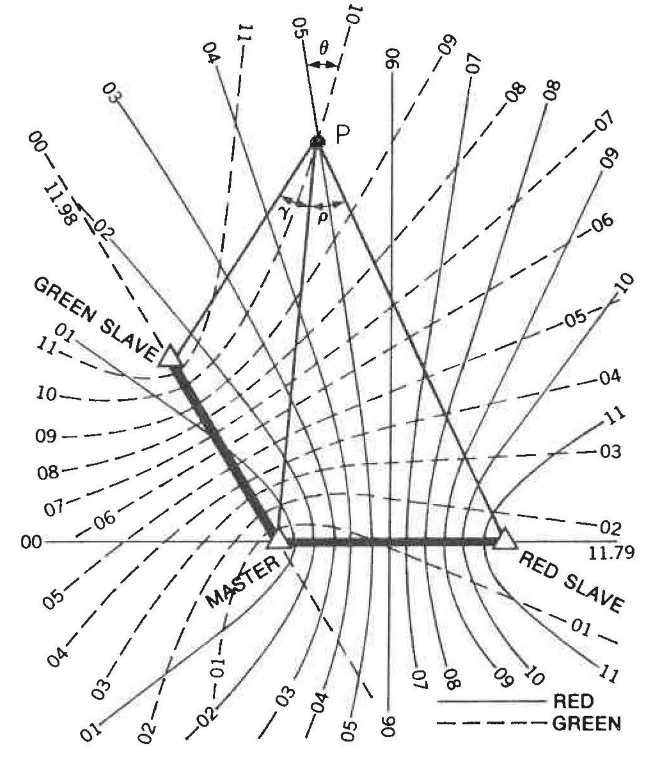


Figure 24

Intersecting Position Lines for a Hyperbolic Triad

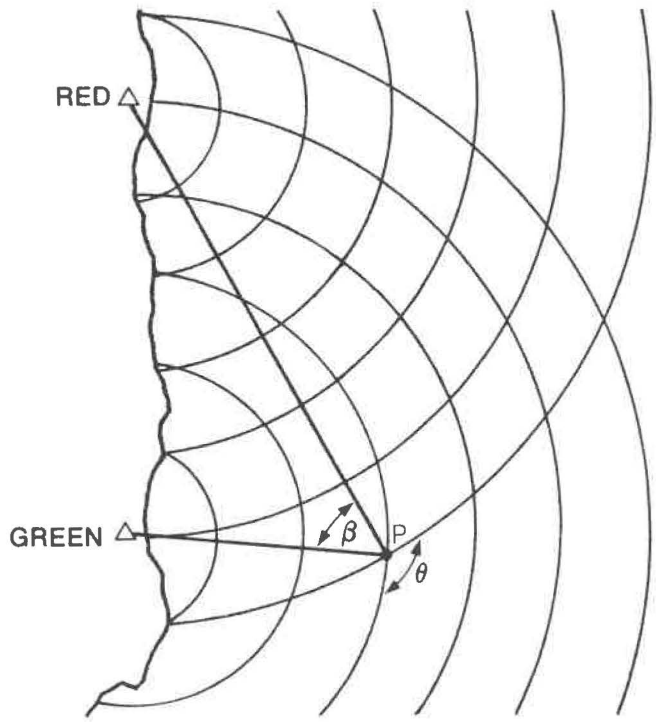


Figure 25

Intersecting Position Lines for a Range-Range Pair

are fully and positively correlated; that is, a large positive error in the red-phase difference is invariably associated with an equally large positive error in the green-phase difference; a situation unlikely to occur. The normal situation is that only a few of the error sources are common to both measurements. Some method of taking into consideration the extent of correlation must be introduced in equations (34) and (36).

If the measurement errors e are replaced by the respective measurement standard deviations σ, and a correlation coefficient is added to the term which involves both range measurements, we have:

$$d_{rms} = \text{cosec}\,\theta \sqrt{\sigma_R^2 + \sigma_G^2 + k_G\,\sigma_R\,\sigma_G \cos\theta} \quad (37)$$

and,

$$d_{rms} = \sigma_m \,\text{cosec}\,\theta\,(\text{cosec}^2 \rho/2\ \text{cosec}^2 \gamma/2 + 2k_{RG}\,\text{cosec}\,(\rho/2)\,\text{cosec}\,(\gamma/2)\cos\theta)^{1/2} \quad (38)$$

where:

k_{RG} is a correlation coefficient between the measurements of the red and green-phase differences;

σ_R and σ_G are standard deviations of the red and green-phase difference measurements;

σ_m is a mean standard deviation of phase-difference measurements and, $d_{rms} = \sqrt{a^2 + b^2}$ is the square root of the sum of squares of the semi-major and semi-minor axes of the standard-error ellipse describing the accuracy of the resulting position fix.

In range-range or rho-rho systems, the corresponding intersection angle θ between position lines at point P (Figure 25) is given by:

$$\theta = 180° - \beta \quad (39)$$

where β is the angle between the range lines at P.

Substituting equation (39) into equation (37) we get a corresponding expression for d_{rms} in the two-range situation;

$$d_{rms} = \text{cosec}\,\theta \sqrt{\sigma_R^2 + \sigma_G^2 - k_{RG} \cdot \sigma_R \cdot \sigma_G \cos\beta} \quad (40)$$

where:

σ_R and σ_G are the standard deviations of the two-range measurements, rather than two phase or range-difference measurements.

Where there is no correlation ($k_{RG} = 0$), equation (40) reduces to equation (18) (see Chapter 6, Positional Accuracy). Where there is high positive correlation k_{RG} approaches 1 and d_{rms} becomes very small. Since the more usual situation is that k has a small positive value, equation (18) may give a slightly high value for the standard deviation of the position error. The value of d_{rms} is $\sqrt{2}$ times the semi-major axis of the standard error ellipse when the fix accuracy is the same in all directions (i.e., semi-major and semi-minor axis equal), but only slightly larger than the semi-major axis when there is a large difference in the two axes. For most of the area covered by a system, particularly those areas where the accuracy is lowest, d_{rms} is a good approximation for the semi-major axis of the standard-error ellipse.

The Circle of Equal Probability (CEP) is a less meaningful but frequently used term. It is the circle within which there is a 50 percent probability of the true position being situated. The radius of the CEP is a less-stringent error estimate and may sometimes be used to give an impression of higher accuracy.

Accuracy Contours

Having estimated the reading errors of this system, the surveyor often wants to find contours of constant-fix accuracy to define areas within which he can work to a required tolerance. There are two approaches: 1) calculate error ellipses at a grid of points over the survey area, and then interpolate accuracy contours between the points; 2) plot contours of fix Geometry Factor or Geometric Dilution of Position (GDOP).

For a hyperbolic system, from equation (38):

$$\text{GDOP} = \frac{d_{rms}}{\sigma_m} = \text{cosec}\,\theta(\text{cosec}^2 \rho/2\ \text{cosec}^2 \gamma/2 + 2k_{RG}\,\text{cosec}\,(\rho/2)\,\text{cosec}\,(\gamma/2)\cos\theta)^{1/2} \quad (41)$$

Once the master and slaves are plotted, the contours can be plotted as described by Bigelow (1965) using a three-arm protractor. The accuracy contours for a navigational hyperbolic Loran-C chain are shown in Figure 26. In deriving these curves, the correlation coefficient k_{RG} is taken either as plus one or minus one, whichever gives the largest value of GDOP; thus, the contours represent the least advantageous case. For example, if the standard deviation of the phase-difference measurements is 50 metres, the contours in Figure 26 indicate locations where d_{rms} is no more than 250 or 500 metres with full correlation in the least advantageous case.

For a two-range system, from equation (40) and assuming $\sigma_R = \sigma_G = \sigma$:

$$GDOP = \frac{d_{rms}}{\sigma} = \frac{2 \operatorname{cosec} \beta}{\sqrt{\sigma_R^2 + \sigma_G^2 - k_{RG} \cdot \sigma_R \cdot \sigma_G \cos \beta}} \qquad (42)$$

As with the hyperbolic system, the value of k_{RG} is taken either as plus one or minus one so that the contours represent the least advantageous case. Accuracy contours (Figure 27), are circles subtending a constant angle at the baseline, and indicate locations where d_{rms} is no more than the indicated multiples of the standard deviation of the measurements. Note the rapid increase in GDOP close to the baseline. The low accuracy "football" is fairly narrow. It may be possible to maintain reasonable accuracy through the contours if a ship crosses them at approximately right angles, and has an accurate distance-measuring log to reduce the larger along-track errors near the base. In general, the two-range geometry gives better accuracy than hyperbolic geometry.

Error Ellipses

The other technique of finding the accuracy attainable within the operating area of a two-range system is to compute error ellipses. The array of error ellipses, shown in Figure 28, indicates the accuracies attainable within a system such as Hi-Fix based on shore control of poor quality. The ellipse information is computed using the GALS (McLellan, 1970) computer program. The initial input requirements of the design mode of this program are:

- The relative accuracy of the control points expressed as a standard deviation (for most circumstances the control can be assumed errorless, but in this case low accuracy control was assumed).
- The estimated standard deviation of each range measurement required to compute a weight for each measured line.
- The approximate geographic location of each control point and the positions for which the error ellipses are desired.

From this data, the error-ellipse information is computed in terms of: the magnitude of the standard deviation in the maximum direction (semi-major axis), the azimuth of the maximum direction, and the standard deviation in the minimum direction (semi-minor axis). The program is not designed to handle correlation coefficients under the assumption that the measurements are not correlated. The figures are slightly large, because a small positive correlation can be expected. Figure 28 indicates that when the angle of intersection between the ranges is small, the major axis is very long in comparison with the minor axis, and the major axis is perpendicular to the direction from the point to the control. The

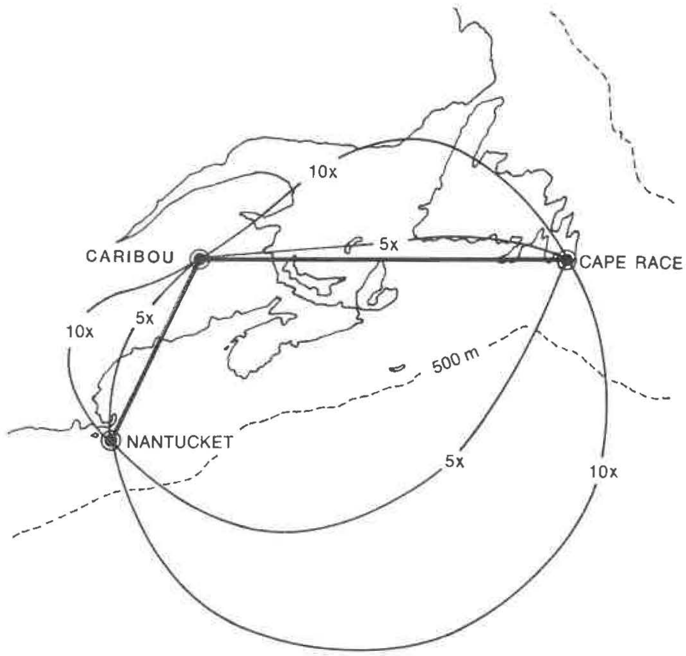


Figure 26

Contours of Geometric Dilution of Position (GDOP) for a Hyperbolic Chain

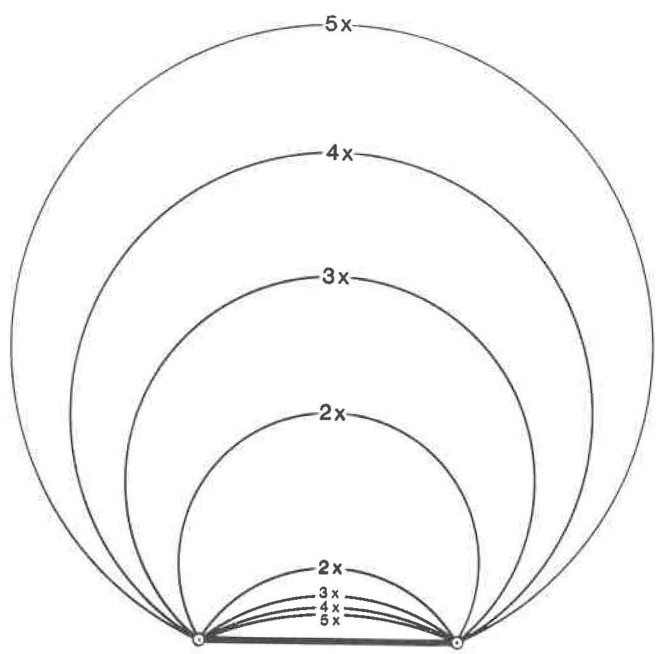


Figure 27

Contours of Geometric Dilution of Position (GDOP) for a Range-Range Chain

figure also shows the improvement which might be achieved by using better shore control.

Main Sources of Error in Radio Positioning

Zero Error Calibration

All radio-measuring systems must be calibrated for zero error. Microwave systems are usually calibrated between geodetic stations, or on a known baseline. Range-range groundwave (MF or LF) systems, which carry a master transmitter on the ship, are calibrated for locking constant. This is done by bringing the ship close to the slave transmitter, and measuring the range simultaneously by microwave and by the MF or LF system. The MF or LF ranges must be corrected for the local-induction field effects. The slave transmitter or ship receiver is then adjusted until both ranges agree.

Alternatively, the ship may be positioned simultaneously by an independent system which is not subject to the same systematic errors (such as Doppler satellite navigation). The measured range is adjusted to agree with the range derived from the independent calibration system. If there is a significant land-path portion of the range, this procedure calibrates out the additional secondary factor at the point of calibration; however the zero error is valid only for an area in which the land path is not significantly different. If the independent system is Doppler satellite, at least 10 comparisons must be made and averaged to eliminate the Doppler system's relatively large random errors. Appropriate transformation of coordinates into a common datum is necessary when using Doppler satellite positioning. In rho-rho systems, an independent survey system is used to determine the initial instant of transmission. The atomic-standard clock onboard ship is used to predict the time of subsequent pulse transmissions. Hyperbolic chains are usually zeroed by adjusting the slaves so that a receiver, at a known location, shows the correct readings for that point. The absolute error resulting from faulty zero setting is obviously as large as the fault in the calibration, and it is prudent to carry out additional checks to confirm the initial zeroing. Repeatability is not affected as long as the zeroing error remains unchanged.

Lane (Cycle) Identification

All radio-positioning systems suffer from cycle ambiguity, with the exception of microwave pulse-matching systems such as Trisponder and Motorola RPS. Freedom from this cycle ambiguity is such an advantage that pulse-measuring microwave should be used whenever its range and accuracy are adequate. Cycle-matching systems use one of two methods to solve the cycle ambiguity instrumentally: either a slightly different frequency is transmitted which, by subtraction from the fundamental frequency forms a coarse lane-identification pattern with enough resolution to pick out the correct cycle (as in Hydrodist, Hi-Fix, Decca, etc.); or, in the case of pulsed transmissions, a coarse measurement is made on the leading edge of the pulse with enough resolution to identify a specific cycle within the pulse (Loran-C). Unfortunately, both of these techniques break down under bad conditions, such as high-radio noise, or low-signal strength. If this happens with a microwave cycle-match system (Hydrodist, Cubic Autotape), where the wavelength is a few centimetres, the only solution is to improve conditions by techniques such as altering the antenna set-up or moving in towards the shore station. But with MF or LF systems, with wavelengths of 50 to 5000 m, the surveyor can confirm the correct cycle (lane) either by means of going to a known position or by obtaining an independent fix.

In the hyperbolic mode, baseline-extension crossings can be used to determine the correct lane because the correct reading on the baseline is known (see Figure 24). In range-range or rho-rho mode, crossing the baseline between the stations, or the baseline extension, may give an indication of errors because the sum of the ranges, or the difference in ranges for the baseline extension crossing case, must equal the known length of the baseline.

Experience shows that the Doppler satellite navigation system gives a vessel's position from which the range, to a shore transmitter, can be derived with a standard deviation of about 120 m. Satisfactory satellite passes occur about every two hours at latitudes of 40° to 55°. The fix must be computed using an accurate course and speed calculated from a simultaneously operating radio-positioning system, bottom-tracking Doppler sonar and gyro-azimuth or all of these methods together. Thus, for Decca which has a lane width of 300 to 400 m, there is about a 90 percent probability of correct-lane identification for one pass. For rho-rho Loran-C, which has a wavelength of 3 km, cycle identification is virtually certain from one satellite pass. The advantage of Doppler satellite fixes is that the identification can be verified wherever the ship happens to be working; there is no need to return to a marker in shallow water.

When surface buoys are used to mark a known position, care must be taken to moor them tautly, so that movement due to wind or current changes is reduced, but not so tautly that they are swept away by storms or strong currents. By this requirement, the depth in which marker buoys can be laid is limited to about 20 m for MF (e.g., Hi-Fix) and 150 m for LF (e.g., Decca). In ice-covered waters, wooden spars which slide underneath ice floes are used instead of buoys.

Expendable sea-water acoustic transponders offer an alternative to buoys as markers. It is difficult to locate a ship accurately with respect to a single transponder, however work is being done on developing improved techniques.

Propagation Velocity

All radio-measuring systems are subject to errors if the propagation velocity is not known. For micro-wave systems, only the atmospheric refractivity affects velocity, and the ranges are generally so short that a mean velocity can be used without significant error. For groundwave systems MF or LF, the ground conductivity and other factors introduce a secondary phase lag which must be taken into account in addition to the primary phase lag, due to atmospheric refractivity. Over water, these phase lags can usually be predicted to adequate accuracy. When the signal passes over ice or land, an Additional Secondary Factor (ASF) is required to account for the different conductivity. Unfortunately, these corrections cannot be predicted reliably at present, although work is proceeding to improve

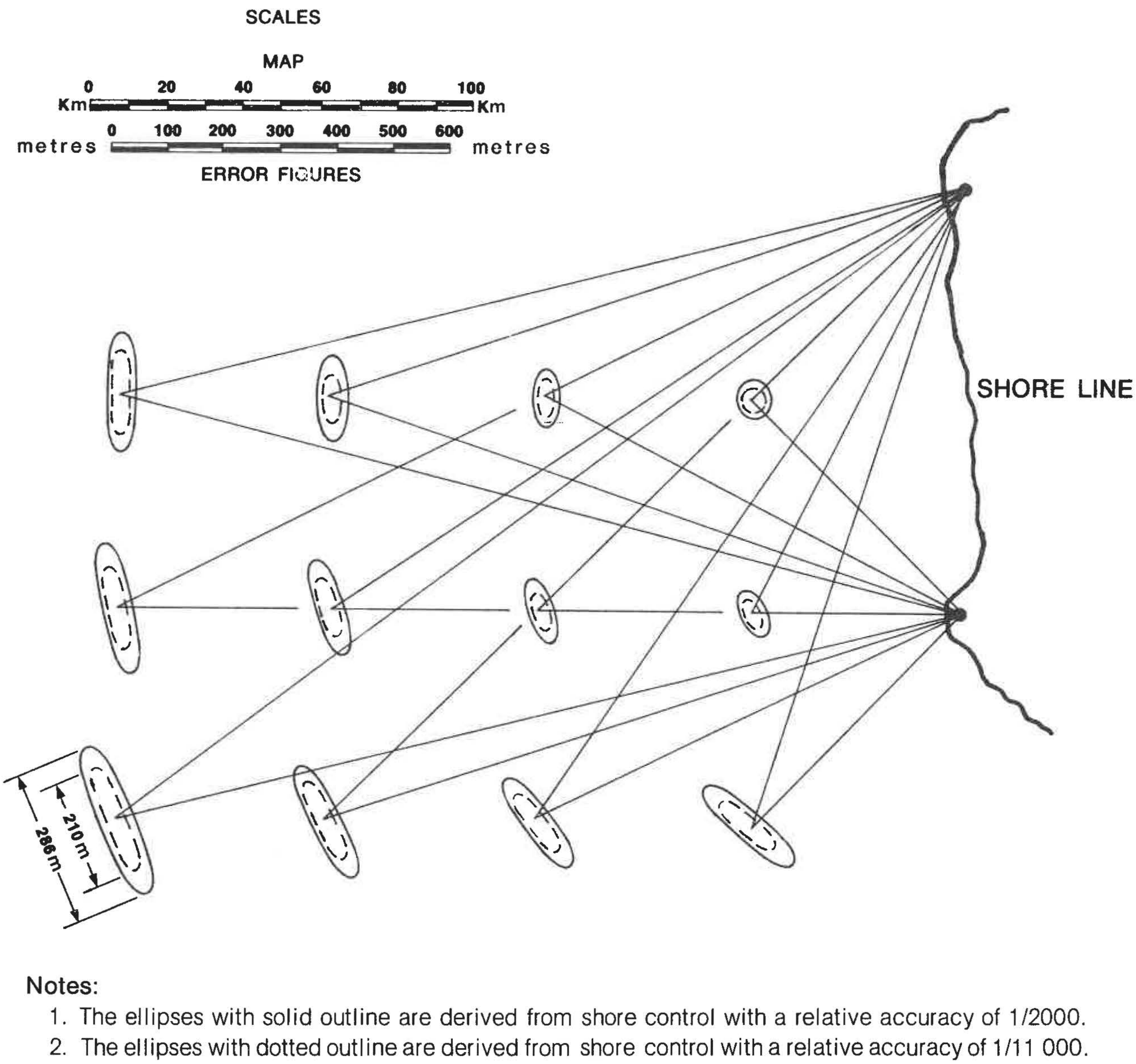


Figure 28

A Grid of Position Error Ellipses for a Range-Range Chain

predictions. At present, detailed calibration is required for precise work overland or over ice paths. More details and error estimates are given in the sections on Primary Phase Lag, Secondary Phase Lag, and Additional Secondary Factor.

Radio Noise and Skywave

Radio noise, which contributes a random error, can be defined as any radiation, man-made or natural, within the frequency pass-band of the receiver, other than the measuring signal. Noise normally causes a jitter of two or three hundredths of a lane or cycle. Some receivers may be damped to reduce the effect of noise, but heavy damping leads to overshoot when the ship alters itscourse or speed. If the signal-to-noise ratio drops below the design limits of the receiver, the measurement jitter increases until the signal is lost. In MF or LF systems, the strength of the unwanted skywave signal increases with distance, especially at night, whereas the groundwave signal strength decreases (See Figure 21). Skywave interference is a common case of loss of lock. Continuous Wave transmissions such as Decca are more susceptible to skywave interference than the pulsed Loran transmissions.

Frequency Stability

Although all radio-positioning systems use frequency standards to make measurements, the accuracy requirement is generally not critical in comparison with the standards available. However, rho-rho systems depend on maintaining a constant, well defined clock rate (frequency offset) between two atomic-frequency standards over long periods, and require frequency control five orders of magnitude better than other systems. Clock rates can generally be determined to an accuracy of about 0.05 seconds per day (1 part in 10^{13}). Such an error introduces a range error at the rate of 15 m per day, and this affects long-term repeatability as well as absolute accuracy.

Pulse Amplitude in Microwave Systems

Microwave systems such as Motorola RPS, and Trisponder, which measure the travel time of a pulse without making a phase comparison, are liable to read too far back in the return pulse when the signal amplitude is attenuated. At extreme range, or near the bearing limits of a directional antenna, this produces too great a range and affects absolute accuracy. Reports indicate that this effect occurs before the loss of signal strength becomes evident from jittery readings. (Eaton, 1981; Casey, 1981)

Data Processing

Traditionally, the surveyor has constructed a lattice of position lines on a geographic grid and plotted his survey positions with respect to the lattice. The measurements were logged manually. Lattice plots are now often produced by a computer-controlled plotter. However, the current trend is towards totally computer-operated data processing. The surveyor specifies end-points and way-points, and the computer acquires and logs the data (although logging may be performed separately), computes present positions, and gives steering instructions either by driving a track plotter or by displaying left/right course corrections and distance-to-go. It can also give warning of seismic-shot points. Computer-controlled operation is almost mandatory for integrated systems. The algorithms used in the computer software are generally sophisticated, and may use least-squares adjustment, Kalman filtering and other statistical techniques for optimizing the position solution. Included are mathematical models for phase lags, and geodetic equations for position calculation over the long lines measured by offshore-positioning systems.

Logistics of System Operation

The cost of installing two LF Decca slaves for range-range positioning and operating them for four months is approximately $100 000 (excluding equipment costs). In comparison, MF transmitters are lighter and operate unattended, although a technician must be available for servicing, and for rapid repair in case of breakdown. Therefore, the cost of the logistics is less, but still significant. Every microwave system requires frequent battery changes unless the shore transponders are located near a reliable power source.

The advantage of the surveyor running his own system is that he can site the shore transmitters to give the best possible pattern geometry over his survey area, while avoiding any overland path. However, if the accuracy requirements are not too stringent and coverage is available, it may be advantageous to use the cost-free transmissions of the Doppler satellite navigation system or the main-chain Decca or Loran-C permanent navigational systems. The main disadvantage of main-chain Decca and Loran-C is that their transmitters are often located inland, making it difficult to predict the propagation velocity accurately; consequently, the survey accuracy is relatively poor. However, repeatability is good and the Doppler satellite system can be used to calibrate the radio system for overland errors.

The Public System Alternative

On May 16, 1974, the United Stated Department of Transportation announced that Loran-C would become the Coastal Confluence Zone Navigation Aid for the United States. Nine stations were built to cover the Pacific coast of North America. Two stations were built in cooperation with the Department of Transportation (DOT) in British Columbia.

On the Atlantic coast, DOT and the U.S. Coast Guard are cooperatively operating a Loran-C chain with a master at Caribou, Maine and secondaries at Nantucket Island and Cape Race. The coverage from this chain extends from Georges Bank to the Tail of the Grand Bank and includes most of the Gulf of St. Lawrence. DOT is presently building another transmitter at Fox Harbour, Labrador which will be a third secondary to the existing chain and a master to a new chain which will have secondaries at Cape Race and Angissoq, Greenland. The coverage will then include all the Gulf of St. Lawrence and the Grand Banks and most of the Labrador Sea. (See Figure 29).

For the Arctic region there is no established, publicly operated radio navigation system that is equivalent to the Loran-C coverage on the east and west coasts. With the anticipated increase in traffic, ship size, and the length of the shipping season due to the oil and gas developments, the Canadian Coast Guard has developed a policy relating to the provision of marine aids. See Appendix B for the full text of this policy as submitted to the 1982 Workshop.

It is not expected that Loran-C coverage will be warranted with the exception of a possible mini-Loran-C chain for the Beaufort Sea. For most of the Arctic, satellite systems supplemented by Omega, Radar, and Gyro are expected to be adequate.

Figure 29

Loran-C Navigation Chains in North America

System Descriptions

Super High Frequency (Microwave) Systems

Frequencies: 2 000 to 10 000 MHz

Characteristics

- Range-range fix, except "Artemis" which is range-bearing.
- Direct wave propagation.
- Measurement either by pulse-matching (akin to radar) or phase comparison (as in tellurometer).
- Accuracy of the order of ± 5 m.
- No reading ambiguity.
- Range limited to line of sight, but with "range holes" where reflected wave interferes with direct wave.
- Small antennas.
- Antennas at shore stations directional.
- Low power requirements.

Representative Systems

Pulse-match:
Del Norte "Trisponder"
Motorola "Mini-ranger"
Phase Comparison:
Cubic "Autotape"
Tellurometer "MRD 1"
Range-bearing:
Huyenslaboratorium "Artemis"

(note: Any microwave system may be used in conjunction with a theodolite to give a range-bearing fix, but only "Artemis" measures the angle electronically.)

Range

The range is governed by line of sight, given by:

$$R = K\,[(h_1)^{1/2} + (h_2)^{1/2}] \qquad (43)$$

where h and h are the antenna heights in metres,

K = 4.13,

and R is the range in km.

Given line of sight, the maximum range is 30 km or more, depending on transmitted power, atmospheric conditions, and the trade-off between increased antenna beam width versus reduced signal strength.

Signals reflected from the sea surface may interfere with the direct transmission in "range holes", where the signal becomes progressively weaker with significant measurement errors, and may fade altogether. Since the effect occurs when the direct and the reflected transmission paths differ by an integral number of wavelengths, the result is one or more ring-shaped zones of a weak signal centred on the shore transponder. A flat surface favours reflection, and the problem tends to be worse in calm weather; however, range holes have been encountered in quite rough seas. One effective countermeasure is to alter the difference in direct versus reflected wave path-lengths by raising or lowering the antenna. Some microwave systems offer a "space diversity" option consisting of two alternate transmitting antennas, one above the other. The signal processor selects the antenna that gives the stronger signal. Metal structures may also give reflections causing signal fading.

Fog or rain also causes loss of signal strength, resulting in decreased range and causing measurement errors. Other obstructions to the signal, such as trees, may reduce signal strength and cause range errors without necessarily cutting off the signal altogether.

A third factor to cause reduced signal strength is incorrect antenna pointing, in either the vertical or the horizontal plane.

Measurement Accuracy

In a moving vessel, under typical conditions, the measurement accuracy for pulse-matching systems is about ± 7 m (2 σ). For phase-comparison systems it is about ± 2 m (2 σ). This assumes correct initial calibration and good signal strength.

As outlined under RANGE, the accuracy of pulse-matching systems tends to degenerate rapidly when the signal strength drops below a critical threshold. Range errors of tens and even hundreds of metres have been reported, with the range-reading error always increasing the measured range.

Manufacturers strive to avoid low signal strength errors, but some survey organizations insist on the use of calibrated signal strength meters as a means of checking that adequate signal strength exists, thus validating the range measurements.

Phase-comparison systems are probably less susceptible to undetected measurement errors due to low signal strengths, but their ambiguity resolution may break down with noisy or weak signals.

Pulse match systems tend to give a large scatter in readings, with occasional spikes of tens of metres, unless they are filtered (smoothed). However, the filtering algorithm must be carefully designed or it may introduce errors such as a constant lag, an overshot on turns, or failure to detect small alterations in the vessel's track.

Cycle Ambiguity

Pulse-match systems are free of ambiguity, while phase-comparison systems will suffer cycle ambiguity under low signal strength or high radio noise.

Shore Stations

Pulse-match systems use small (25 cm) storm-proof transponders with relatively wide angle antennas (typically 75°) and a relatively low power requirement (typically 12 W when measuring, 8 W when quiescent). A continuous power source is preferable, but the transponder will run about 5 days on a pair of car batteries.

Phase comparison systems have larger (45 cm) shore station units, showerproof only, with relatively narrow angle antennas (typically 25°), and a relatively high power comsumption (typically 50 W).

Convenience In Use

Modern equipment is automatic in operation and provides a wide choice of options (see REMARKS).

Remarks

Many users strive to measure at least three ranges whenever possible, as a check against gross errors. Modern equipment will measure not just the minimum pair of ranges but four or more ranges, usually as an added option. Multi-user capability, allowing a limited number of users to range on the same transponder almost simultaneously, is becoming standard equipment.

Shore stations are identified by their code. If two shore stations of the same code operate in one area, they almost always interfere with each other, even though one may be beyond measurement range. Early systems allowed only three or four codes to a net; the modern trend is to allow several times that number.

A wide range of data recorders and processors, plus navigation accessories, are now available as options.

The accuracy of under-way measurement does not justify applying meteorological corrections. The manufacturer is responsible for using a reasonable mean value in making the time to distance conversion, which the user checks by calibration.

The range-bearing mode is generally used only where range-range fixing is impossible (e.g. off an elongated point, such as the east or west end of Sable Island). For "Artemis", which manufactures state has 2 σ accuracy of $\pm$ 1.5 m, $\pm$ 2 minutes of arc, the bearing is the weaker component of accuracy with an error of $\pm$ 1.5 m at 2.5 km range, and $\pm$ 15 m at 25 km range. This is as good as, or better than, range-range accuracy using pulse-match equipment, but the "Artemis" equipment is heavier and is restricted to a single user.

Interference from ships' radars in the S band from 9370 to 9440 MHz may cause a problem with SHF systems operating close to those frequencies.

Some equipment may not have spike suppression on the supply line, in which case batteries cannot be charged from an ordinary battery charger while the system is in use.

Cost

Pulse-measuring equipment costs about $80 000 for a bare-bones system with three transponders. Phase-comparison systems cost about one and a half times this amount.

Ultra High Frequency (UHF) Systems

Frequencies: 420-450 MHz

Characteristics

- Can be used in range-range or hyperbolic mode.
- Direct wave propagation, plus diffraction and tropospheric scatter at long range.
- Spread spectrum techniques used to produce the equivalent of a high power, low noise, pulse.
- Measurement by code correlation.
- Accuracy, about ± 5 m for line of sight, and ± 10 m to 100 km.
- Reading ambiguity of the order of 10 km must be solved by the operator.
- Range is least in cold weather. However, present experience indicates reliable operation to 100 km, even in the Arctic winter.
- Antennas similar in size to TV antennas.
- Antennas on shore stations are directional.
- Relatively low power requirements.

Representative Systems

Sercel "Syledis"
"Maxiran"
Del Norte model 435 UHF Transponder
XR Shoran (obsolescent)

Range

The range of UHF transmissions extends beyond line of sight, to 100 km or more, depending on climatic conditions. Much greater ranges than this have been reported from the tropics. A booster amplifier may be used, but current experience indicates a range improvement of only about 20 percent from this.

Signal strength is little affected by whether the transmission path is over land or sea, and signals can be received in the "shadow" of islands or cliffs where SHF signals would be lost.

Accuracy

Manufacturers claim accuracies of a few metres within line of sight, rising to 10 m at 100 km range. User reports tend to bear this out, though with some question over the effect of mixed land/water paths on accuracy. Zero error calibration is essential and must be repeated wherever the antenna leads are changed.

Cycle Ambiguity

An ambiguity of about 10 km occurs, in some systems, requiring that the user know his initial position to better than ± 5 km, by independent means.

Shore Stations

The antennas, which are about 2 m long, are usually mounted on a 15 m tower. The shore transmitters are waterproof. They require about a 50 W power supply.

Convenience in Use

As with SHF equipment, the shore antenna must be kept correctly pointed.

The UHF shipborne transmitters are more powerful than those used with SHF equipment and they may affect ships' radios unless they are well grounded.

Remarks

Over the past five years UHF systems have come into general use with the oil industry, in exploratory surveys, for laying pipelines and for navigation during exploitation. Permanent Syledis chains have been set up in the North Sea and Persian Gulf. In Canada, UHF has been used year-round in the Beaufort Sea as well as on the East Coast.

UHF is intermediate in characteristics between SHF and HF positioning equipment. It overcomes the line of sight limitation of SHF and so covers about ten times the area, and does not suffer so severely in the shadow of obstructions. In comparison with HF, it is not affected as seriously by transmission over land or across sea ice, and the 10 km ambiguity is far less limiting than the 100 – 500 m ambiguity of HF.

The presence of an atmospheric inversion may increase signal strength due to ducting, but this phenomenon has been found to cause ranging errors of tens of metres. A "space diversity" arrangement of two antennas, one vertically above the other, is used to alleviate the problem.

UHF systems may be used in multi-user range-range mode, or hyperbolic, or a combination of the two.

Cost

A minimum chain with three shore transponders costs about $150 000.

Medium Frequency (MF) Systems

Frequencies: 1.5 to 5 MHz

Characteristics:

This group includes systems providing positioning coverage over medium ranges with good accuracy. Measurement is made with the ground wave signal from two or more shore transmitters using phase comparison techniques. At these frequencies skywave interference limits range over water, particularly at night. Range overland is extremely limited. The MF signal is more susceptible to atmospheric interference than signals at lower frequencies. The transmitters in the chain may be phase locked to the master transmitter (Argo or Hi-fix) or may be free running with a repeater station to transmit master-slave phase changes to the receiver (Honore principle used in Toran and Raydist). Phase locking systems require only one frequency for a chain. An additional frequency is used in Argo and Hi-fix to provide lane indentification. The free running systems use multiple frequencies or sidebands.

These MF systems are primarily used in the range-range mode; however, they can also be configured to generate hyperbolic position lines for use with small launches or aircraft where it is not possible to operate a transmitter. In the range-range mode the number of mobile users is limited, but in the hyperbolic mode the number of mobile users is unlimited. It is also possible to operate these systems in the rho-rho mode with some modifications to the equipment.

Range

Daytime range over salt water is normally 400 km (200 nautical miles). Ranges up to 800 km have been reported and the transmitter power may be boosted to achieve more reliable reception at long ranges. Maximum range during the day depends on power output, antenna length, station installation, especially grounding and conductivity along the transmission path. At night range is sharply reduced by skywave interference.

Measurement Accuracy (at the 2 σ level)

The repeatability under good conditions is $\pm$ 10 m for an over salt-water path; range accuracy is up to three times this figure depending on the distance and phase lag corrections applied. Sea ice and overland path reduce accuracy and repeatability significantly. Position accuracy may be improved by using the multiple position line capabilities of such systems as Hi-fix or Argo.

Cycle Ambiguity

This is a serious problem. The lane identification feature provided with most phase locked systems can give some resolution to this problem. However as the lane identification frequency is relatively close to the measuring frequency, it suffers from the same instabilities that cause the lane jumps, such as skywave interference or precipitation static. It is usually necessary to provide some additional means of ensuring correct lane identification. Fixed reference buoys or another positioning system can be used to check lanes. Statistical techniques using multiple position lines or position line filtering algorithms have also been used successfully.

Station Installation

The transmitting equipment of modern medium frequency systems is of relatively light weight construction. The power supply is the heaviest and bulkiest part of the installation. Thermo electric generators, consuming about 45 kg of propane every 6 to 7 days have been found to provide a satisfactory source of power for Argo shore transmitters. These generators provide about 100 watts to the transmitter. The vertical antenna can vary from 10 m to 30 m for MF systems depending on the range required. A ground mat of wires radiating from the base of the antenna is required. The use of grandmats that are larger and denser than those recommended by the manufacturers can improve transmissions where the site grounding is poor.

The site should be carefully selected with regard to pattern geometry in the service area, avoiding land on the transmission path. A good site will be on clear, level land, with no local obstructions, preferably with good soil for efficient grounding. Some consideration should be given to site security. An elevated site improves range, but may degrade accuracy at close range. Erection of a station usually takes 3 men from half a day to two days depending on the amount of site preparation and type of equipment shelter required.

Ship installation for range-range operation usually calls for a 10 m whip antenna sited clear of, and preferably above all local obstructions. Obtaining a good ground in a steel ship does not present a problem. However, in smaller wooden or fiberglass vessels it is necessary to install grounding plates on the hull of the vessel. Ranges of 100 km have been measured in the range-range mode from 8 m fiberglass launches using 4 "Dynaplates" as ground. For vessels operating in the hyperbolic mode, all that is required is 2.5 m whip antenna, an appropriate antenna coupler and a good ground. Again it is necessary to use ground plates in non-metallic vessels.

Convenience in Use

Transmitters can be run unattended, but must be accessible for servicing and trouble calls.

The calibration constant for each range or hyperbolic pattern must be determined before a chain can be used.

Manufacturers provide data outputs for peripheral devices. Navigation micro-processors are available for some systems. Mini-computers and calculators have been interfaced to mobile units to provide real-time navigation and positioning information. Analog strip chart recorders are useful in monitoring and detecting lane jumps.

Remarks

The local induction field extends 5 km over sea water and 10 km over fresh water. Overland signal path should be avoided if possible. Errors may be particularly large under cliffs or mountains. However, consistent hyperbolic and range-range measurements have been made over flat marshy tundra at ranges up to 100 km. MF systems are more susceptible to atmospheric interference than any other group. Precipitation static or lightning, either at the mobile or the shore transmitter can cause loss of lock.

A helicopter can easily be fitted with a hyperbolic receiver system, and can be useful in measuring baseline calibration constants and carrying lane identification to a ship. The antenna should be deployed vertically from the helicopter. When using the system in the hyperbolic or rho-rho mode, an automatically recording monitor receiver can be run at a fixed point ashore, to record pattern shifts and thus improve accuracy. The monitor should be sited as close to the operational area as possible.

Fresh-water transmission paths have been found to reduce range considerably. Non-homogeneous propagation paths of brackish estuarine water have been found to cause considerable errors in estimated phase lags and effective propagation velocities. Sea ice also affects the propagation velocity significantly, thus the system accuracy is reduced over drifting ice, or ice of variable thickness. Very thick polar pack-ice caused complete loss of signal in a survey north of Ellesmere Island.

Cost

The cost is approximately $300 000 for a minimal system. This would include power supplies and antennas. Rental can be arranged from contract survey companies.

Use in Canada

Argo:	Widely used by industry and government
Hi-Fix:	Used by government survey organizations
Mini-fix:	Still used occasionally
Raydist:	Some use by industry
Toran:	Some use by industry

Low Frequency (LF) Systems

Frequencies: 80 to 130 kHz

Characteristics

Decca and Loran-C, the two common systems in this group, have the longest range of any of the shore based radio-positioning systems commonly used in hydrographic surveying. Accurate measurements depend on the use of the ground wave. Beyond about 650 km, the ground waves of the continuous wave Decca system suffer severely from skywave interference, particularly at night. Skywave interference does not affect Loran-C because it is a pulsed system. The portable Loran-C chains have much the same range as Decca, but the powerful main chain transmitters give clear signals up to 2000 km day and night. Loran-C is slightly less accurate than Decca because pulse transmissions provide less information on which to base measurements; also, when main-chain Loran-C is used, a considerable overland path is generally involved. Loran-C can only be used in hyperbolic or rho-rho mode, whereas Decca can also be used in the more accurate range-range mode.

Range

Ranges are 650 km (350 nautical miles) for main-chain Decca, Portable Decca (Lambda), Portable Loran-C (Accufix, Pulse/8); 2000 m (1000 nautical miles) for main-chain Loran-C. The overland range of either system is about 2/3 of its range over sea water.

Measurement Accuracy (at the 2 σ level)

The repeatability, under good conditions, is $\pm$ 25 m for Decca and $\pm$ 50 m for Loran-C. Range accuracy is two to four times these figures for well calibrated systems, depending on the distance and phase-lag corrections applied. Because the propagation velocity cannot be accurately predicted overland, the accuracy is reduced when an overland path is involved.

Cycle Ambiguity

This problem occurs near the range limits of either system. In addition, lane slip occurs much more frequently with Decca, particularly at night. The doppler-satellite system provides an excellent means of resolving cycle ambiguity or lane slip.

Shore Station

The required electronics and diesel generators weigh about 300 kg for each station. The mast should be at least 45 m high, requiring four or five men and reasonable weather for erection. The ground mat consists of about 100 cooper wires of the same length as the mast and radiating from it. The shore station must be manned, therefore accommodations and sizeable shelters are required for the electronics and diesel generators. A station can be erected in two days if the site is clear.

The site should be carefully selected by: considering pattern geometry in the service area; avoiding land on the signal paths; finding a clear and level site with no local obstructions, preferably with good soil for efficient grounding.

Convenience in Use

Because transmitter stations must be manned, they require extensive logistic support. The chain requires very careful calibration before use.

Remarks

To attain high accuracy, overland signal paths must be avoided and the effect of phase lag must be considered. If used in hyperbolic or rho-rho mode, an automatically recording monitor receiver at a fixed point on shore should be maintained to record pattern stability and provide corrections in case of significant pattern shifts.

Sea ice, when in a continuous sheet, causes variations in the propagation velocity. The amount of variation depends on the homogeneity and thickness of the ice. The effect of broken pack ice has not been measured, but it is likely to be smaller as the ice is salt-soaked.

Rho-rho operations require checking the receiver clock drift (due to a slight frequency difference between atomic standards); the doppler-satellite navigation system provides a highly recommended checking method (see Lane [Cycle] Identification).

Some publications give the coordinates of main-chain Loran-C stations with respect to the WGS-72 datum. It is therefore necessary to use NAD27 published values (available in Radio Aids to Marine Navigation or directly from CHS) if precise NAD27 positions are required.

With rho-rho operation of Loran-C, it is sometimes possible to measure three or more ranges to a point. The redundant intersection of the ranges provides an excellent means of assessing accuracy and identifying blunders.

Cost

Portable chain, of the order of $250 000
Masts and diesel generators, approximately $50 000
Doppler-satellite receiver about $50 000
Rho-rho receiver, $50 000 (including frequency standard)
Certain systems are available on rental.

Use in Canada

Decca: Widely by industry and government;
Rho-rho Loran-C: By Canadian Hydrographic Service and industry.

Very Low Frequency (VLF) Systems

Frequencies: 10 to 30 kHz

Characteristics

The accuracies of OMEGA and VLF Communications Broadcasts are too low to be of general use in survey work. VLF transmissions can be received by submarines near the surface.

For the past 20 years, navigation experiments have been conducted, first using powerful VLF naval communications transmissions and recently using navigational Omega transmissions. Because of the experience gained, it is planned to provide worldwide coverage using eight Omega transmitters by 1983.

Omega transmitters use time sharing, enabling all stations to transmit on the main navigation frequency of 10.2 kHz. Other frequencies are used for lane identification.

Omega is intended as a hyperbolic aid to navigation, but since its transmitters as well as those of the VLF communications stations are controlled by atomic-frequency standards, any of them can be used in the rho-rho mode.

Range

The range is about 10 000 km (6000 nautical miles) when transmitting at full power. The signal is not useable close to the transmitter.

Measurement Accuracy (at the 2 σ level)

Using predicted skywave corrections, the accuracy is $\pm$ 1.5 km on the hyperbolic baseline and $\pm$ 3 km rho-rho.

Using differential corrections from a monitor within about 500 km of the ship, the accuracy is $\pm$ 500 m on the hyperbolic baseline and $\pm$ 1000 m rho-rho.

Cycle Ambiguity

Lane identification may be provided by using a dual channel receiver, but good signal reception is essential.

Shore Stations

Permanent Omega stations are now located in Norway, Liberia, Hawaii, North Dakota, La Réunion, Argentina, and Japan. A station in Australia will complete the Omega system in 1983.

Convenience in Use

Current procedures involving manual skywave corrections are very tedious.

Remarks

Omega is not at present a survey system, but it has some prospects in differential mode as a stop-gap where nothing else is available. The system does not look promising for integration with the Doppler satellite navigation system because the signals do not appear stable enough to give accurate course and speed.

A possible solution to the skywave correction problem is Composite Omega. In this technique, the difference in phase shift at two separate frequencies (dispersion) is used to derive the absolute phase shift in a manner analogous to the solution for ionospheric refraction in the Doppler satellite transmissions. Automatic differential receivers are being developed to use this technique.

Cost

A single-channel receiver costs about $9000.

A multi-channel differential receiver would cost about $20 000.

Use in Canada

Evaluation only, by industry and government.

Chapter 8

Satellite and Inertial Positioning Systems

Transit Satellite System

Also known as the Doppler satellite system, the Transit system consists of five satellites with polar orbits at an altitude of about 1000 km above the earth's surface. The observation of the Doppler effect on satellite broadcast signals with an appropriate receiver is used to derive the position of the receiver antenna by first converting Doppler observations into range differences and then solving for the observing station coordinates. Satellite positions are derived either from messages broadcast by the satellite at the time of observation or from post-mission precise ephemerides calculated by the U.S. Defense Mapping Agency on a selective basis. These satellite positions can either be held fixed or treated as weighted constraints in the least-squares solution for the observing station coordinates. For a detailed description of the Transit system, receiver and auxiliary equipment, data processing programs, and various applications, see (Defense Mapping Agency 1976, 1979, 1982, Stansell 1978).

The position of a stationary point can be determined using the Transit system in either of two modes: single point, involving observations only at the required point; or multi-station, involving simultaneous observations at more than one station, including at least one on a nearby station with previously established coordinates. A drill-rig on location is stable enough that it can be considered a stationary point. Accuracy depends on the reduction program used, network geometry and number of satellite passes observed, stability of the point of observation and the type of ephemeris used. In a single point positioning mode, a 5 to 10 metre accuracy using broadcast ephemerides can be achieved with about 25 passes, provided the geometry is good (balance of north-going and south-going satellites passing east and west of the observer's position). In Canada, 25 passes can be observed in less than two days. In the multi-station positioning mode, a 1 to 2 metre accuracy can generally be achieved with 25 passes. Accuracy improves as the number of passes increases. A basic network of several hundred Doppler satellite stations is now available for Canada (Kouba 1978). For this network, a multi-station positioning mode was used and sub-metre relative accuracy was achieved. All stations are monumented and several of these are located along coastlines and would therefore be useful for positioning a stationary point offshore in the multi-station mode (Geodetic Survey of Canada, 1976 to 1982). The use of Doppler satellite positioning techniques for rig positioning is discussed by Adams et al (1981).

Although the Transit system was not designed as a survey system, it can be used as an aid in offshore surveys (Eaton et al 1976). For this application, the Doppler effect of the moving point of observation combines with the Doppler effect of the moving satellite. The component caused by the moving point of observation must be subtracted from the combined effect in order to get position information. Thus, for dynamic applications, Doppler satellite observations must be combined with other measurements or systems such as ships' log and gyro and/or the Loran-C system which provide information on the ships' speed and direction. Very successful integrated systems making use of the Transit system have been developed in Canada (e.g. Wells & Grant 1981, Falkenberg 1981, Swift & Fagan 1981, Delorme 1981).

Transit system positioning yields coordinates of the observing stations that are in principle, geocentric. This geocentricity is currently realized with an accuracy of about 5 metres which is sufficient for most offshore positioning requirements. The type of ephemeris used will affect the geocentricity of the coordinates within the above 5 metre criteria. Several other factors also enter into account (e.g. Jenkins & Leroy 1979, Lachapelle & Kouba 1980, Seppelin 1974).

Cartesian geocentric coordinates obtained by Transit system observations can be easily converted into geodetic coordinates on a given ellipsoid, provided the relationship between the geocentric system and the relevant geodetic datum is known (see the section on Geodetic Reference Systems for details). Derived heights above the ellipsoid can be converted into sea level heights, i.e., heights above the geoid, using current geoid models that are accurate to about 1 to 2 metres in Canada and on the Canadian shelf (Lachapelle & Rapp 1982).

Navstar/GPS Satellite System

The Navigation Satellite Timing And Ranging (NAVSTAR) system, also known as the Global Positioning System (GPS), is a satellite-based radio navigation system being developed by the United States Department of Defense. GPS is scheduled to be fully operational by 1988. It is being developed primarily as a military navigation system for land, sea, and air vehicles. Although the extent of civilian access to GPS is yet unclear, it is intended that by the mid-1990s, GPS will replace many of the present military and civilian navigation systems now operated by the U.S. Government (USDOD/DOT, 1980). For a description of GPS, see (Institute of Navigation 1980, Defense Mapping Agency 1982, Canadian Institute of Surveying 1982).

While primarily a navigation system, GPS can also be used for precise positioning of fixed points. When fully operational, GPS is designed to provide continuous real-time, three-dimensional single point static and dynamic positioning accurate to 16 m (SEP – Spherical Error Probable, i.e., 50 percent confidence level) when using the pseudo-ranging mode. Multi-station or relative static positioning is expected to have a much higher accuracy, e.g., to within a few cm over distances of 100 km, depending on the type of measurements (International Association of Geodesy 1979, Defence Mapping Agency, 1982).

GPS-derived positions will be geocentric and compatible with Transit-derived positions. At the present time, only four prototype GPS satellites are continuously operational with accuracy near that expected for the production satellites. This already allows for several hours of unaided dynamic positioning in Canada (Wells & Lachapelle 1981). Various types of receiving equipment for single-point and relative positioning techniques are already available or are being developed (Defense Mapping Agency 1982). Static single-point positioning results obtained in Canada (Lachapelle & Beck 1982) confirm the accuracy estimates quoted above. Results to date are encouraging for single-point dynamic positioning offshore (Wells et al 1982), and show clearly that GPS could become a major positioning system for offshore applications when complete in 1988, provided it is available to the civilian community.

Relative positioning between a fixed shore station and moving offshore station(s) will improve the accuracies quoted earlier. Such a method is expected to help overcome the lack of civilian access to the full capability of GPS which might occur after 1988.

Intertial Positioning Systems

An inertial positioning system consists of sets of accelerometers with associated gyroscopes which provide information on their orientation. An online computer integrates the outputs of the accelerometers twice to derive displacements along three, mutually perpendicular axes.

The system of measurement is fundamentally different from conventional survey techniques, as it computes the differences in latitude, longitude, and elevation between points, and also some parameters of the gravitational field of the earth. It computes data at high speed, in any weather condition, and without the need for line of sight or knowledge of precise time.

When mounted in a helicopter or motor vehicle the system is able to produce much better than 1 metre accuracy for intermediate points in a traverse between known points 40 to 50 km apart.

The use of inertial surveying systems (ISS) for positioning on land is now wide spread in Canada for geodetic surveying. Inertial technology is described in detail in the proceedings of two international symposia on Inertial Technology for Surveying and Geodesy (Canadian Institute of Surveying, 1977, 1981). A major limitation to the inertial systems now being used is the requirement for the sensors to be brought to a stationary condition for about 40 seconds every 4-6 minutes to allow for an updating calibration. This has precluded its application onboard ship. Alternative updating techniques are under development.

Application of inertial technology to civilian offshore positioning is still in its infancy and no reliable results are available. However, intensive research work is in progress to solve the updating problem by onboard comparison with velocities measured by other techniques. This would make stopping unnecessary. No reliable results are yet available. However several related research projects are underway (e.g. Hagglund 1981, Wong & Schwarz 1982) and significant results are expected within the next few years. Inertial systems will be integrated with other systems such as Loran-C or GPS in order to improve relative accuracy and bridge the gap between fixes provided by the auxiliary system.

Chapter 9

Other Systems and Integrated Systems

Astronomic Systems

Astronomic observations for latitude and longitude can be made from a stable, bottom-mounted offshore platform. The accuracy would not be better than about 30m relative to the astronomic reference system. Experimental high-precison astronomic observations have been made from a ship, but the system required a very expensive stabilizing platform. The accuracy was not as high as it would be from a bottom-mounted platform or shore station. The comprehensive gravity data needed to transform the astronomic positions to NAD27 positions makes this method prohibitively inconvenient and costly.

Photogrammetric Systems

Photogrammetric methods of positioning by extending from shore control were examined by the 1970 Workshop participants and found to be impractical. There have been recent developments in the use of fixed airbase simultaneous photography, thus opening up the possibility of precise positioning near shore; in the use of LANDSAT photography to investigate the possibility of islands off the Labrador coast; and, in the experimental use of airborne inertial surveying equipment to compute the camera centres and orientations across open bodies of water between shore control. Nevertheless, there have been no proven developments to modify the 1970 Workshop finding.

Acoustic-Positioning Systems

The signal energy of high, medium, and low-frequency radio systems used to position airborne or surface vehicles does not penetrate water (or land) significantly. The signal energy of the very low-frequency radio systems penetrates the water to a depth of several metres; but neither the penetration nor the accuracy are adequate for positioning bottom-located objects such as instrument packages, wellheads or survey monuments. Since acoustic waves are transmitted through water, acoustic techniques have been developed for subsurface positioning. Acoustic-positioning systems employ acoustic beacons or transponders lowered into the water. Acoustic positions are positions relative to those of the beacons or transponders. If the geographical coordinates of the reference beacon, transponders, or markers are determined, the relative positions can be converted to true positions. In an operation involving acoustic transponders or beacons, the first step is to obtain the positions of the reference markers so that all relative positions can be converted to true geographic coordinates.

The basic difference between acoustic beacons and acoustic transponders is that the transmission sequence of beacons may only be programmed before deployment, while transponders, having both receiving and transmitting cabilities, may be interrogated by a shipboard command system. There are two basic geometric modes used in acoustic positioning: the short-baseline configuration using either a beacon or transponder and, the long-baseline configuration.

The short-baseline beacon configuration consists of a single-beacon transmitter on the sea-bed, and a ship-mounted hydrophone array that is either stabilized or steerable. By measuring the difference in arrival time of the acoustic energy at the hydrophones, the bearing to the beacon can be determined. The short-baseline beacon configuration is used when the primary interest is in accurately positioning a vehicle over, or nearly over, a beacon. An example of this is a well-drilling operation where the drilling vessel is to be positioned over the wellhead and the beacon is mounted on or near the wellhead structure. In this mode, the manufacturer's stated accuracy is 0.5 percent of the water depth.

The short-baseline transponder configuration derives its position from a range-bearing measurement. The system consists of an acoustic transponder on the sea-bed and a shipboard system containing an interrogator (transmitter) as well as a hydrophone array. Using this system, the range and bearing from each hydrophone to the transponder are determined.

Long-baseline systems employ two or more transponders to form a baseline array on the sea-bed, and surface positions are obtained relative to this array by a range-range method. The range to each transponder is obtained by interrogating from the ship and measuring the time of arrival of the coded return from each transponder. Processing this range-range data establishes the position of the vessel relative to the transponder array. The transponder array may consist of as many transponders as required to cover the survey area; however, all transponders must be identifiable.

Many companies produce acoustic hardware for ocean surveying. The primary development activity in recent years has been in the associated interfacing and software necessary to construct an operational system.

A typical long-baseline system with a two-transponder array would have a range up to 10km with baseline links of approximately 5km between transponders. The relative positioning accuracy would be better than 10m (at the 1 level) and the system would cost approximately $40000 including ship fitting.

Generally, beacon-type systems are less than one-half as expensive.

Doppler-Sonar Navigation Systems

A Doppler-sonar system consist of four transducers tilted downwards in the fore, aft, starboard and port directions. The transducers transmit and receive sound energy at 300 to 600 kHz and measure the Doppler shift of the signal reflected from the ocean floor.

The frequency received by each transducer differs from the transmitted frequency by an amount proportional to the transmitter-receiver velocity, relative to the reflecting bottom surface. It is then possible to resolve fore-aft and starboard-port velocities. When a gyrocompass is coupled with the system, these velocities may be resolved into true course and speed. The transmitter array is mounted in the ship's sea-well with each transducer precisely directed at a 30° angle to the vertical. This arrangement constitutes a Doppler-sonar navigation system.

The system must be referenced to a known position at the start of the operation, and if it is interfaced with a computer, the (X,Y) coordinates with respect to the point of commencement can be displayed. Most Doppler-sonar systems are further integrated with the Doppler-satellite navigation system. In this combination, the Doppler-sonar system provides accurate velocity information required for the satellite fix and ongoing positional information between fixes. The Doppler-satellite navigation system can provide the initial positional information and periodic position checks.

Until recently, Doppler-sonar systems could only be used satisfactorily in water depths less than 200 m. Reflections from the ocean floor at greater depths could not be reliably received because of the difficulty of determining whether received signals were reflections from the ocean floor or from discontinuities between layers in the mass of water. Unless the system is used well within its design specifications, and unless periodic checks are made at known reference points, the continuous danger exists that both velocity and positional data may contain significant errors. Sudden motion of the survey vessel due to rough weather or sudden manoeuvers can cause loss of accuracy.

Several manufacturers are now redesigning Doppler-sonar equipment so that it can receive reflections from the ocean floor in water depths up to 500m.

System Accuracy

- Real-Time Vessel Position
  Providing that the Doppler-sonar can maintain continuous contact with the ocean bottom and that it is suitably coupled with a gyrocompass and a Doppler satellite received, a repeatability of about 300 m at the 1 σ level can be achieved within the area of the survey.
- Post-Mission Analysis
  By adjusting the real-time data at the end of the mission, an overall positional accuracy (relative to the NAD27) of about 300 m at the 1 σ level can be obtained.

System Cost

Housing and installation of transducer array	$ 30 000
Doppler sonar equipment	$ 80 000
Suitable gyrocompass	$ 10 000
Total	$120 000

Integrated Systems

System integration is more than the mere computerizing of the output of a positioning system. Rather, it is the combining of two or more positioning systems so that the strengths of one system compensate for the weaknesses of another. Then the result of integrating can be very effective.

One example is the integration of Doppler satellite receivers with rho-rho Loran-C. The Doppler satellite navigation system is relatively free from systematic errors, but has fairly large, random errors that depend critically on the correct measurement of the ship's course and speed; therefore, repeatability is poor. It provides discrete position fixes at only one to two hour intervals depending on latitude and is therefore useless for continuous positioning while the ship is underway. Rho-rho Loran-C requires synchronization and is subject to systematic errors caused by anomalies in propagation velocity, and by clock drift due to frequency differences between atomic-frequency standards at the transmitter and at the receiver. However, over a period of a day or so and at a distance of several hundred kilometres, its repeatability is excellent. When integrated, the two systems give continuous fixing with good long-term repeatability, because Loran-C provides good course and speed information during the Doppler satellite pass which enables the position fix to be accurate. The accurate satellite fix is used to compute theoretical Loran-C ranges, which, when compared to the observed ranges, allows for the determination of the clock drift and Additional Secondary Factor (ASF) (Grant, 1976).

A further development of the same basic integrated system is the addition of the speed log and gyro. Both of these instruments have significant systematic errors. The speed log measures the ship's speed relative to the surrounding water, not the speed over the bottom. The gyro measures the angle from north to the ship's head and not to the course made good. Together they provide a better short term picture of the motion of the ship while the Loran-C provides a longer term updating of the systematic biases in the log and gyro.

Another integrated system, incorporating Doppler satellite systems and Decca 12f was reported on by Hittel and Kouba (1971). The reasons for combining these two systems are much the same as for Doppler satellite and Loran-C. The combination of Doppler satellite positioning with almost any radio positioning system is possible. The systems known to have been used are: Loran-C, Pulse/8, Accufix, Decca 12f, rho-rho Decca, Hi-fix and Argo.

Another type of integrated system is the combination of Doppler satellite positioning with Loran-C and Argo. The accuracy that was desired required the use of Argo since Loran-C could not achieve that accuracy. Loran-C was integrated into the system because the Argo system tended to lose lanes during the night. Therefore, to allow night-time operations and eliminate time lost to re-acquire the correct Argo measurement, Loran-C was added. (Falkenberg, 1981)

If the area to be surveyed is sufficiently shallow to allow the Doppler-sonar log to maintain contact with the bottom (often called bottom tracking), then Doppler satellite positioning, coupled with Doppler-sonar log and gyro, will provide good positioning. CHS has used this system in Hudson Bay.

The Canadian Hydrographic Service contracted for an investigation of the possible use of the new GPS satellites that are available with Doppler satellite positioning and Loran-C, for use in the Baffin Bay area. In the area, only one Loran-C range is available although one other is available on skywave, and from one to four GPS satellites are available up to 14 hours per day. With one GPS satellite pseudo-range and a Loran-C range, the position can be computed, but the GPS synchronization constant and the clock rates would remain unknown. Knowing that the GPS satellites have stable atomic frequencies, the synchronization constants and the clock rates for the Loran-C and GPS satellites, with respect to the atomic frequency standard on the ship, could be determined by comparison of the ranges with the Doppler satellite position-derived ranges over a period of several days. With two GPS satellite pseudo ranges and one Loran-C range, the position and GPS synchronization constant can be determined and the clock rating can be determined from Doppler satellite position comparisions. With three or four GPS satellites and one Loran-C range, the solution is fully determined at each iteration.

Generally, the accuracy of the position fix improves as the number of GPS satellites above the horizon increases. However, the geometry of the fix is always changing and there are periods when the solution will be weak because the satellites are in a particularly poor configuration with respect to the position of the ship (Wells, Delikaraoglou and Vanicek, 1982). The field operations using the techniques developed in the contract are now under investigation.

The integrated systems depend on computer processing, usually in real-time but also in post-processing. The computers can handle the sophisticated algorithms of long-line geodetic computations, least squares adjustments or Kalman filtering and phase lag computations, including Millington's method of estimating the Additional Secondary Factor. To date, most users of integrated systems have designed and built there own computer software and in some cases, some of the hardware. Industry is only starting to get into the business of manufacturing and/or supplying integrated systems and it is likely in the next few years that industry will become more involved in this field.

Chapter 10

Hydrographic Surveys

This chapter gives some explanation of the equipment and techniques used in the offshore for the guidance of the surveyor operating in the area for the first time, and draws attention to some of the items which have to be considered in planning and executing a hydrographic survey.

The objective of a hydrographic survey in the offshore is to measure the depth of water and to locate the positions at which the various depths occur. Ashore, a land surveyor can see what he wants to position and can use direct methods such as triangulation, trilateration and traversing; the hydrographer can not see the sea-bed — in the offshore he cannot even see land and must therefore use indirect methods to get a position and depth.

Planning

Due to the high costs of operating a ship, the key to an economical and successful hydrographic survey is planning. A successful survey manager must be a logistics expert and when free of time constraints, should study the meteorological conditions prevalent in his proposed area of operations. High winds create conditions which affect both vertical and horizontal accuracy. Launches cannot be raised or lowered and the ship itself may have to run for shelter. Rain and/or fog will affect electronic positioning systems particularly the low powered, short range system. Electrical storms are a most annoying problem as they too affect such systems and when working at long range, local electrical storms may not even be evident from the ship. Solar storms are predictable seasonally and by area; however the duration and intensity of the storms cannot be precisely predicted. Effects of such storms include the elimination of radio communications at certain frequencies and the range reduction or intermittency of ground wave positioning systems. Sunrise and sunset periods similarly affect some positioning systems as do solar storms but for brief periods only. A study of past records will frequently give an indication of the most suitable time of the year for the survey.

Also inherent in planning is the choice of equipment. Today's market offers a wide range of echo sounders and positioning systems. Characteristics of the positioning systems are discussed in an earlier chapter and those of echo sounders are discussed in this chapter.

The availability of shore control should also be thoroughly investigated as far in advance of the survey as possible.

Survey control along the coast and the nature of the coastline are also of importance to the hydrographer. Table 1, Chapter 4 gives a general overview of the control available and its order for the various areas of the Canadian coastline.

Geodetic control tends to be located inland and in many cases on top of hills whereas the hydrographer wants his control on or near the high water mark. Thus the hydrographer must frequently carry his own control from, and tie into, suitable Geodetic positions for his control network. The location of control stations established should be within the limits for third-order control, based on *Specifications and Recommendations for Control Surveys and Survey Markers* (1978), Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa and International Hydrographic Bureau (IHB) Special Publication No. 44. An accuracy higher than third-order is highly desirable for positioning shore stations of electronic systems used for surveys of the offshore.

In addition to the aforementioned control from the Geodetic Survey of Canada, control may be available from the Canadian Hydrographic Service (CHS) or other agencies. The National Geodetic Data Base established by the Geodetic Survey of Canada and described in Chapter 4, gives information on available control in Canada. Any contractor undertaking an offshore survey would be well advised to contact the Geodetic Survey of Canada, Ottawa, or a regional office of the CHS, Department of Fisheries and Oceans, to get the latest listing of available control in a particular area. Additional information such as elevations, datums and connections to other networks are also available.

Site Selection for Shore Stations of an Electronic Positioning System

For a typical hyperbolic chain for an offshore positioning system the following criteria should be considered:

a) The stations should be sited so as to give good pattern geometry over the survey area.
b) The baselines should be of equal length.
c) The angle between the baselines should be between 90° and 120°.
d) There should be minimum land between the stations and any part of the survey area.
e) Land path on the master/slave baselines should be avoided if possible.
f) The sites should be clear and level to facilitate setting up the mast ground mat.
g) The site should have good ground conductivity. Damp soil is best; rock is poor; dry sand, worse. Avoid varying conductivity.
h) The site should be clear of:
    - Power or telephone lines within 100 m.
    - Trees or other obstacles comparable in height to the antennae height on the signal path.
    - Cliffs or trees behind the antennae which could act as reflectors.
    - Radio transmitters in the area near the system's frequency or half frequency.
i) The site should be high, especially for long ranges; however the requirement to be near the water's edge is more important.
j) Sites should be selected so that baseline crossings are possible to assist in calibration.
k) The site should be easily accessible (helicopters, truck or launch).

l) If the site is privately owned, the owner's permission must be secured to erect a station.

Naturally not all these criteria can be met in any one situation and the hydrographer must make his choice and recognize the limitations and constraints placed upon him by the selection. Once the site has been selected and surveyed in, it should be permanently marked, referenced, and described.

There is always the possibility of the same survey point being used for a positioning system for an exploratory or production well. It may be advantageous to refer to the detailed requirements set out in Appendix E for an exploratory well survey or, to the *Manual of Instructions for the Survey of Canada Lands* (Department of Energy, Mines and Resources, 1979) for a production well survey.

The Echo Sounder

It is essential to understand that an echo sounder does not measure depth but does measure time – the time taken for a pulse of sound to travel from the transmitter to the sea bed and back. This interval of time is then converted to depth by multiplying it by the velocity of sound in water, thus:

$$\text{Depth} = \tfrac{1}{2}\, t \cdot v \qquad (44)$$

where t = time taken for the pulse to travel from the transmitter to the sea bed and back
v = velocity of sound in water

The Echo Pulse

The pulse of energy emitted into the water when an echo sounder transmits is in the form of a sound or compression wave. This pulse may vary in its frequency, duration and shape depending on the type of transducer; it may be allowed to spread out equally in all directions from its source or it may be concentrated into a beam.

Low frequency pulses, less than 100 kHz, transmit energy efficiently over long distances and give good penetration of the sea bed producing echoes off the underlying layers. However they require a large transducer if they are to be concentrated into a beam.

High frequency pulses, greater than 100 kHz, have the advantage of compact transducers but their power is quickly reduced in water and will not penetrate deeply into the sea bed.

The hydrographer normally choses as high a frequency as possible provided that the range of the set is satisfactory. Dual frequency sounders, typically 30 kHz and 100 kHz, are available where compromise is difficult.

Increased depth capability may require increased power output. This increase in energy can be achieved by increasing sounder pulse length. For shallow depths a short pulse length of about 1/5000 second is normally used. Sounders designed to operate in deeper waters generally vary in pulse length between 1/1000 second to 1/25 second to overcome losses due to attenuation.

Transducer Beam Width

Consideration must be given to the selection of the beam width of the transducer when selecting an echo sounder. It is wasteful to allow the echo pulse to spread out in all directions. Therefore, transmitting units are fitted with transducers which concentrate the beam.

Conventionally the beam pattern of a transducer is considered to be a cone whose vertex angle is about 30°. Most of the energy is concentrated in the main lobe whose limits are typically defined as the 3dB points. Outside these points, power decreases rapidly but there are additional buildups of intensity levels in the form of side lobes. These side lobes serve no useful purpose and can at times produce false echoes. (See Figure 30)

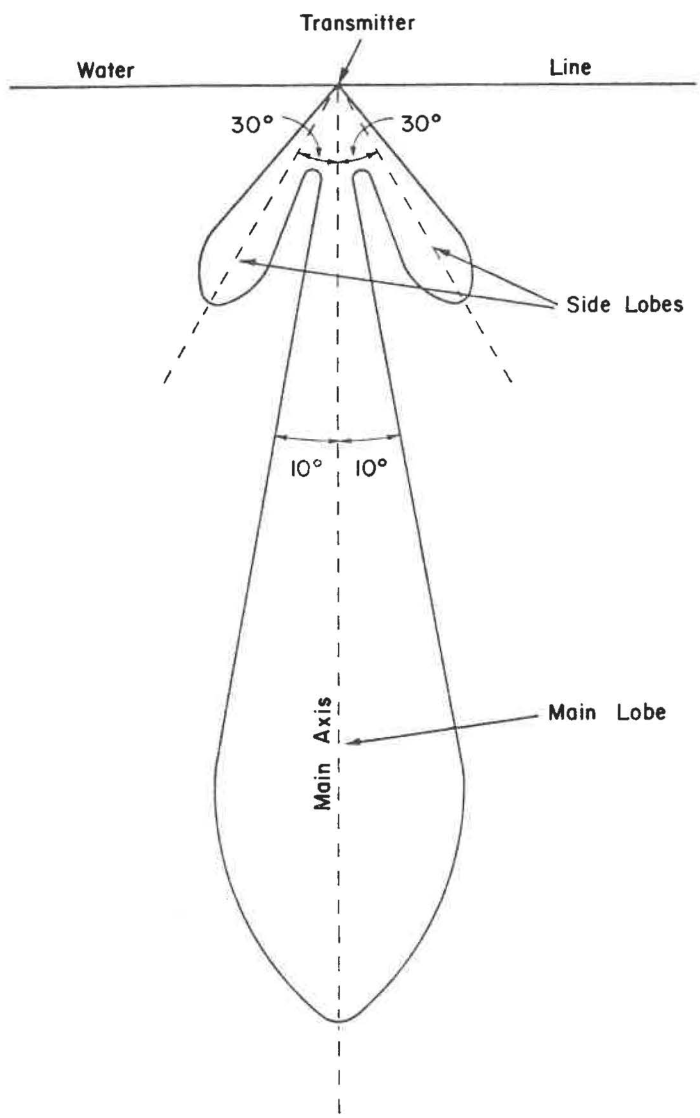


Figure 30

Echo Sounder Transducer Lobes

Most transducers used with hydrographic echo sounders have a beam width of 20°-30° which allows the hydrographer to detect anomalies on either side of the vessels track. Figure 31 shows the effect of beam width on survey line spacing.

The first returns of a transmitted pulse come from the closest reflector to the transducer and not necessarily from the bottom directly underneath the vessel. Over a sloping bottom this gives rise to a depth error (See Figure 32).

Phenomena such as hyperbolic effect and side echo also occur and will be discussed later.

The gain control obviously effects the quality of the analog record. If set too low, weak first returns from a bottom which is a poor reflector may not be detected. If set too high, noise may appear on the record and add to the problems of interpretation, particularly when using a depth digitizer.

Sound Velocity Determination

As shown earlier, the velocity of sound through water is one of the two major factors in determining depth. The velocity varies with temperature, salinity and pressure and an increase in any of these three parameters will result in an increase in velocity. The maximum range likely to be encountered is between 1387 m/s for fresh water at 0°C and 1529 m/s for warm salt water. By measuring temperature, salinity throughout a column of water, an average speed of sound throughout the water column can be calculated.

A velocimeter can be used to measure the sound velocity at a point and from several points in a column, an average velocity can be ascertained. Expendable sound velocimeters (XSV's) are now available. These probes can be fired underway to quickly and conveniently provide a velocity profile. The costs of each probe is about $80 (1981) exclusive of deck equipment.

Profiles should be obtained throughout the area to be surveyed and from them, an average determined for the area. This figure is then used in processing data. In areas of extreme changes in velocity, naturally more intensive and more frequent sampling is required.

Transmission Lines: Depths are measured from the surface of the sea to the sea bed but the transducers are below the waterline of the ship. An allowance must be made for this difference between the waterline and the transducer; this allowance is called the transducer draught. Each time the transducer emits a pulse, a small portion of the emitted pulse is coupled to the sounding recorder, causing a small mark on the sounding paper. A series of these marks forms a line which is known as the transmission line. This transmission line only occurs on the first phase and it should be adjusted so that its scaled value is that of the transducer draught, thus giving a true depth. It is important that this be checked as it is the practice on many ships, particu-

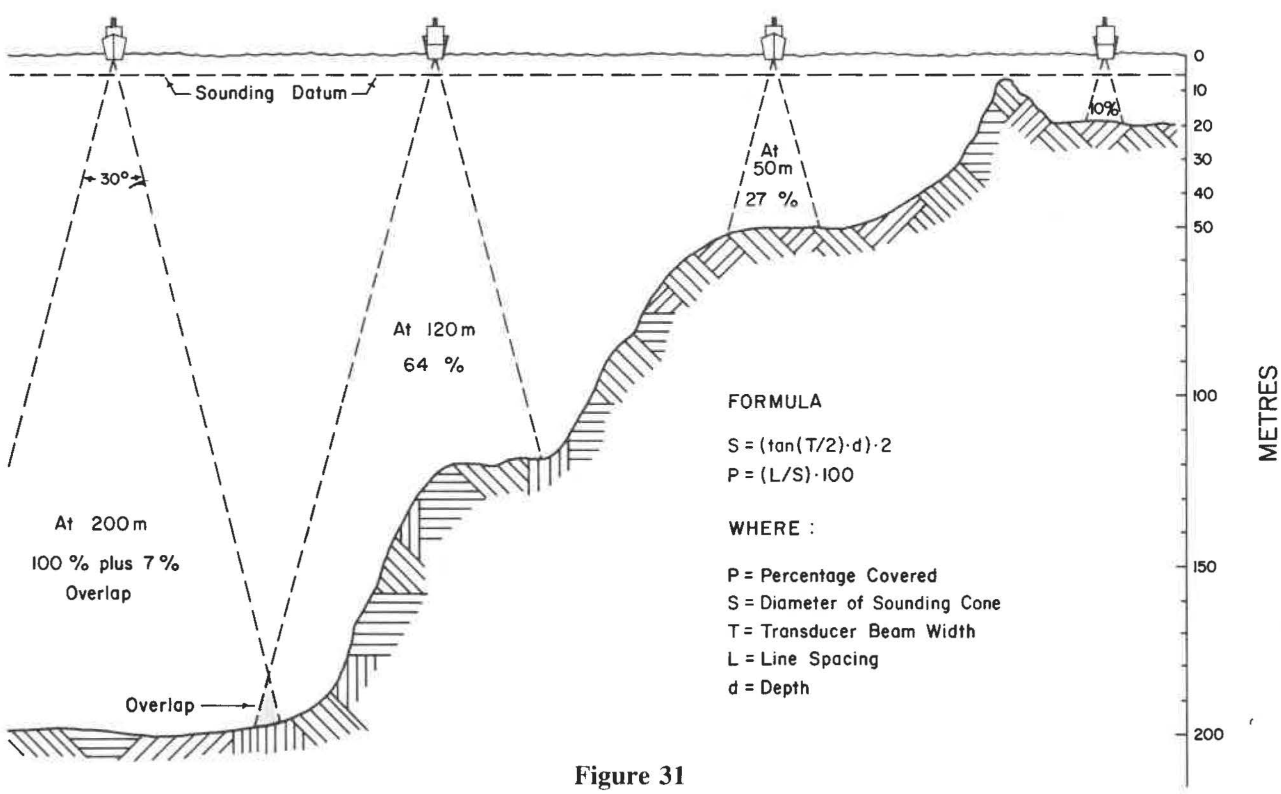


Figure 31

Variation with Depth of the Percentage of Sea-bed Covered by Sounding with Transducer Beam width 30° and Line Spacing 100 m

larly those not normally engaged in hydrographic surveying, to have the transmission line set to read below the keel and thus display the safe depth for the ship. One should bear in mind that due to squat or settlement, the draught of the ship and therefore the transducer draught may differ between the vessel at rest and the vessel underway.

Phasing: Since it would be inaccurate to show the full depth across one width of the echo recording chart, the depth is broken into several full width sections, called phases, so that depth can be scaled with better accuracy. Phasing means a shifting of the transmission line either mechanically or electronically so that the bottom depth is within the range that can be shown on the chart. Typical phases would be 0-80 m; 60-140 m; 120-200 m. There is always an overlap and the alert hydrographer will always note the trend in the bottom and alter his phase in advance to ensure a continuous bottom trace. Some sounders give a periodic coding to indicate which phase the sounder is in but it is still important to carefully annotate all phase shifts on the sounding graph.

It is also important to ensure that the phasing steps are correctly adjusted; for example, that a bottom of 70 m is the same on the 0-80 m and the 60-140 m phases. Another pitfall to guard against is "once around the clock" where the recorded depth, for example, falls on the 120-200 m phase scale, while in actual fact, the phase switch of the sounder has been turned more than one complete revolution. A much greater depth is thus taken to be a relatively shallow one.

Hyperbolic Effect and Side Echoes: In deep water, the transducer beam width gives rise to a hyperbolic effect. If the vessel in position "A", Figure 33, is vertically over a flat portion of the sea bed, the leading edge of the 30° sounding cone begins to detect the shoal "X". As the slope distance to the shoal is equal to the vertical distance to the sea bed, the echo returns from each are coincident. As the vessel moves to a position vertically over "X", the slope distance decreases causing the hyperbolic effect illustrated. Similarly, as the ship approaches position "B" the trailing edge of the sounder cone reaches shoal "Y". The valley between the shoals is almost obliterated on the record and in normal circumstances would not be discerned. In three dimensions the record can be further confused by hyperbolae from targets at each side of the vessel's track. Figure 33 is a typical sounding record showing hyperbolic effect.

In shallower water the side echo lobes of the main sounding cone may pick up targets closer than the bottom which is vertically below the transducer. Side echoes should not be discounted as they may be an indication of a critical but yet undetected feature off one side of the vessel's track.

Miscellaneous spurious returns: In addition to hyperbolic effect and side echoes, interpretation of sounding records may be complicated by miscellaneous spurious returns such as:

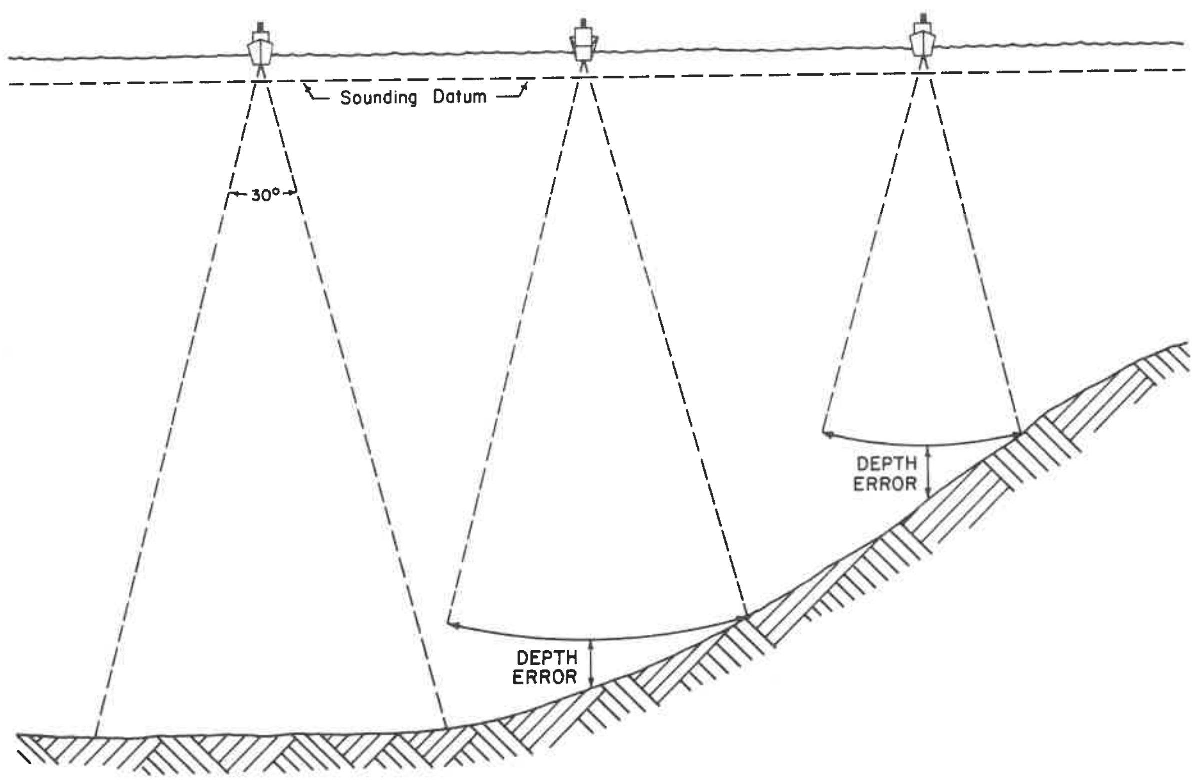


Figure 32

Depth Error of Sounding due to Slope of Sea-Bed

a) Fish — Single fish are readily identifiable but a shoal of fish near the bottom may obliterate bottom returns.
b) Thermoclines — A sharp change in temperature in the water column may cause bending or reflection of the sounder pulse.
c) Deep scattering layer — A layer of plankton, which lies at about the 500 m level in the open ocean in daylight but which rises toward the surface at night, is a good reflector.
d) Kelp or weed — This occurs in shallow water only, particularly around shoals, and may completely mask the bottom necessitating the use of a lead line or sounding pole.
e) Freshwater springs — An upwelling from such sea-bed springs can cause the sounder record to indicate a shoal.

Sounding Operations

The survey vessel is conned along pre-selected sounding lines. These lines may be steered along by using a compass course, or by using a left-right indicator which is optional equipment, provided with electronic positioning systems. Such systems also allow for running along a hyperbola or a range circle. Some of these systems also allow for X and Y displays of coordinates, and track plotters are often available as options. Wherever possible the lines should be run to give a good cut on depth contours. At frequent intervals a position fix is taken and the echo sounder marked with the fix number and time. If continuous automatic logging of depth and position is possible then note-keeping is minimal. The beginning and end of line notations should be made on the trace. In manual logging situations, additional fixes must be taken when any alterations of speed or course are made. *Check lines should be run through the area at approximately right angles to the normal sounding pattern to verify the main sounding lines.* CHS Standing Orders specify that these check lines shall be approximately 7.5 cm apart at the scale of the field sheet in depths of 180 m or less and 15 cm apart at that scale in depths greater than 180 m.

Data Processing

After the required soundings are read from the graph or recovered from the depth digitizer tape, they must be corrected for:

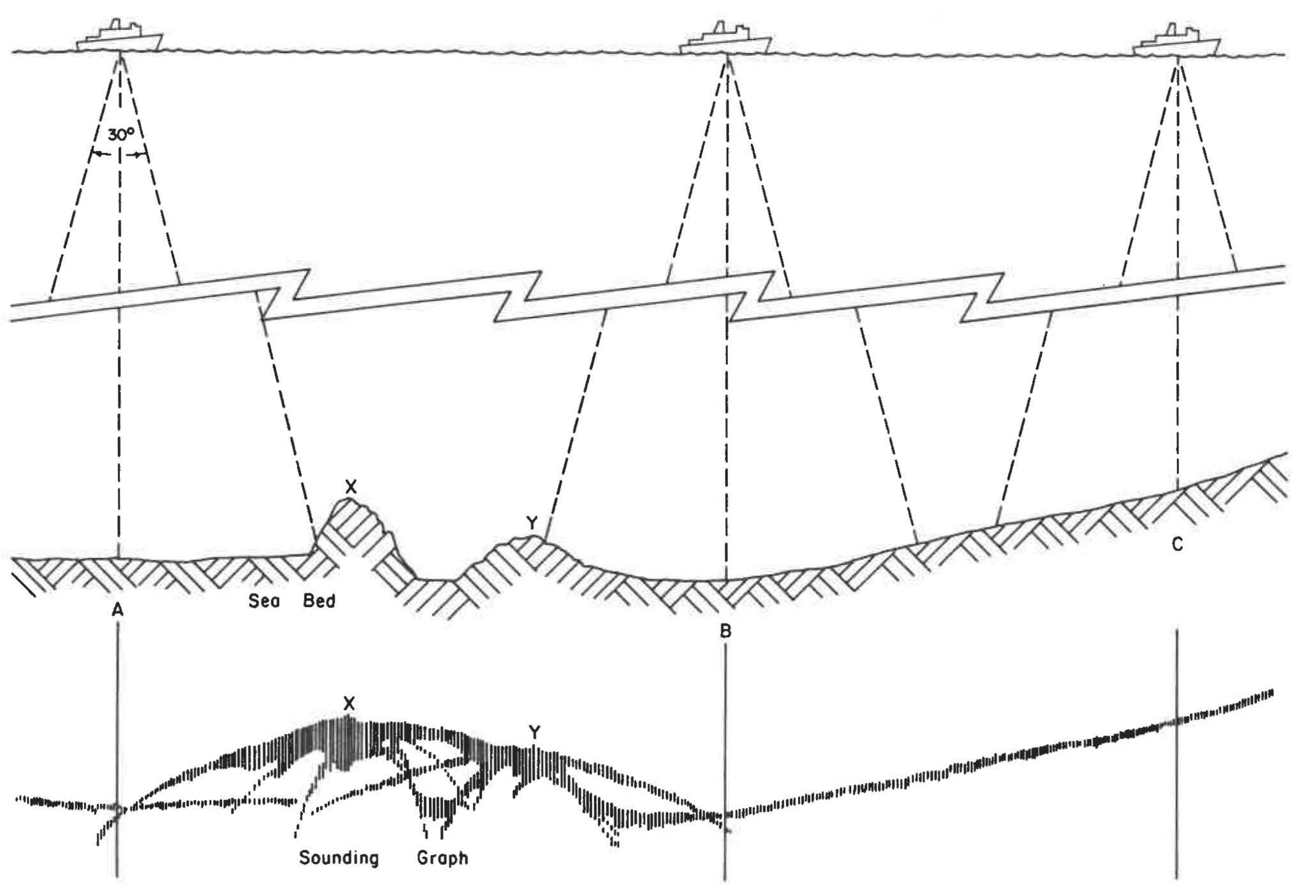


Figure 33

Hyperbolic Effect in Sounding

a) State of the tide. The tidal information is correlated by time to the sounding fixes.
b) Sounder calibrations independent of sound velocity error.
c) Sound velocity errors.

It is important to plot the day's soundings as quickly as possible after the day's work so that additional lines may be run over shoal areas. Areas of bad data can be rerun or holes in coverage may be filled before the ship moves too far from the area requiring the additional coverage.

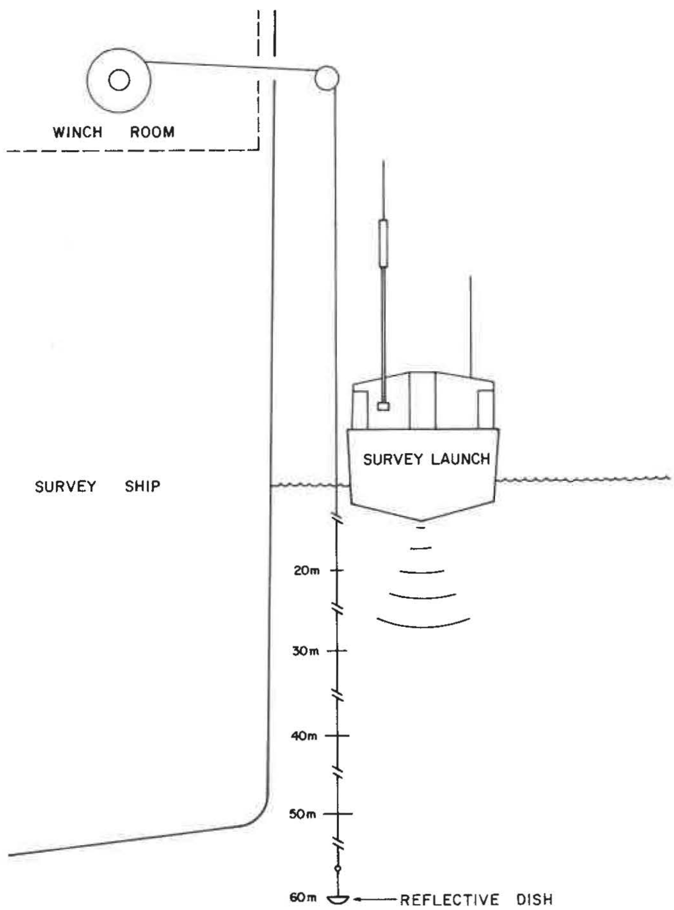


Figure 34

Prodedure for Sounder Calibration

Bar Check (Calibration)

At the beginning and end of each day's sounding, the sounder is bar checked. A weighted reflective target, traditionally a bar (hence the name), is lowered on a marked line to different depths below the transducer. In place of the traditional bar, an inverted dish has been used successfully (see Figure 34). The depth read from the sounder record is compared to the depth at which the target is suspended. Bar checks are typically carried out to 20 metre depths; but in favourable conditions good results have been obtained up to 50 metres (see Figure 35). The difference between the compared depths may be due to the difference between assumed sound velocity and actual average velocity to the bar check depth. If this bar check difference is solely due to sound velocity error it could be corrected by adjustment of sounder stylus speed in some types of sounder. However, many sounders have an assumed velocity of sound in water that cannot be changed. In this case soundings can be corrected during processing, the correct velocity having been determined independently as described previously. With variable speed sounders it should be noted that in water depths greater than the bar check, where the difference is not attributable to sound velocity error, a fixed mechanical error could be converted to a percentage error. This error would be magnified in deeper water.

Tides and Water Levels

This section presents a general overview of the importance of tides and water levels to hydrographic surveying. Each of the regional offices of CHS has a section specifically charged with the study of Tide and Water Levels in their region.

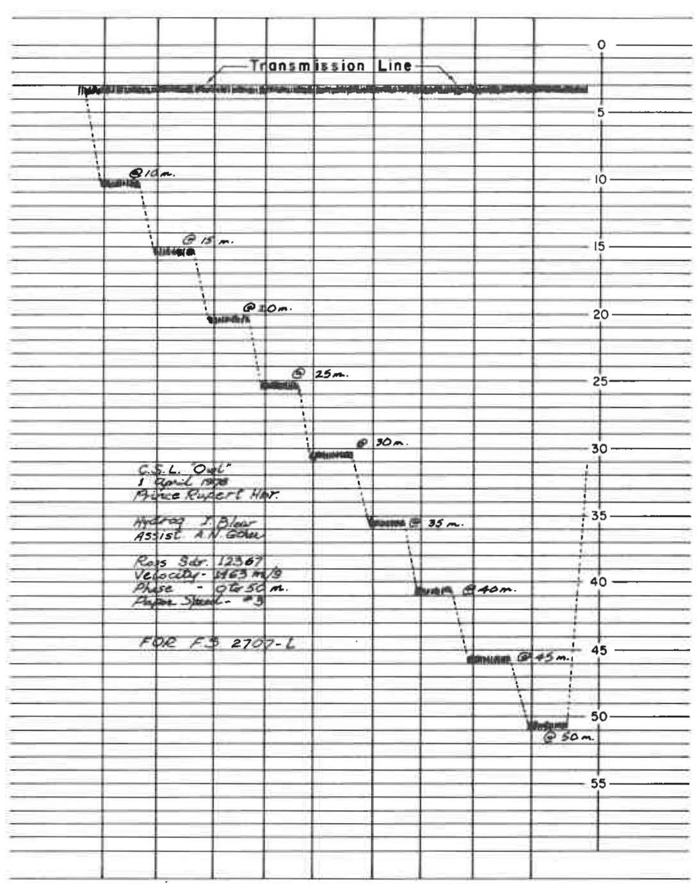


Figure 35

Typical Record of Sounder Bar Check

Specific information on any aspect of tides and water levels is available from:

a) Office of the Dominion Hydrographer
615 Booth Street
Ottawa, Ontario
K1A 0E6

b) Regional Tidal Superintendent — Pacific Region
Institute of Ocean Sciences
P.O. Box 6000
Sidney, B.C.
V8L 4B2

c) Regional Tidal Officer — Central Region
Bayfield Laboratory
P.O. Box 5050
Burlington, Ontario
L7R 4A6

d) Regional Tidal Officer — Atlantic Region
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
B2Y 4A2

Water levels are never static. The reasons for the movement of the surface are many – in tidal waters the tidal raising forces are the obvious ones. However, in both tidal and non-tidal waters, meteorological influences are strong. Wind friction over the water surface can result in a build-up of water on the downwind shore. Barometric pressure variations across a large water body will cause the surface to slope. In some circumstances, lakes and bays oscillate at their fundamental reasonant frequency, causing the surface to tip back and forth, a phenomenon called a seiche. In addition, inflow, outflow and control of lakes can cause water level variations during a 3-4 month hydrographic survey.

Since the depth soundings obtained during a hydrographic survey are reduced to depths below a common level plane (sounding datum), it is necessary to document the elevation of the water surface, relative to this plane, during the survey.

Datum Planes

When selecting a datum for soundings the following factors must be considered:

a) The datum should be sufficiently low so that under normal weather conditions there will always be at least the charted depth of water.
b) The datum should not be so low as to give an unduly pessimistic impression of the least depth of water likely to be found.
c) The datum should be in close agreement with that of neighbouring surveys.

The International Hydrographic Bureau recommends that chart datum should be a plane low enough that the tide will seldom, if ever, fall below it. For tidal waters, the Canadian Hydrographic Service has adopted the level of Lower Low Water Large Tides as its datum plane for chart datum, and Higher High Water Large Tides for its datum plane for elevations. Depending on the range of the tide, the datum varies from place to place. Figure 36 illustrates various datum planes in tidal waters.

Definitions

a) *H.H.W.L.T. — Higher High Water Large Tides* — is the highest predictable tide from the available constituents.

b) *H.H.W.M.T. — Higher High Water Mean Tides* — is the average of the predicted heights of the higher high waters of each day.

c) *L.L.W.M.T. — Lower Low Water Mean Tides* — is the average of the predicted heights of the lower low waters of each day.

d) *L.L.W.L.T. — Lower Low Water Large Tides or Lowest Normal Tides (L.N.T.)* — is the lowest predictable tide from the available constituents.

e) *M.W.L. — Mean Water Level* — is the average of hourly water levels for a period of observations.

f) *M.S.L. — Mean Sea Level* — is the average of hourly water levels for a period of several years of observations.

g) *M.T.L. — Mean Tide Level* — is the average of all the high and low water heights over a period of observation.

h) *Chart Datum* — coincident with L.L.W.L.T.

i) *Charted Elevation* — is the vertical distance between an object and the reference plane of H.H.W.L.T.

j) *Height* — is the vertical distance between the top of an object and ground level.

k) *Charted Depth* — is the vertical distance from the Chart Datum to the bottom.

l) *Drying Height* — is the vertical distance of an object above Chart Datum. It can not exceed the Large Tide Range.

Water Level Gauges

Here we are mainly concerned with the operating principles of water level sensors. In all but one case, the data is automatically recorded in either a digital or analog form that can be either stored or transmitted as required. Those most used by the Canadian Hydrographic Services are:

1) Staff gauge — a vertical graduated rod, permanently mounted within the tide range, and read directly.
2) A float sensor in a stilling well. The float follows the movements of the water, driving a recorder. The stilling well inlet damps out any unwanted signals such as wind waves (for this purpose the ratio of the inlet area to the well cross-sectional area is usually approximately 1:100).

3) Various types of pressure sensors:
   (a) a submerged rubber diaphragm joined by capillary tubing to a pressure sensitive element (Bourdon tube) which is linked to a strip chart recorder.
   (b) a quartz crystal with a pressure sensitive resonant frequency. Found in self-contained, completely submersible tide gauges that are often used on bottom-anchored, offshore moorings.
4) Bubbler type gauge. A pressure gauge measures the hydrostatic head at the end of an air filled bottom-mounted tube. A pump ensures a continuous flow of air through the tube. The pressure gauge can be linked to a strip chart recorder.

Further information on how and where to set up a temporary gauge is contained in the Canadian Hydrographic Service Tidal Manual (1970).

Datums on Tidal Waters

At numerous locations on most Canadian tidal waters, with the exception of the high Arctic, Chart Datum (LLWLT) has been established from long periods of tidal observations. Bench marks have been established at these locations and the elevations of the bench marks both above chart datum and, in most cases, above the vertical Canadian Geodetic Datum have been published. Chart Datum can therefore be recovered either by levelling from an established bench mark (or by transfer from a suitable reference gauge). In tidal waters the actual level of the datum differs from place to place as the nature and range of the tide changes.

This effect is shown for an open coast in Figure 37. Here mean sea level can be assumed to be a relatively level surface along the coast. As the tide range increases and LLWLT lowers relative to MSL, Chart Datum lowers correspondingly. In practice, Chart Datum is altered in steps as shown. A difference of 0.5 metres between two places would normally indicate the need for a change in datum somewhere between them.

Establishing Chart Datum During Surveys in Tidal Waters

In recovering a datum where one has previously been established, gauges are installed so that the lowest water levels will not expose the staff zero or the pressure diaphragm, and level lines are run from the existing bench marks to the gauge. Sounding reductions based on water levels measured at this location should not extend outside the area where the associated Chart Datum is reliable.

If Chart Datum has not been previously established in the survey area, then it must be transferred from a suitable reference gauge where water level elevations referred to Chart Datum are recorded. Advice on these procedures is obtainable from Regional Tidal Offices.

Co-Tidal Charts

Another method which can be used for obtaining sounding reductions during hydrographic surveys involves the use of

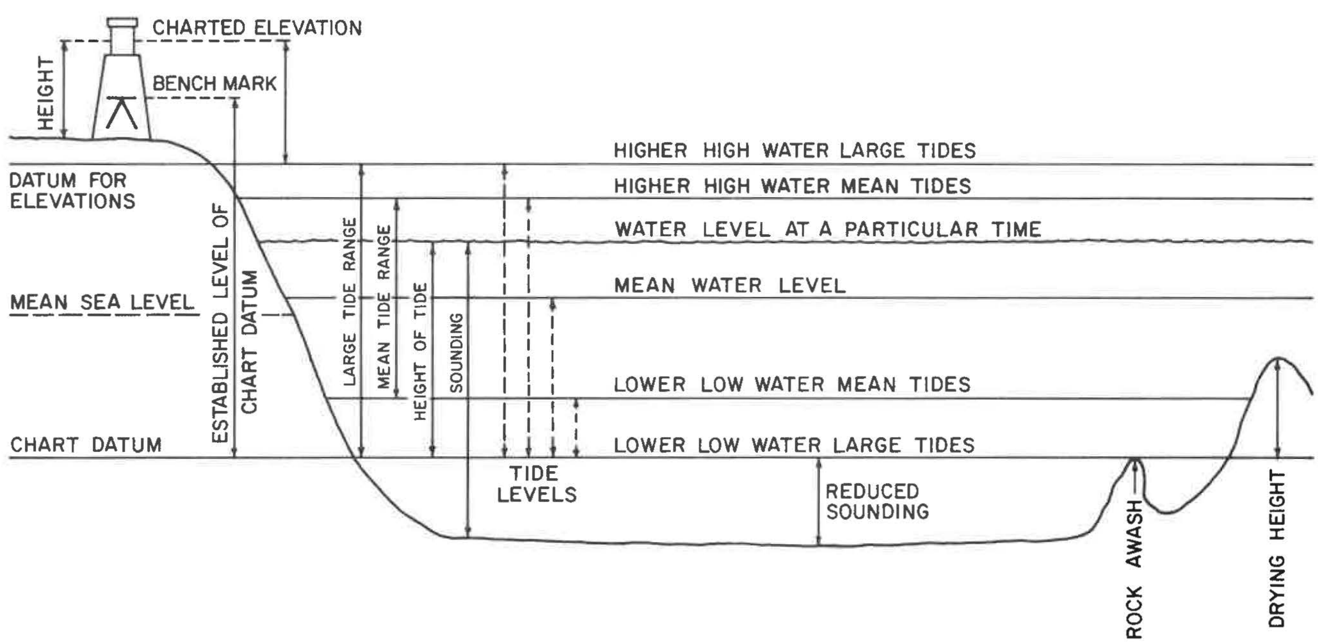


Figure 36

Datum Planes and Water Level Variations in Tidal Waters

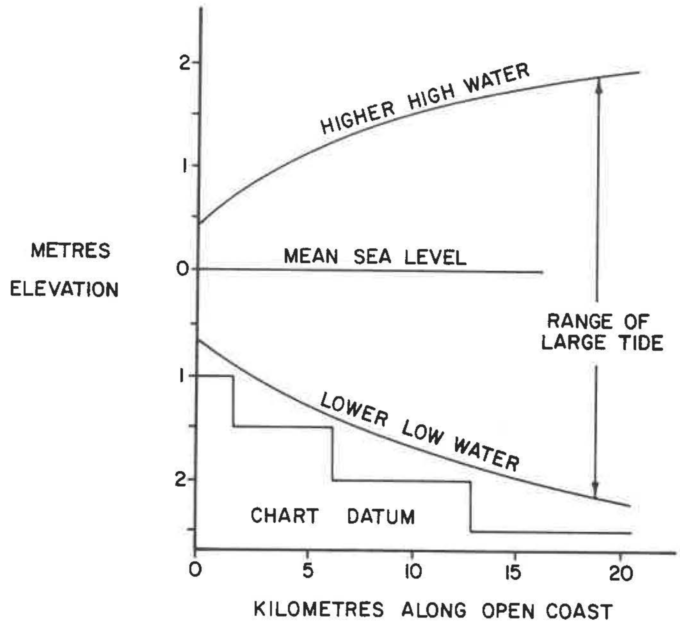


Figure 37

Chart Datum and Tide Levels on an Open Coast

co-tidal charts for offshore surveys. On these charts, two sets of curves connect points having equal tidal ranges and points having simultaneous high and low waters.

A typical semi-diurnal co-tidal chart is shown in Figure 38. All the co-tidal curves indicate relationships to the tide at the Reference Point A, where the range is large compared with that in most of the remaining area. The full lines indicate time corrections which must be applied to the times of the tide at A; thus the time of high or low water water at B is 30 minutes earlier than it is at A, while at C it is 30 minutes later. The pecked co-range lines give range ratios on the tide at A; thus at B the tidal range is 0.65 times the range at A. Soundings obtained at D may then be reduced from tide gauge readings obtained at A by adding 15 minutes to all times, and multiplying all heights by 0.68, to obtain the tidal curve.

Most of the information on which present day co-tidal charts are based comes from observations obtained ashore. The inshore ends of co-tidal curves should, therefore, be reasonably accurate. Comparatively few offshore tidal observations have been obtained, and therefore co-tidal curves in offshore waters will usually have been sketched in between observations on facing coasts. As more tidal information becomes available from ship observations or offshore tidal gauges, it will be possible to produce better co-tidal charts for offshore waters.

Constructing A Co-Tidal Chart

A semi-diurnal co-tidal chart may be constructed provided that time differences and tidal ratios are available for at least three suitable positions. These should, if possible, enclose the sounding area within an equilateral triangle. The more positions that are available, the more accurate the chart will be.

Figure 39 shows a large survey area which lies some 20 to 50 kilometres offshore. Reductions for soundings in this area will be obtained from observations taken at A where chart datum is established. The time difference and ratios at B, C, D, E, and F, relative to A, are known.

To construct a co-tidal chart using this information, proceed as follows:

a) Join adjacent tidal stations with straight lines, and interpolate time difference along these lines. The lines and interpolated times are shown in Figure 39(a).
b) Sketch in the time difference curves; these are shown as dark lines in the figure, and it can be seen that the survey area is well covered.
c) Repeat this process for the range curves, to obtain the results shown in Figure 39(b).

Common sense and judgement are required when these curves are being drawn, if errors are to be reduced to a minimum. Note that the 0.90 interpolated point on the line BE in Figure 39(b) has been disregarded, preference being given to its neighbour on the line AC. Interpolated points will always be more reliable if the line on which they lie cuts the curves being drawn at a broad angle. Similarly, points on short line will always be better than those on a long line.

Suppose now that tidal observations had been obtained at A, B and D only. Co-tidal curves may still be drawn, but they will not be as reliable as the ones described above. Consider the lines DE and EA in Figure 39(b). If values were interpolated along them, neglecting the observed value at E, the rest would be quite different from that shown.

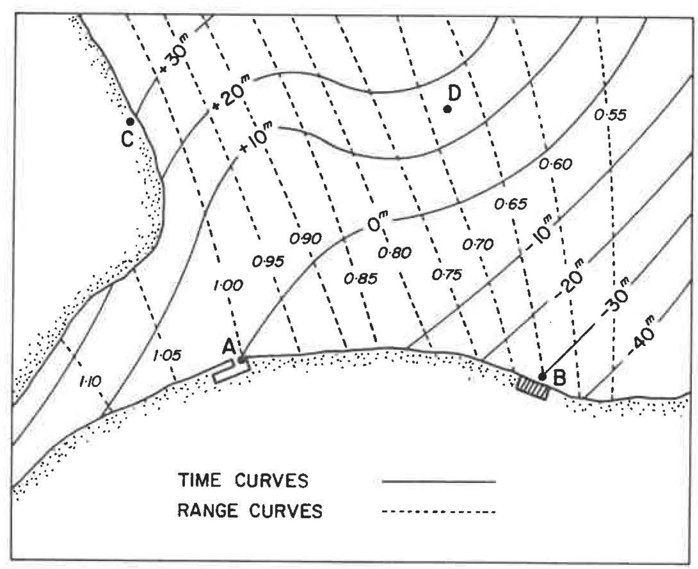


Figure 38

Semi-Diurnal Co-Tidal Chart

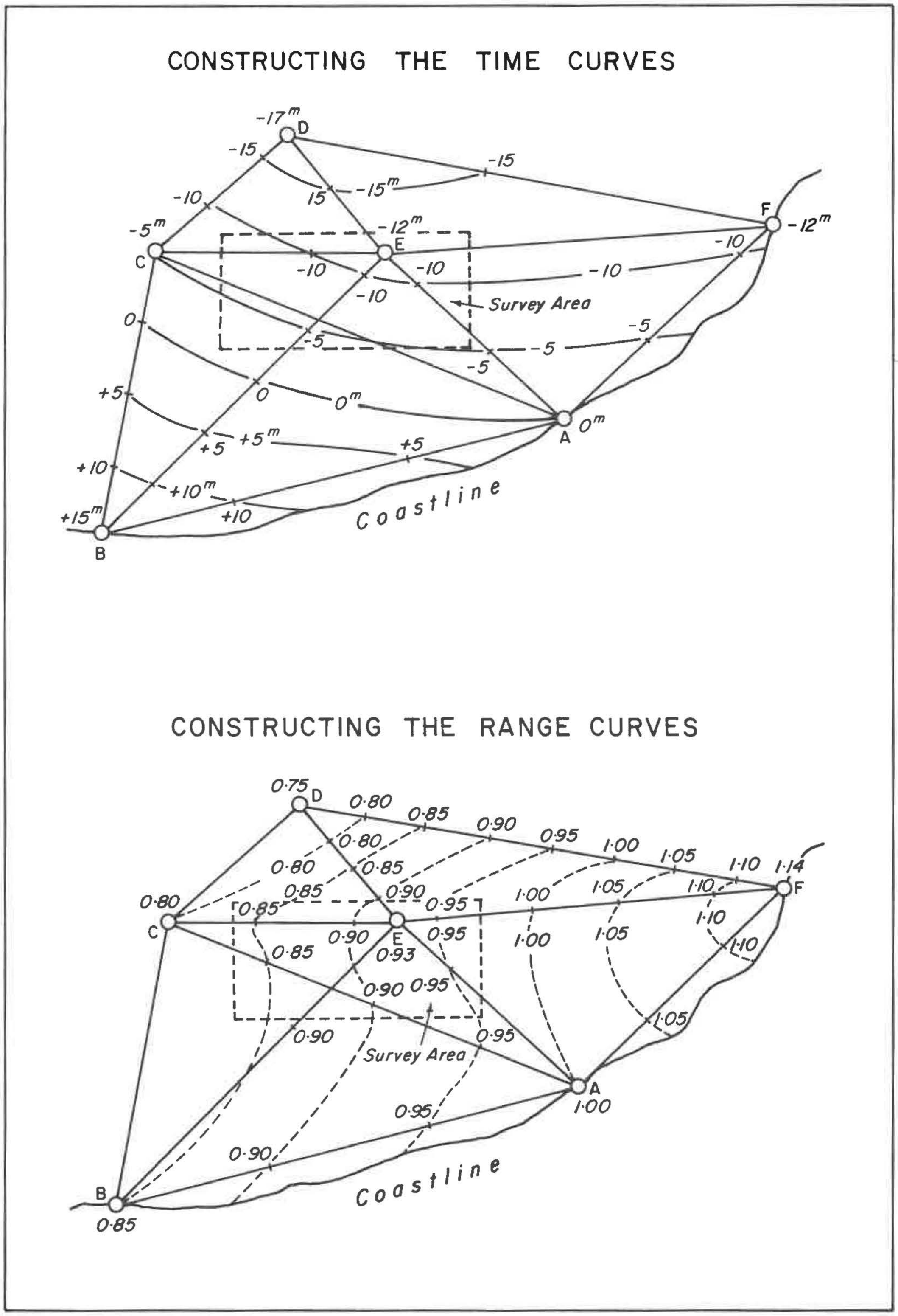


Figure 39

Constructing a Co-Tidal Chart

Tides in Canadian Waters

East Coast

South Coast of Newfoundland, Southeast Coast of Nova Scotia and the Bay of Fundy (Figures 40, 41, and 42)

Along the Atlantic coast from Cape Race to Cape Ray, Newfoundland, across to Glace Bay, Nova Scotia, and along the shores of Nova Scotia and New Brunswick, the tide is semi-diurnal. High water occurs almost simultaneously along all coastal points from Placentia Bay, Nfld., to Shelburne, N.S. The tidal range is not very great, the difference between high and low water seldom exceeding 2 m. Around the southern end of Nova Scotia, there are rapid changes both in the time at which high water occurs and in the range of the tide.

The most remarkable tide not only in Canada, but probably anywhere in the world, occurs in the Bay of Fundy, where the tidal range reaches over 12m. This is due entirely to a peculiar combination of geographical factors.

East Coast of Newfoundland and Labrador (Figures 40, 41, and 42)

Along the east coast of Newfoundland, and along the Labrador coast as far as Cartwright, the tide is mixed but mainly semi-diurnal. Further north it tends to become more and more semi-diurnal, being entirely so at Cape Chidley, Labrador's northernmost point. High water occurs simultaneously along the Labrador and east coast of Newfoundland, and the tidal range is about 1 m. However, towards the northern end of Labrador (Davis Strait) the range increases considerably.

Gulf of St. Lawrence (Figures 40, 41, and 42)

The tide propagated through Cabot Strait and Belle Isle Strait into the Gulf of St. Lawrence is of a mixed type, but mainly semi-diurnal, except along the coast between Cape Tormentine and Richibucto, N.B., and near Savage Harbor, P.E.I., where diurnal inequalities dominate. At the southern tip of the Magdalen Islands and near Crossman Point, N.B., the tide is entirely diurnal, with only one high and one low tide occurring every day. The range of the tide throughout the Gulf is less than 2.4 m.

Arctic

Hudson Strait, Hudson Bay and Foxe Basin (Figures 40 and 43)

In this entire area the tide is semi-diurnal, except for the short stretch between Povungnituk and Port Harrison, on the northeastern coast of Hudson Bay, and Hall Beach, Foxe Basin, where the semi-diurnal rhythm is affected by large diurnal variations.

Hudson Strait serves as a communication between the open ocean and a large "inland" sea; also, it is much narrower at its waist than at either end. These factors affect the range of the tide in Hudson Strait, which, along the northern coast, increases from 5.5m to about 9m at Ashe Inlet, decreasing again to 5m towards Schooner Harbor. In Ungava Bay, the tide coming in from the Atlantic increases rapidly toward the end of the bay, reaching a mean range of 12m at Leaf Basin.

The tide setting into Hudson Bay describes a roughly circular movement, following the contour of the shoreline, starting from the northwestern end of the bay, moving south along the western shore, and almost petering out along the eastern shore. In the entrance to the Bay the average range of the tide is 2 m, increasing to 4 m along the western shore, after which it decreases gradually along the southern and eastern shores to about 0.3 m at Port Harrison. The tidal rise and fall may sometimes be obscured, particularly near the head of James Bay, by weather effects which may cause the sea level to rise or fall by a few metres.

Davis Strait, Baffin Bay and Lancaster Sound, Western Arctic (Figures 40 and 44)

The tidal range which, as noted, increases northward into Davis Strait, diminishes again as the tide moves on into Baffin Bay, until it comes close to zero halfway along the coast of Baffin Island. From that point on, the tide increases again as it moves into Smith Sound and Lancaster Sound.

High water occurs almost simultaneously along the coasts of Davis Strait, but in Baffin Bay, high water at the southern entrance coincides with low water at the northern end. In Smith Sound, the tidal range is about 3 m, and in Lancaster Sound at Resolute, the mean range is 1.2 m. The inlets leading off Lancaster Sound have a mean range under 2 m.

In those portions of the western Arctic lying west of Barrow Strait,the range of the tide is small, being no larger than the changes in water level caused by meteorological influences.

Although the CHS is carrying on continuous exploration and surveying work in the Canadian Arctic, data on tides are still comparatively scanty. For this reason, the tidal characteristics shown on Figure 40 apply only to the few points where observations have been made.

West Coast

West Coast of Vancouver Island and Queen Charlotte Islands (Figures 40 and 45)

Along the northern two-thirds of Vancouver Island's west coast — from Barkley Sound to Cape Scott — the tide occurs almost simultaneously and has a range of 3 m. The range increases slightly as the tide moves up into the island's numerous inlets, without being slowed down, except at Quatsino Narrows where, owing to the restriction of the channel, the tide occurs 45 minutes later than elsewhere on the coast.

Along the west coast of the Queen Charlotte Islands and along the mainland shores of Queen Charlotte Sound, high water occurs simultaneously about 30 minutes later than at Vancouver Island. The shallowness of the sound increases the range of the tide along the mainland, an effect that is further enhanced as the tide rolls up the deep inlets, where at the heads, the tidal range reaches 5 m.

Hecate Strait (Figures 40 and 46)

The tide propagated into Queen Charlotte Sound sweeps northward into Hecate Strait, increasing in range with the shallowness of the passage. Around the northeastern spit of Graham Island the tide is slowed down, reaching Masset Inlet about an hour later than at Hecate Strait. On the mainland side of the Strait, both the time difference and the range of the tide increase from south to north; at Prince Rupert the tide arrives about an hour later than off Vancouver Island and has a range of 5 m. The tide wave propagated up the inlets reaches the end about 10 minutes later than at the entrance, with a slight increase in range.

Juan de Fuca Strait and Strait of Georgia (Figures 45 and 46)

It takes about six hours for the tide wave to travel up Juan de Fuca Strait and into the Strait of Georgia. The range increases from the entrance towards Victoria, where it is 2 m to 3.8 m at the north end of the Strait of Georgia. The entire strait may be regarded as a single tidal basin, the time difference between any point along its shores and Point Atkinson at Vancouver not exceeding 30 minutes.

Queen Charlotte Strait and Johnstone Strait (Figure 45)

This narrow, island-strewn passage separating northern Vancouver Island from the mainland is host to two tidal currents – the one coming from Queen Charlotte Sound in the north, and the other from the Strait of Georgia in the south.

Since the tide from the north takes about three hours longer to reach the narrowest parts of the channel separating Vancouver Island and the mainland than the tide from the south, a furious alternating current is set up in the passage, especially at such narrows as Seymour, Okisollo, Surge, Hole-in-the-Wall, Yuculta and Arran Rapids. The range of the "northern" tide shows wide variations, owing to the highly irregular shape of the channel; at Alert Bay, the mean range is 4 m, at Knight Inlet, 5 m, decreasing again as the channel narrows.

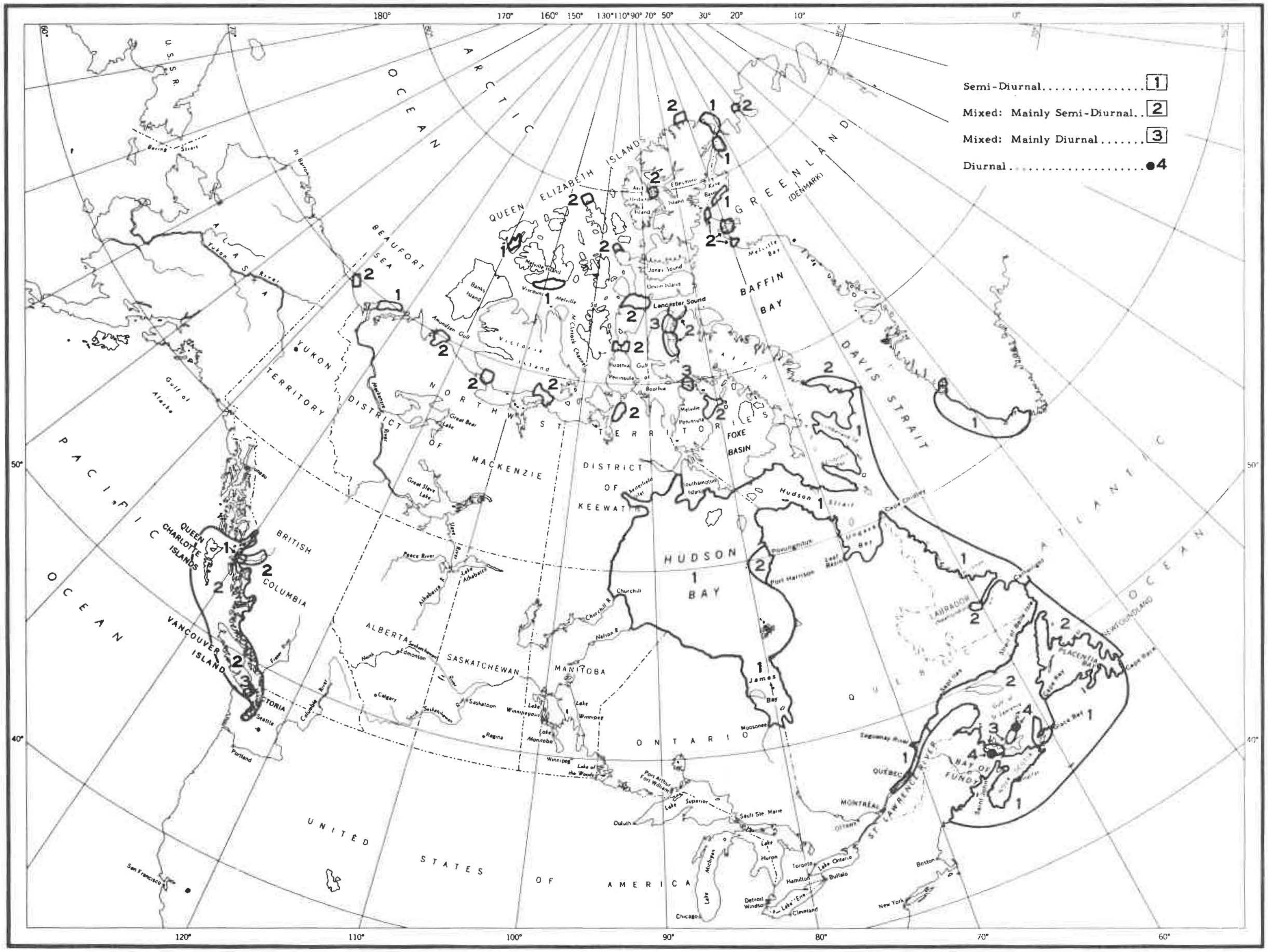


Figure 40

The Character of Canadian Tides

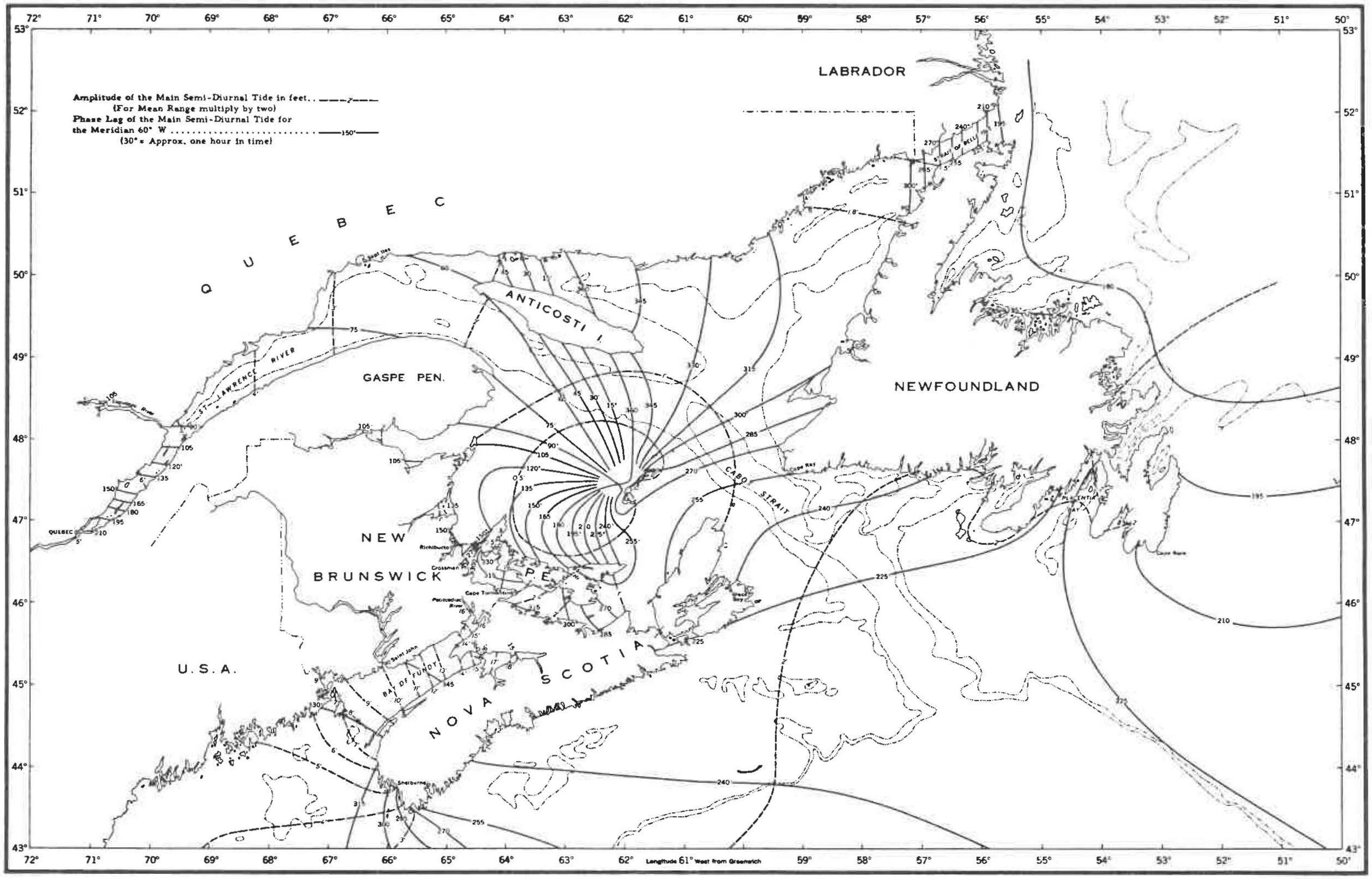


Figure 41

The Average Progression of the Semi-Diurnal Tide in the Gulf of St. Lawrence and Offshore from Newfoundland and Nova Scotia

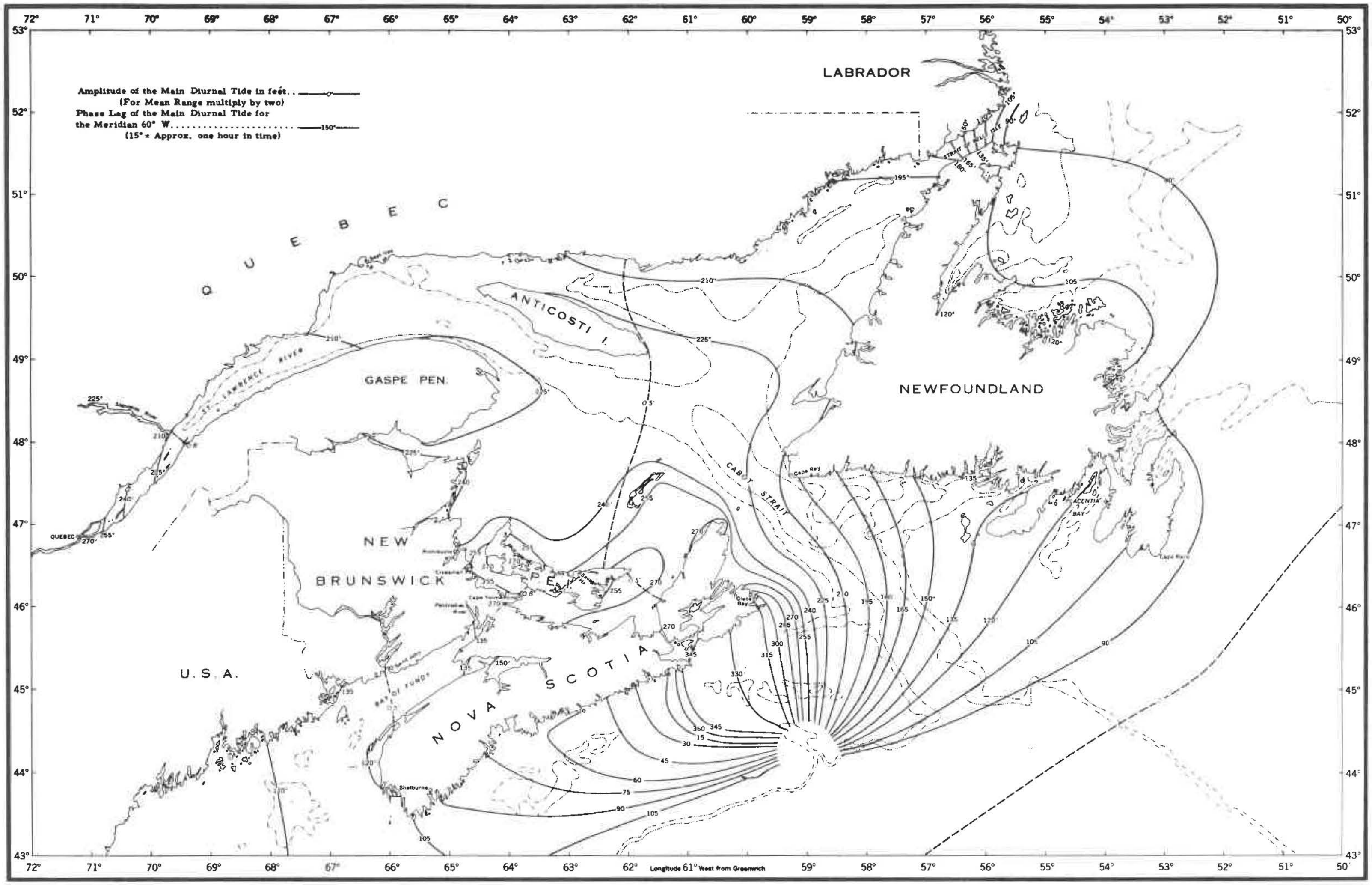


Figure 42

The Average Progression of the Diurnal Tide in the Gulf of St. Lawrence and Offshore from Newfoundland and Nova Scotia

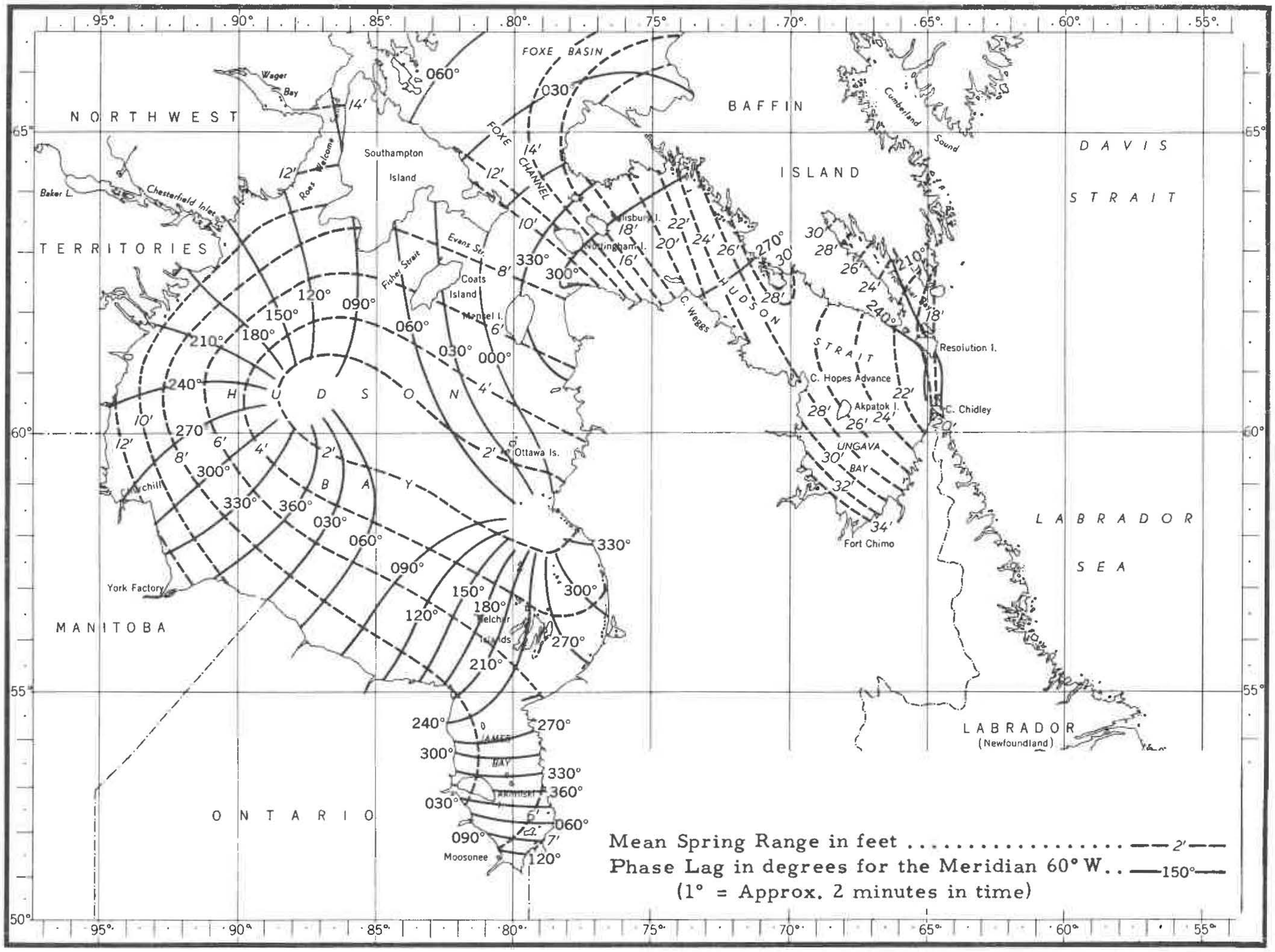


Figure 43

The Average Progression of the Tide in Hudson Strait and Hudson Bay

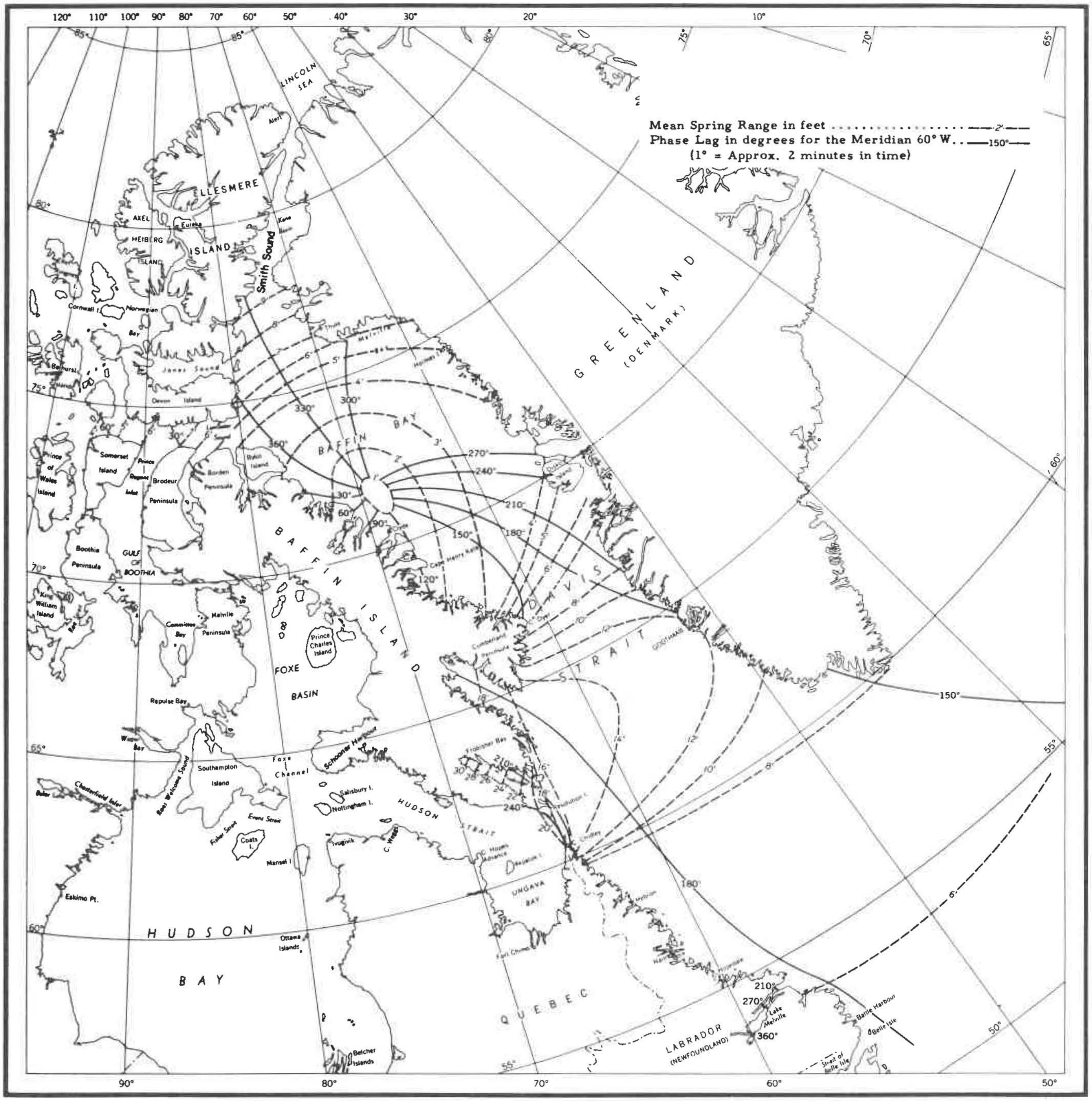


Figure 44

The Average Progression of the Tide from Newfoundland to Baffin Bay

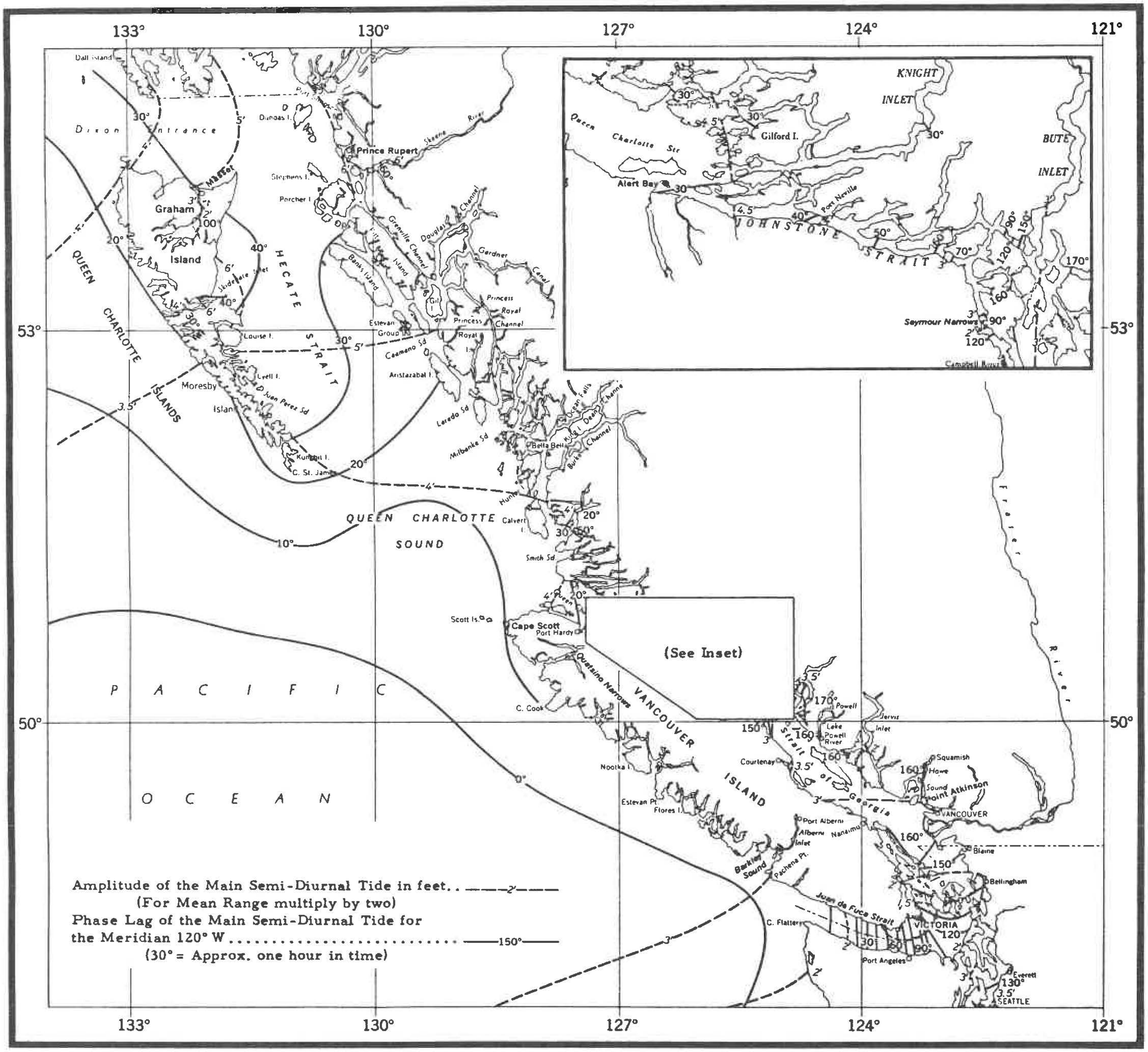


Figure 45

The Average Progression of the Semi-Diurnal Tide on the Pacific Coast

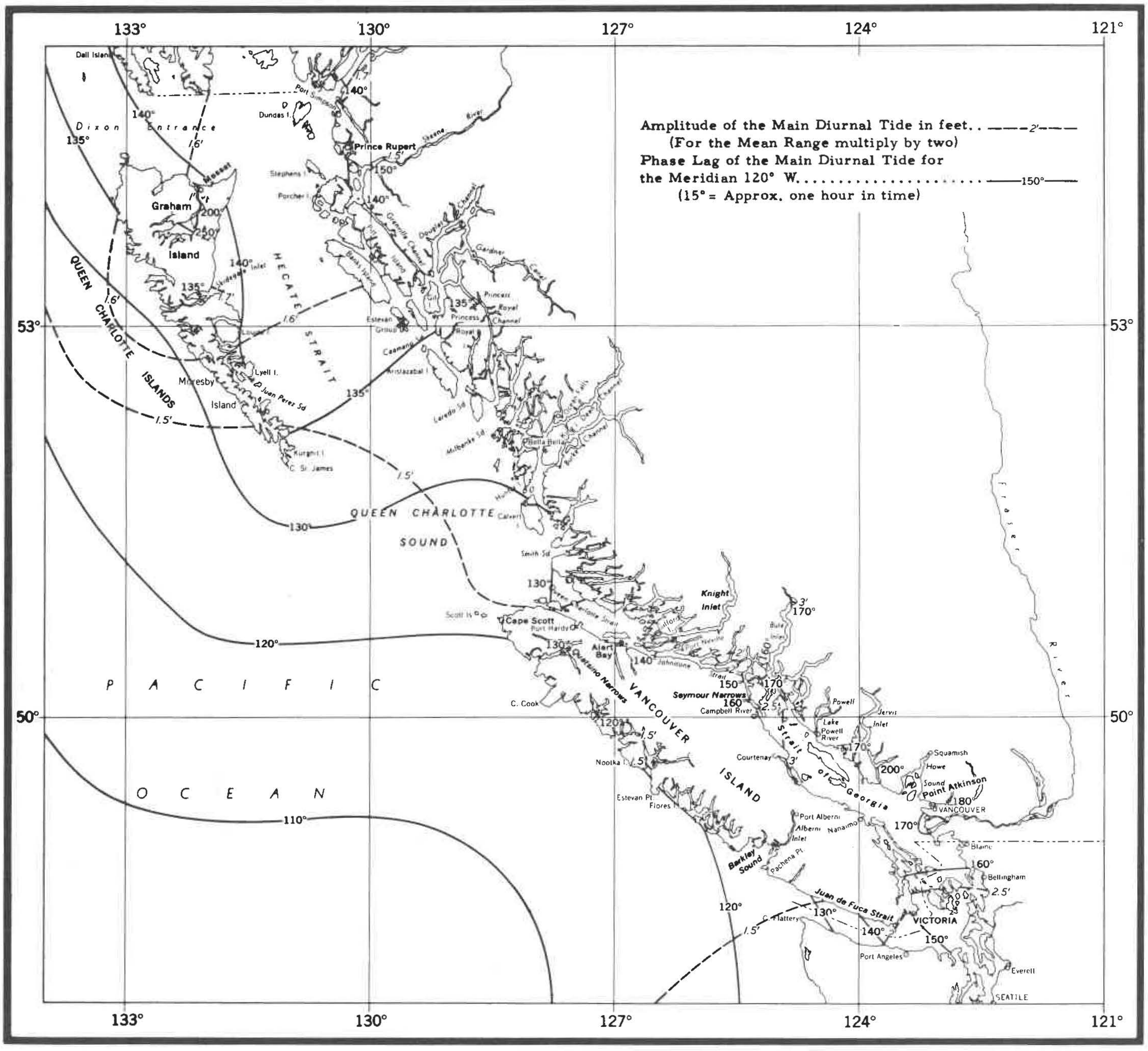


Figure 46

The Average Progression of the Diurnal Tide on the Pacific Coast

Chapter 11

Geophysical Surveys

Introduction

The petroleum industry relies almost entirely upon geophysical methods to locate prospective drilling locations in offshore exploration. When a location is chosen, geophysical methods are used to establish a safe and suitable sea floor drilling site. Should a well be successful, geophysical surveys will define the likely limits of the new reservoir. This chapter provides a simple overview of the equipment and methods used in the marine environment.

Potential Field Methods

Magnetometer

The simplest and easiest geophysical exploration method is the magnetometer survey, and particularly, the aeromagnetometer survey. It is the easiest to do because it usually involves towing a magnetometer below an aircraft or carrying it in a carefully placed external housing, and continuously measuring the changes in the earth's magnetic field while the aircraft flies along a grid of flight lines at a constant altitude. A similar procedure is adaptable for use with boats. The usual navigation aids are adequate for positioning the grid of survey lines in either case.

Magnetometers can be used on the ground or used shipborne or airborne. Ground magnetometers are used to measure the vertical or horizontal components of the earth's magnetic field or sometimes, the total intensity. Since careful alignment of the magnetometer is necessary for measurement of the vertical and horizontal components, a measurement that this is impractical on moving vehicles, only total intensity measurements are made on ships or aircraft.

Magnetometer surveys are designed to measure variations in the earth's magnetic field, normally about 50 000 gammas. The variations in the magnetic field are produced by variations in the susceptibility and polarization of rock masses in or beneath the sedimentary section. These variations are of the order of 100 to 1 500 gammas. The effect of local relief is also measureable and is of the order of 5 to 50 gammas. These variations are then interpreted to give the approximate depths, size and orientation of the causative bodies. This information may lead to the determination of the depth to the magnetic basement and its general configuration. In this way the shape of sedimentary basins can be defined.

There are six types of total intensity magnetometers; namely, flux-gate, nuclear precession, proton resonance, vector, optically pumped and cathode ray.

The interpretation of magnetometer surveys is usually done by analyzing the recorded profiles and maps, comparing their features to the theoretical effects of bodies of various simple shapes, sizes and depths. Many analytical procedures are employed, such as continuation upward or downward of the observed magnetic field, second and higher derivative analysis, residual analysis, and the application of simple depth approximation rules such as those of Peter, Sokolov, Tilburg, Hannel, and others.

Magnetometer surveys are inherently ambiguous since many different shapes, sizes, susceptibilities and polarities of magnetic bodies can produce very similar observations. Magnetic storms originating from sunspot activity produce very intense "noise", resulting in meaningless data, and forcing the interruption of surveys in progress.

Magnetometer surveys carried out aboard ship are usually done in connection with other geophysical surveys. Though the general procedure is similar to airborne surveys, shipborne surveys produce much less detailed coverage. Progressively less use is being made of magnetometer surveys since they are essentially reconnaissance surveys.

Gravity Surveys

Gravity surveys on land are another simple and easily conducted type of geophysical survey, and are considered to be refined, reconnaissance surveys.

This type of survey measures variations in the earth's gravitational force. It is done by making absolute measurements by means of pendulums or torsion balances at selected "station" sites, and by making relative measurements at a large number of stations. The latter group of measurements can be tied to the absolute values at coincident stations. Many corrections must be applied to the survey measurements before they can be used. They include: latitude, elevation, instrument drift, terrain corrections and the most serious type, in the case of vehicle-borne gravity meters, the acceleration components due to motion of the vehicle.

Once the measurements have been corrected, they are interpreted to give the approximate distance to, and the shape of, the masses which produce the variations in the gravitational field. The procedure is much like that done with magetometer surveys, but much shallower, anomalous bodies can be described and defined as to composition.

There are two types of exploration gravimeters, represented by the LaCoste-Romberg and the Worden meters.

When gravimeters are placed aboard any moving vehicle, they respond directly to the components of acceleration of the vehicle, in whatever direction it moves. This is called the Eotvos Effect and it constitutes a very serious problem in carrying out gravity surveys using boats or aircraft. In the case of aircraft, the greater speed and additional height above the surface are added problems, making the survey all but impractical.

Shipborne gravimeters have been developed which are isolated to a large degree from the ship's motion, and computers are used to remove most of the spurious acceleration effects in the measurements. The gravity data obtained from shipborne surveys are less precise and lack the optimum areal distribution obtainable on land.

Though precise vertical and horizontal control is required for land surveys, the usual, less precise navigational aids are adequate for positioning the gravity meter at sea, in view of the overall level of accuracy of the survey.

The interpretation of gravity surveys is based on the comparison of the observed profile and map anomalies with theoretical curves and maps produced for masses of various densities, shapes, and distances, just as in the case of magnetometer surveys. Residual and 2nd derivative maps obtained from the total field maps (Bouguer gravity maps) are frequently employed.

Seismic Surveys

The potential field surveys have been almost entirely supplanted by seismic reflection and refraction surveys, particularly in offshore exploration. The latter are much more definitive and lend themselves to much more sophisticated analysis and interpretation.

There are basically two broad classes of seismic surveys: refraction and reflection. The first is not used nearly as extensively as the latter, and the latter is used in several different ways and for different purposes.

Refraction Seismic Surveys

Refraction seismic surveys are characterized by the arrangement or array of hydrophones. They are located at such distances from the energy source (shot point) that the energy released at the shot point travels via horizontal, refracted paths through the layered rock formations, to the hydrophones, with very little arriving by way of reflection from those formations. The survey is usually conducted with stationary arrays; though moving arrays and moving energy sources are frequently used.

Positioning for moving refraction surveys is somewhat more complicated than for stationary surveys, or for moving reflection surveys. The equipment used in refraction surveys is essentially the same as that used in reflection surveys and will be described later.

Analysis of the data provides a knowledge of the depth to, and the velocity properties of, the sub-bottom formations. It can be used to delineate salt dome features, and can provide some information about the stratigraphy underlying islands where reflection seismic surveying would be discontinuous.

Reflection Seismic Surveys

Much more versatile and informative are the reflection seismic surveys. They are divided into two classes according to the depth of penetration of the energy released. Deep reflection seismic surveys are used for exploration purposes, while shallow reflection seismic surveys, including echo sounders, side-scan sonar, and sub-bottom profilers are used to evaluate potential drilling sites.

The types of deep reflection seismic surveys are divided into “2D” and “3D” according to the nature of the arrays used and the resulting characteristics of the information obtained. The 2D seismic surveys gather data along a profile, or a time, cross section, in two dimensions. The 3D seismic surveys gather data along closely spaced and parallel lines, or profiles, in three dimensions. The 2D surveys are used in an exploration sense, while the much more expensive and informative 3D surveys are used to delineate features located by 2D surveys or, more characteristically at this stage, to delineate reservoirs whose existence has been established by one or more wells.

The order in which these various reflection seismic surveys are usually conducted is the order in which they will be described in this chapter, i.e.; the 2D deep reflection seismic surveys used to discover hydrocarbon reservoirs, the 2D shallow reflection, side-scan sonar and echo sounder surveys used to establish drilling sites, and the 3D deep reflection seismic surveys used to delineate the discovered reservoir.

2D Deep Reflection Seismic Surveys

The essence of seismographic surveying is the measurement of the reflection time and the wave shape of seismic energy as it arrives at the surface, having been initiated by an energy source near the water surface. This is done by means of arrays of hydrophones connected by cable to amplifiers and then to magnetic tape recording equipment aboard ship.

The energy is released at a “shot point” and the reflected energy is detected by hydrophones usually arranged in line with the shot point. In marine seismic surveys, the hydrophones are imbedded in a specially constructed watertight cable called a “streamer”, which is towed through the water. It is kept at a suitable depth by means of “depth controllers” or “depressors”. Streamers can be 1 500 to 2 750 m long. The recording is done on-the-go since stopping the whole assembly for each shot would be impossible. Hydrophones are spaced in groups so that there are 24, 48, or 96 groups in a spread or streamer (see Figure 47). The streamer is moved a particular distance between recordings so that groups will occupy the same position as other groups have occupied on previous shots. The object, in later computer processing of the recorded data, is to be able to sum the recordings together from a number of shot-detector pairs of different separation but of the same reflection point (common depth point). The process is called “stacking” and is a very effective way of increasing the signal to noise ratio of the recordings. The summed energy is displayed as a record trace, which is essentially an amplitude versus time plot from an oscilligraph. In this way, energy recorded from all the shots as the streamer moves is output or “displayed” as a succession of wiggle traces on a time scale, producing a record “section” for the whole line of shots. The record section, roughly speaking, is a time, cross section through the geologic section, and is often called a “profile”.

For this to be useful, the location and speed of the streamer must be accurately known at all times, so that the record section and all its shot points can be referenced to a map. Many data processing steps will have been applied to the data before it is finally output, to enhance the appearance and improve the interpretability of the record section. Many filters are used, and signal gain functions are applied. Time or depth migration routines are used to locate the position of the reflection which conforms to the spatial position of the reflectors. Many other processes are applied as needed. Among these are designature,

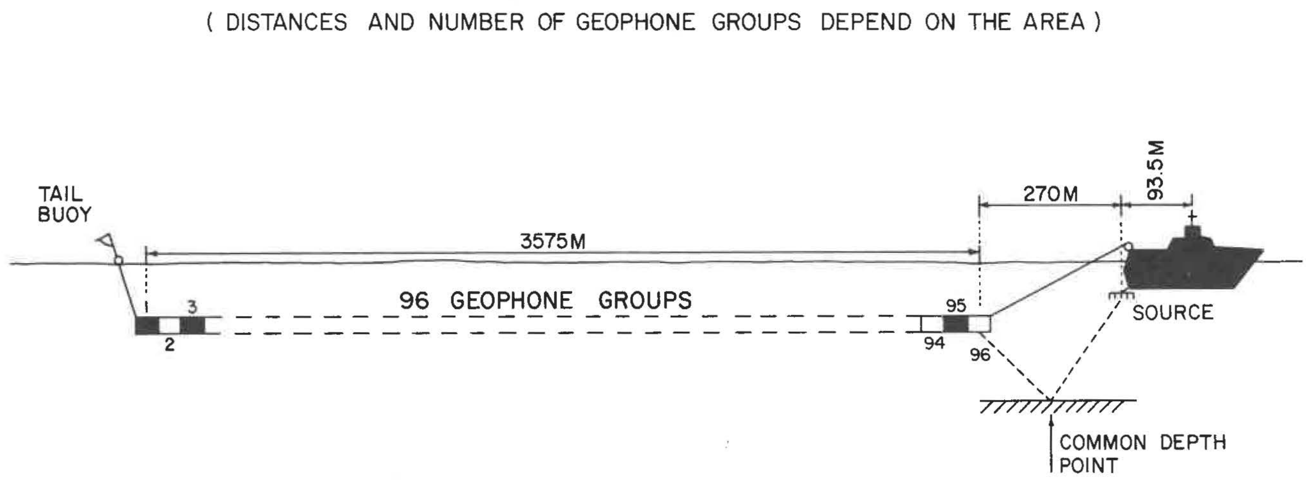


Figure 47

Typical Streamer Configuration for Marine Seismic Surveys

demultiple, various mutes, deconvolution before or after stack, dereverberation, depegleg and flattening.

The interpretation of the results proceeds by mapping the times, or computed depths, and inferring what the prospective geologic formations might look like. The profiles are studied for reflection "character" which can be indicative of bed thickness, facies changes, density and porosity changes, and amount of dip. They must be studied to isolate the misleading events that get recorded: sideswipe, reflection multiples, ghosts, point source events, amplitude anomalies, defractions, and reflections from surfaces "out of the plane". If there is a lot of control the task is easier; if not, it can be very difficult and the conclusions will be ambiguous.

The hydrophones used in marine reflection seismic surveying are pressure sensitive devices as opposed to the velocity sensitive detectors used for land reflection or refraction seismic surveying. The encapsulization of the hydrophones in the streamers groups them in sections which are "live". The live sections are separated from one another by "dead" sections. The streamer is towed by a specially constructed vessel. The entire geometry of the vessel, energy sources and streamer is accurately known and is used by the navigation and position fixing systems aboard the vessel. The energy systems used in marine seismic surveys are of several types and no longer include explosives, except in special circumstances. There are air guns, air gun arrays, steam guns, water guns, electrically driven plate separation devices, electrical discharge devices, and balloon collapse devices. They each initiate a typical, high energy pulse into the water. Some of the names of these sources are:

HIGH ENERGY SOURCES		LOW ENERGY SOURCES	
Steam gun:	Vaporchoc	Exploding wire (Sparker):	Wassp, Acer
Air gun:	Bolt, Pnu-Con		
Water gun:		Sleeve exploder:	Aquapulse
Cage shot:	Flexotir	Implosive:	Boomer, Flexichoc, Hydrosein
Gas gun:	Gas Exploder	Explosive cord:	Aquaseis

Navigation of the vessel and positioning of the streamer and shot point positions require integration of the seismic data with positioning data from one or more of the following systems: Argo, Syledis, Decca, Doppler radar, Doppler sonar, Lambda, Lorac, Loran, Omega, Raydist, Shoran, Toran, and other (see Chapter 7). There are integrated combinations in dedicated systems under various trade names. Though the accuracy is not "pin-point" in any system, it is adequate for the purpose, in view of the inherent sources of error in the overall conduct of the survey and the processing and interpretation of the data. Improvements are continually being made in this area.

Sub-Bottom, Sidescan Sonar

Once the 2D reflection seismic survey has been interpreted and a suitable location chosen for drilling, the next group of geophysical operations is initiated. The objective of these operations is to map detailed bathymetry of the wellsite area, determine the nature of the seafloor topography and of the water-sediment interface, determine the characteristics of the first 50 metres of sediment below the seafloor, and to identify shallow geological hazards (e.g., high pressure zones, permafrost zones, frozen natural gas) in the seabed in the first 600 metres of sediment. All this is to ensure that the site can be occupied successfully and safely. A closely spaced grid of echo sounder and bottom profiler traverses of one quarter to one half km spacing over an area of two km^2 or so are obtained and correlated with photographs and bottom samples. These surveys must be controlled by accurate and repeatable positioning systems. Tables IX and X summarize the types and characteristics of the geophysical systems used.

TABLE IX

Guide To Bathymetry and Near Surface (± 50 Meters) Seafloor Information and Instrumentation

	Objective	Purpose	
Sidescan	Seafloor Topographic Mapping	Identify iceberg scours, sandwaves, relics, seafloor obstructions, and man-made hazards	The combined effect of the high frequency beam shape and very short acoustic pulse enables the system to resolve details on seafloor micro and macro features from the differing strength of the acoustic return. Optimization must be achieved in range, tow depth, bean angle and depression. Geometry of the towfish is important and scalar corrections are necessary for positional mapping accuracy. Similar to echo-sounding in principal except the vertical beam width is narrow and the signal is propagated normal to the ship track.
Echo Sounder	Detailed Bathymetry, Topography and Morphology	High resolution, topographic profiling and mapping	Accurate determination of water depth is the most fundamental piece of information which a survey can provide. The echo sounder records are compiled and contoured to map bathymetry. The accuracy is largely dependent on the velocity conversion, tidal corrections and calibration of the instrument. Checks should be made with microprofiler records or independent depth measurements. A velocity error of 2 m/s can produce a depth error in the order of 1.3%.
Sub-Bottom Profiler	Near surface (to 50 ± metres) high resolution mapping	Identify seabed sediment structure; stratigraphy, and sediment type; bolder till, channel fills, slumping, faulting	Acoustic sources such as transducers, boomers, sparkers, and air guns are used to generate broadband spectrum pressure pulses for continuous high resolution shallow seismic reflection profiles. For optimum penetration and resolution in both hard and soft sediments a trade-off must be achieved between power source, pulse length, and frequency spectrum. While the bottom towed boomer (300 Hz – 12 kHz) gives highest resolution, a multielectrode sparker (50 Hz – 3 kHz) provides a deeper investigation source in maintaining resoundable resolution. Sparker energy has a much broader frequency spectrum as compared to the other sources; and the relative maximum energy is generally of a higher frequency then an air gun source.

The sub-bottom survey equipment is generally similar to deep reflection equipment but does deserve description to point out the differences.

The features being looked for with this equipment are: slump scars, faulting, gas, shallow trap closure and permafrost zones.

High resolution systems use sources which generate a pulse of short duration, broad frequency spectrum, high energy, and consistency. The recording equipment must have fast sampling and fast gain ranging rates. Streamers for this application must be highly sensitive. Several energy sources are used.

Boomer

This is an electomechanical sound source using an electrial coil which is magnetically coupled to a plate. Energy contained in electrical storage capacitors is discharged into the coil, causing induction currents that result in an outward force against a rubber membrane. A mechanical coupling device eliminates the cavitation pulse.

TABLE X

Marine Engineering Geophysical Survey Systems

Characteristics	Sidescan	Echo Sounder	Sub-Bottom Profiler	Boomer	Sparker	Airgun	Flexichoc, Sleeve Exploder, & Air Gun Array
Source, Useable Frequency Range	20-500 kHz	40-400 kHz	400 Hz-14 kHz	300-12 000 Hz	50-3 000 Hz	20-1 000 Hz	50-1 000 Hz
Energy Output (Estimated Range)	50 Joules	150-500 Joules	100-10 000 Joules	100-3 000 Joules	230-30 000 Joules	350-30 000 Joules	± 20 000 Joules
Output Pulse Length	150 ms	0.15-8 ms	2-30 ms	0.5-4 ms	1-10 ms	1-10 ms	± 3 ms
Repetition Rate	Dependant on Range	16-20 per sec	0.2-6 per sec	1/64-8 sec	0.25-2 pulses/sec	Dependant on Charging Size	Dependant on Charging Rate
Resolution	60 cm	5 cm	0.1 m	0.5 m	1-25 m	1-25 m	7-20 m
Penetration	0	0-0.1 m	10-60 m	25-75 m	100-500 m	100-500 m	1-600 m
Beam Width	± 1-2° Vert. ± 28° or 55° Hor.	Conical ± 8°	Conical ± 36°	Omni – Directional			
Utilization	- Surficial distribution of sediments and bedrock - Location of out crops and submerged objects - Identification of obstructions - Topographic mapping - Sea bottom morphology	- High resolution topographic profiling - Bathymetry - Sea-bottom morphology	- Sub-surface stratigraphic mapping - Ice scour depth, channel in-filling aggregate, and alluvial mapping	- Geologic: sedimentology, stratigraphy, lithology & structural mapping - Wellsite analysis surveys - Alluvial, aggregate borrow search - Ice scour character, abundance & mapping - Detailed delineation of shallow and deeper sub-bottom structures, hazards and gas zones - Shallow sub-sea bottom shoreline structural and sediment mapping including permafrost zones - Quantitative information on elastic properties, layer velocity etc. - Mapping bedrock & fault zones			

Sparker

Source and hydrophone towing considerations are the same as those for the boomer, but in this case a capacitor bank is discharged and an acoustic pulse is generated electrically by a number of simultaneous, underwater sparking electrode discharges. The basic period of the acoustic pulse is proportional to the number of Joules of energy discharged per electrode. A single trace, high resolution hydrophone displays the seismic echoes on a graphic recorder.

Airgun

An airgun is an omni-directional source utilizing a sudden, explosive release of high pressure air through a chamber which can be of various sizes. This source produces a secondary bubble impulse. To obtain optimum resolution, the smallest firing chamber is used which permits the maximum penetration into the bottom. Various power spectra and time signatures are obtained by varying firing chamber volume, gun pressure, and towing depth.

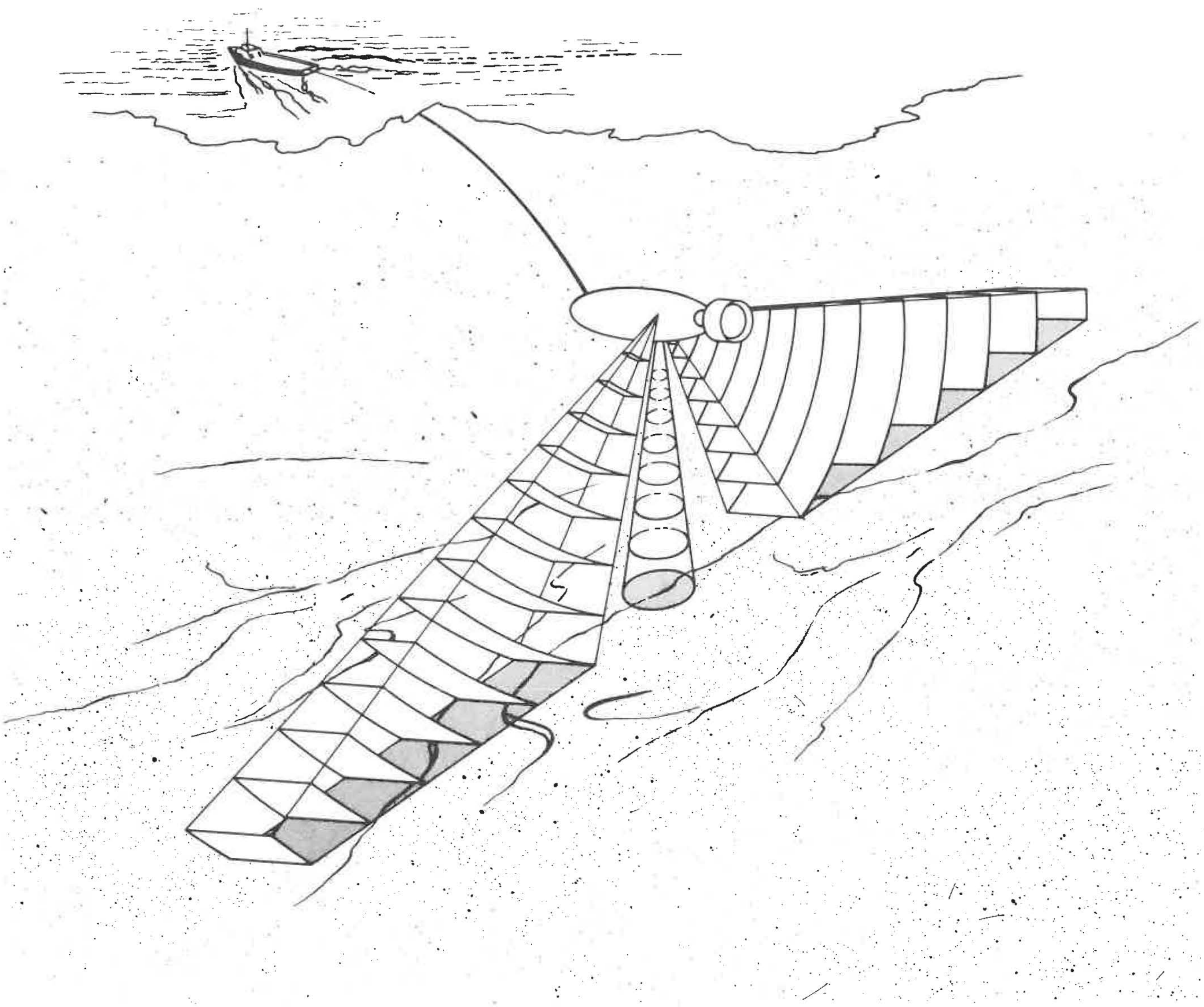


Figure 48

Sidescan Sonar Survey Vessel, Towline, Fish and Sensing Beam

Flexichoc, Sleeve exploder, and airgun arrays

Flexichoc bridges the gap between the above techniques by providing an implosive source by hydraulic high pressure oscillations of a rubber membrane between plates. A wide frequency spectrum and high resolution is obtained. This source is used with multi-channel arrays and is omni-directional without producing a bubble pulse. Sleeve exploders consist of two pontoons which support a number of separate elastic sleeves. A solenoid valve controls oxygen and propane supplies to the sleeve where the mixture is exploded by a shooting control unit. The rapid expansion of the sleeve transmits a compressional wave with a characteristic signature and amplitude. Airgun arrays of varying sizes of chambers and pressure can also be used to provide various time signatures and frequency spectra.

Sidescan Sonar

This device is used to investigate irregularities in the sea bottom such as ice scours, debris, rock outcrops, and boulders. A "fish" is towed 15 to 150 metres above the bottom, depending on the resolution sought, and pulses of sonar energy at about 120kHz are emitted by an array of elements. The display of reflection times and the relative amplitude of energy returns from the objects on the bottom give a graphic presentation of their position and attitude. See Figure 48

The sub-bottom profilers differ, finally, from the 2D deep reflection seismic surveys in that their penetration is much less, and each has characteristics which restrict the amount of analytical and interpretational reprocessing that can be done with their recorded data.

3D Reflection Seismic Surveys

The 3D surveys could be described as being made up of numerous, parallel, closely spaced 2D reflection seismic survey lines. However, every aspect of the survey becomes extremely complex, versatile and fastidious.

The concept of three dimensional data collecting began with the use of crossed spreads, and progressed to multiple line and multiple shots to provide definitive reflection paths. The present methods date back to 1974. The survey employs a large number of parallel lines 20-75 metres apart with shots every 25 metres. As in 2D surveys, the streamers used are of the order of 2500m long and contain 48 or 96 groups (Figure 47).

The streamers may contain compasses placed in the cable to assist in computing the positions of the groups and in navigating the towing vessel. This will help to overcome the errors in position due to cable drift. The course designed for survey vessels must permit wide turning circles at the end of each line so that the streamer will move straight and accurately along the lines.

The energy sources most commonly used in this type of survey are Vaporchoc, airgun, and airgun arrays.

It is essential that the position of each shot and each group be accurately known for every shot. Mini-Ranger, Syledis, Argo, GeoNav, Transit, and Navstar systems are used to achieve this. Remoteness of the project from land can pose serious positioning problems for 3D surveys.

Once the data collected during the survey has been properly organized into the computer "bin" configuration with the relatively exact x-y position of all of the groups and shots and resultant common depth points, the real sophistication of the method is available. Three fundamental procedures can be followed.

a) It is possible to choose any number of profiles through the 3D space for display and interpretation (see figure 49). They can be 2D profiles in the direction of the original lines. They can be 2D profiles orthogonal to them. Most importantly, they can be 2D profiles in any direction. Any of these are available at any subsequent time.

b) A revolutionary, new display is obtainable from this data — the trace amplitude for all bin locations at any record time can be displayed as a map or plan view. By studying a succession of these maps, produced for specific times a particular interval apart, a display of the change in hori-

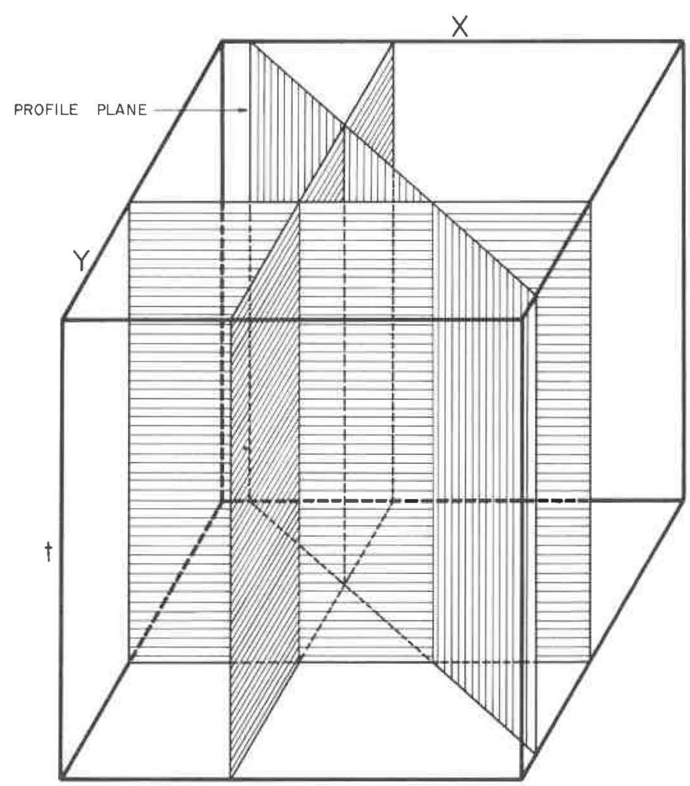


Figure 49

3D Data Space, Analogous to the Computer Bin for 3D Reflection Seismic Data

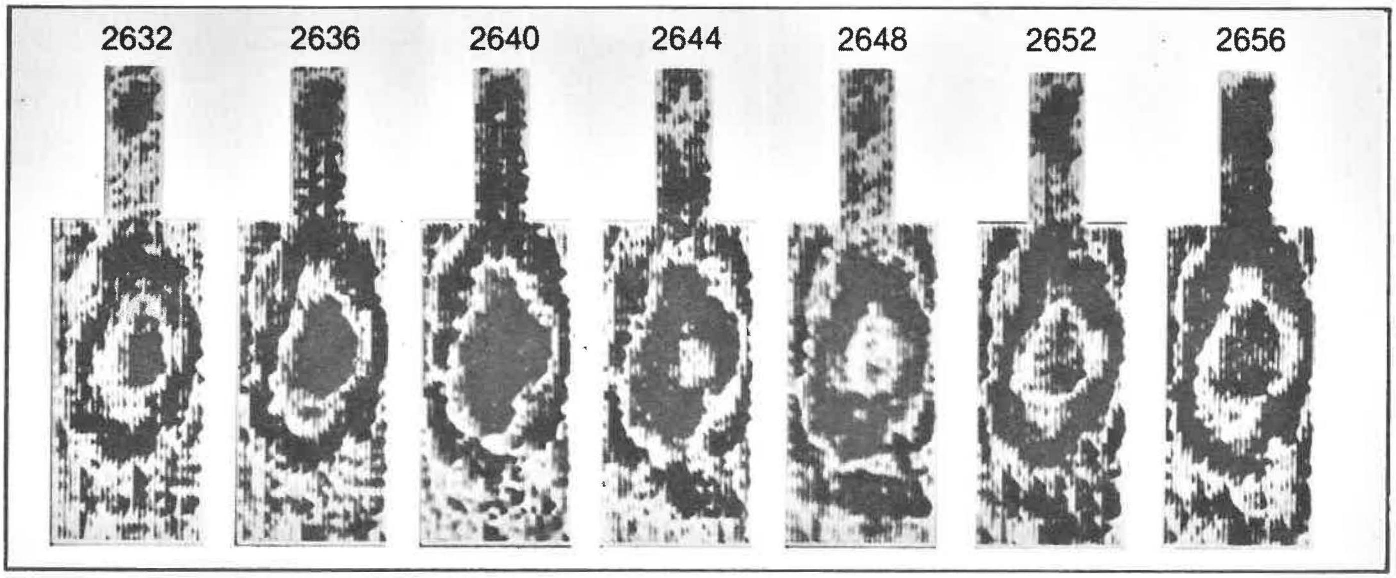


Figure 50

Typical Isotime sections, 4 msec apart from 3D Reflection Seismic Survey

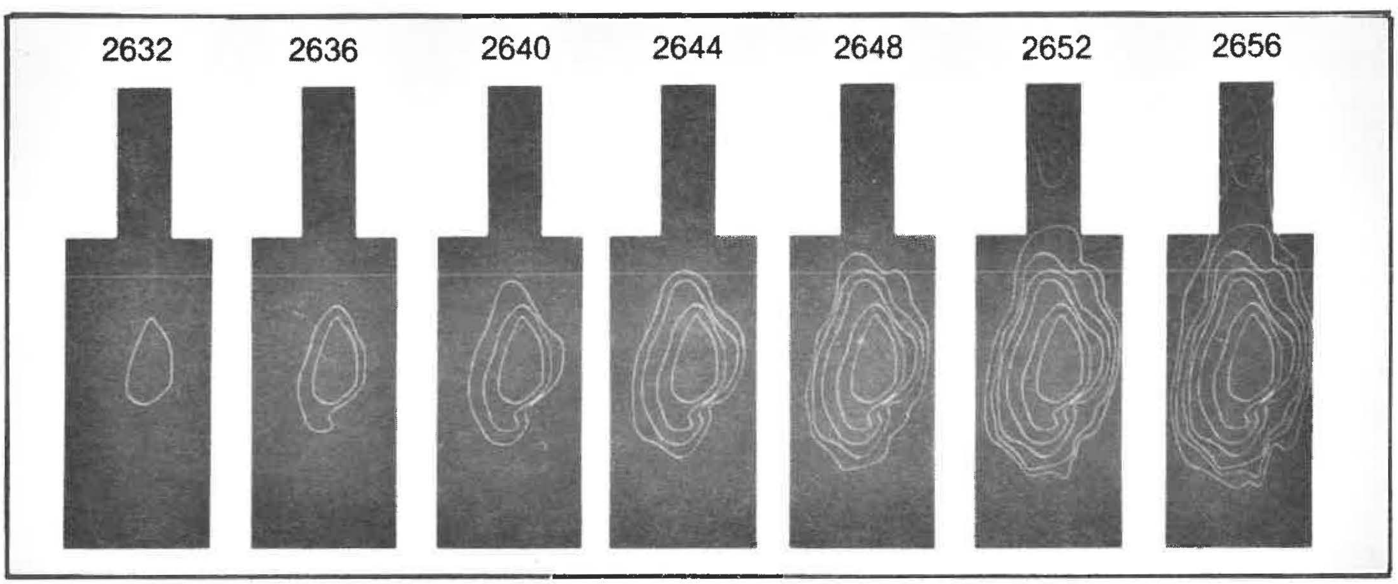


Figure 51

Contours Drawn for each Isotime section for 3D Reflection Seismic Surveys

zontal shape of the reflections, in "layers", is obtained, and the collection of these has the appearance of a three dimensional map. Any number of these can be prepared, and at any time interval. See Figures 50 and 51.

c) The other product of the method is also very important. The 2D deep reflection seismic surveys always contain a fundamental ambiguity when dip exists in the reflecting formations. It is not possible to determine where reflections actually come from when ordinary 2D profiles are interpreted, unless there is a high density of coverage. The 2D migration in time or depth cannot resolve this problem adequately. The 3D data lends itself to the correct migration of reflections because the ambiguity in the direction of the dips no longer exists. This leads directly to the accurate delineation of the known reservoir and greatly reduces the risk of drilling dry holes.

Chapter 12

Sea Ice and Offshore Surveying

The presence, absence, or motion of ice is an overriding factor in offshore surveying operations off Canada's east and Arctic coasts. It limits the mobility of survey vessels, makes the establishment of permanent bottom-mounted platforms impossible, and creates extreme hazards for the installation of pipelines, well head valves or other equipment on the ocean floor, where icebergs may scour the bottom. Also, ice limits the range and reduces the accuracy of some electromagnetic distance measuring instruments (see Chapter 7).

Classification of ice commonly found in waters along Canada's eastern seaboard, according to internationally accepted terminology (Sea Ice Nomenclature of the World Meteorological Organization), is primarily based on the following two definitions:

> *Sea ice* is any form of ice found at sea which has originated from the freezing of sea water.
>
> *Ice of land origin* (glacier ice) is ice formed on land or in an ice shelf, found floating in water or grounded.

A complete manual of ice terminology, classification, standard ice reporting codes and ice reconnaissance practices and procedures used in Canada is available from the Atmospheric Environment Service of the Department of the Environment under the title MANICE.

In general the hardness and toughness of sea ice increases with age due to the gradual reduction of brine cells within the ice.

Ice Conditions in Hudson Bay

Because of its inland location and its latitude, Hudson Bay is ice covered for a longer period than it is open water. Freeze-up is a lengthy process because of the great size of the bay, but ice is plentiful from early November until mid July, and open water only occurs from mid August until mid October.

The first ice formation in the bay is usually in late October in the coastal inlets in the northwestern sector, but in some seasons there may also be a simultaneous development in the cold waters of Foxe Channel in the northeast portion. As the weather grows progressively colder, the ice spreads southward along the shore more rapidly than it extends seaward.

During the winter a 5-10 mile belt of fast ice develops in most sectors and in addition it is not unusual for the whole area south and east of the Belcher Islands to be covered with fast ice. Thickness grows from 75 to 90cm on 1 January to 150 to 180 cm by 1 May in this fast ice.

Outside the fast ice, the bay is nearly filled with drifting pack ice which moves about in response to the wind. In the sub-zero temperatures of January, February and March any leads soon refreeze, only to be disrupted by the other ice motions. In this manner a variable pack is built up composed of ridges and hummock areas of new, young and first year ice that is somewhat thicker and rougher in the southern areas because of the mean wind flow from northwest to southwest.

As temperatures rise in May and June, refreezing no longer occurs after the ice has been displaced by the winds. The normal progression of clearing is for the pack to retreat southward from the Chesterfield Inlet — Southampton Island area and westward from the Quebec side of the bay during the first half of July.

In August the ice covered area continues to contract and the pack will often separate into a few large patches before melting completely in the second half of the month. Intrusions of ice from Foxe Basin may develop in the northeastern sector at any time from late August until freeze-up.

Ice Conditions in Hudson Strait

The ice of Hudson Strait is mostly formed locally but winds and currents can carry floes from Foxe Basin and Foxe Channel, or from Baffin Bay and Davis Strait into the area. The Foxe Basin ice is of one winter's growth – first year or young ice – almost exclusively, and is distinguishable by its extreme roughness and a discoloured appearance. The Baffin Bay ice can include numerous old floes, mostly if the preceding summer in Baffin Bay has been a cool one, but first year ice is most common.

Freeze-up in this area usually begins in late October and ice formation progresses eastward through the strait to cover the whole area by late November. The ice grows to 60 to 75 centimetres by 1 January and to 1.5 to 1.6 metres by mid May.

Because of strong tidal currents and frequent gales, the ice in the offshore areas is in constant motion throughout the winter. Leads form and close, new and young ice is added to the thicker floes and of course ridging, rafting and hummocking are continually taking place. There is commonly a flaw lead along the Baffin coast.

In May leads become more persistent as temperatures rise and the rate of refreezing is reduced. Complete clearing of the sea ice usually develops by mid August and for the remainder of the shipping season, icebergs and the intrusions from Foxe Basin are the only potential hazards.

Ice Conditions on the Labrador Coast

The ice formed in this area is partially of local formation and partially "imported" from Hudson Strait or from the Davis Strait-Baffin Bay area. In addition to the pack ice, numerous icebergs from West Greenland are a navigational hazard. The locally formed ice is, of course, in the new, young or first year ice category and the same is true for Hudson Strait ice; since both areas clear completely every summer. Baffin Bay on the other hand may not clear, and as a result, second year and multi-year ice can intrude into the Labrador area during the late

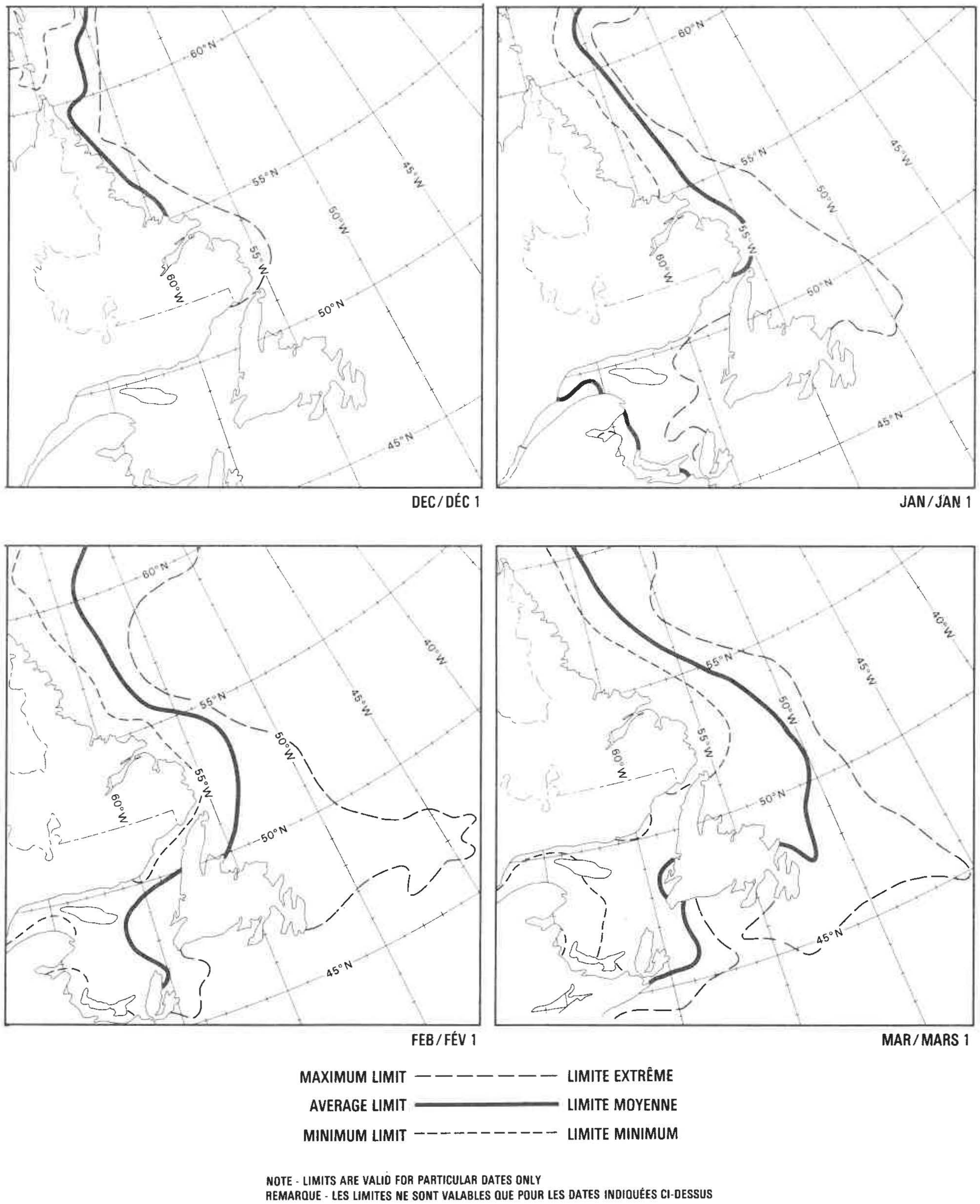


Figure 52a

Average Extent of Sea Ice off the Labrador and Newfoundland Coasts, 1964-79 (December — March)

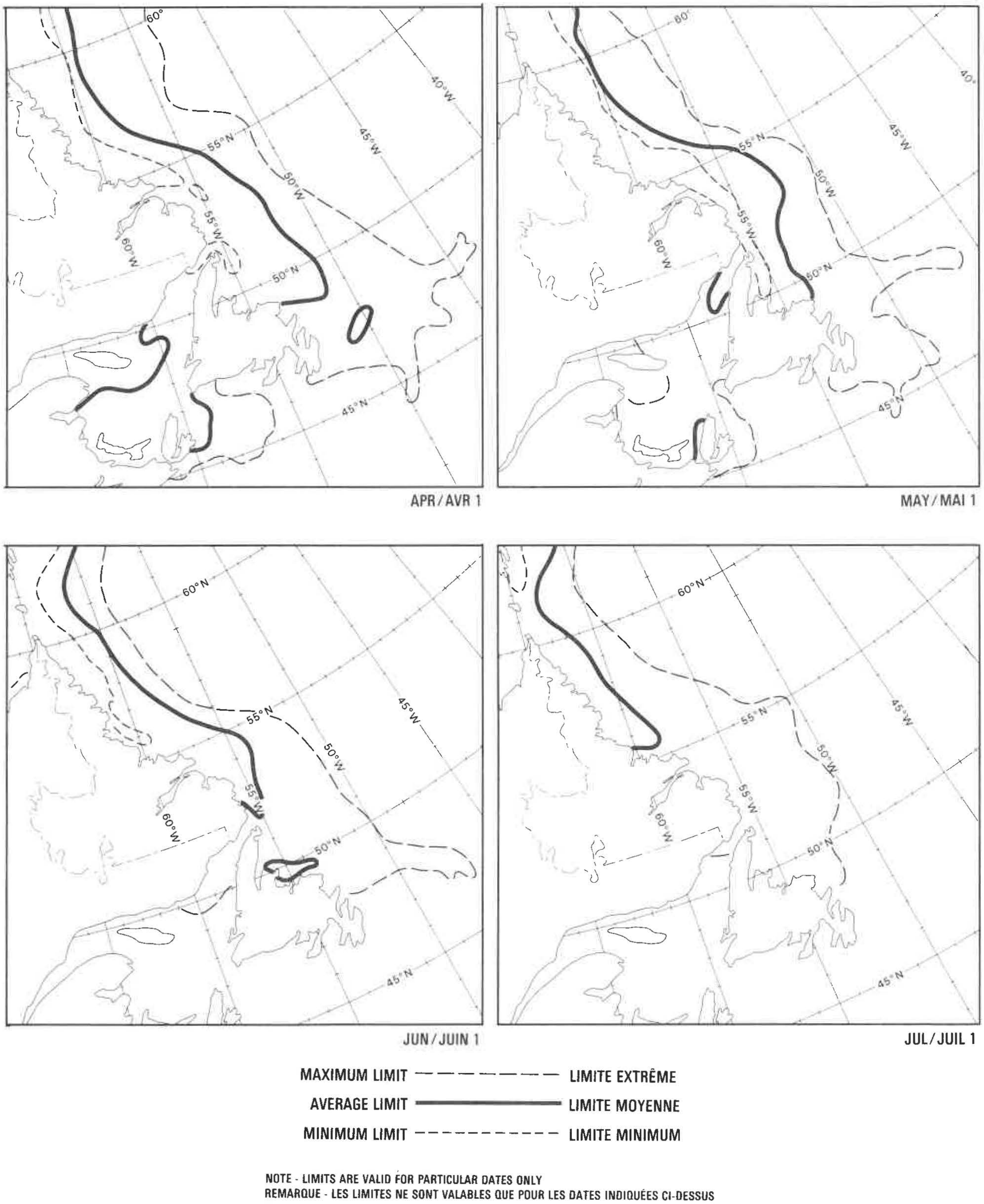


Figure 52b

Average Extent of Sea Ice off the Labrador and Newfoundland Coast, 1964-79 (April — July)

winter and spring months, as it is carried south by wind and current. Such occurrences are not common and when they do arise, the old floes are well dispersed among the pack, resulting in usually hard floes being encountered even in South Labrador and Newfoundland waters.

During December the offshore pack ice spreads seaward and drifts southward in response to wind and current. Motions of 20 km per day are not uncommon but an average of 10 km is probably maintained.

Fast ice fills the bays and inlets along the coast during the winter and becomes particularly extensive from Cape Harrison to north of Nain, (latitude 57°N). In response to wind variations, a flaw lead can often be found between the fast ice and the offshore pack and although it eventually may refreeze, the moderate temperatures compared to those of Hudson Bay mean that a closing of the lead as the winds change is more likely than rapid refreezing.

During the winter the pack becomes more and more extensive and may reach 200-300 km in width before melting begins. Obviously the ice thickness of the pack is not only the result of local temperatures, as the southward drift induced by winds and current can bring ice from Davis Strait as far south as Groswater Bay in February, and thicknesses there can reach 1.5 metres.

Melting begins in southern Labrador waters in the last week of April, reaches mid Labrador in late May and Resolution Island in mid June. Clearing of the pack ice on the Labrador coast is a gradual process as melting progresses northward. The pack slowly becomes narrower, it may separate into large patches and the concentration falls as any new and young ice is completely melted. By mid June the southern edge has cleared Belle Isle; by the first week of July it is north of Hamilton Inlet; and by the end of the month, it is in the Cape Chidley area where patches of ice may linger into the first week of August. For the remainder of the season, open water prevails until the fall freeze-up begins. The extent of sea ice off the Labrador and Newfoundland coasts from December to July is shown in Figure 52.

Ice Conditions on the East Coast of Newfoundland

Two kinds of ice are encountered in this area, the dramatic and picturesque icebergs of glacial origin and the prosaic sea ice (frozen salt water) which has a much more important effect on navigation. The sea ice forms in the coastal waters from Fogo Island northward and is carried down the coast by wind and current. It sometimes rounds Cape Race but its more common path is south or southeast onto the northern part of the Grand Banks of Newfoundland.

Sea ice begins to form on the coast of southern Labrador in mid December and spreads south to Newfoundland waters in early January. It gradually spreads seaward and southward to reach Notre Dame Bay and Fogo Island in late January. In most years the ice pack drifts off to the southeast from Cape Freels, and the Newfoundland coast south of Cape Bonavista has only loose floes for brief periods.

Sea ice which forms early in the winter in the waters of northern Newfoundland and southern Labrador grows to a maximum of about 0.6m during the winter, and much of it is carried southward by wind and current to the waters east and southeast from Cape Bonavista. The floes which remain, in the White Bay area for instance, can reach 1m. There is, in addition, a southward drift of ice from central Labrador which replenishes the supply of ice east of Belle Isle.

These floes may reach 1.2 m in thickness. By spring some of the sea ice found off Newfoundland may have originated as far north as Davis Strait or even Baffin Bay. Because Baffin Bay does not completely clear of sea ice every summer, a few floes of old ice may appear in the Belle Isle/Newfoundland waters late in the season.

Retreat of the ice begins in late March but changes are relatively slow at first. By the end of April the southern edge has usually retreated to Bonavista Bay. In May, the rate of melting increases and the pack has usually retreated to southern Labrador waters by the final week in the month. This retreat releases many of the icebergs carried south by the Labrador Current and their numbers, in Newfoundland waters, reach a peak at this time.

Ice Conditions on the South Coast of Newfoundland

This area is usually considered to have open water on a year-round basis, for any ice intrusions are brief and affect only a limited area. Despite this, some local formation during cold spells does occur in the inner reaches of Placentia Bay, Fortune Bay and the smaller inlets to the west.

Offshore ice more often occurs as the result of the eastward movement of Gulf of St. Lawrence ice, which has been known to penetrate as far as Saint-Pierre and Miquelon. East Newfoundland ice may round Cape Race and penetrate as open pack ice as far westward as Saint-Pierre and Miquelon. As a rule, these two drift patterns cannot occur simultaneously.

Icebergs

Sea ice constitutes a hazard to navigation because of its extent and thickness, and consequently it is of vital importance in determining usefulness of routes and accessibility of ports. Icebergs, on the other hand, are major local hazards wherever they occur, but they do not actually prevent ship passages as the sea ice does. Icebergs make the establishment of a permanent oil rig impossible, and they are a severe constraint to the operation of floating oil rigs which must be able to leave a drill site on short notice with the ability to return and continue drilling.

Most of the icebergs found off the east coast of Canada originate in Baffin Bay and by far the greatest proportion of these come from west Greenland glaciers, specifically from the area between Disko Island (70°N) and Melville Bay (76°N). They are carried in a counter-clockwise direction around Baffin Bay and move southward through Davis Strait to the Labrador coast and Newfoundland waters.

Icebergs vary widely in size and shape, both above and below the water. The International Ice Patrol has reported heights as great as 80 m and lengths up to 517 m, but the average height is about 30 m and weight about 204 000 tonnes. The height/draught ratio of icebergs is highly dependent upon iceberg shape.

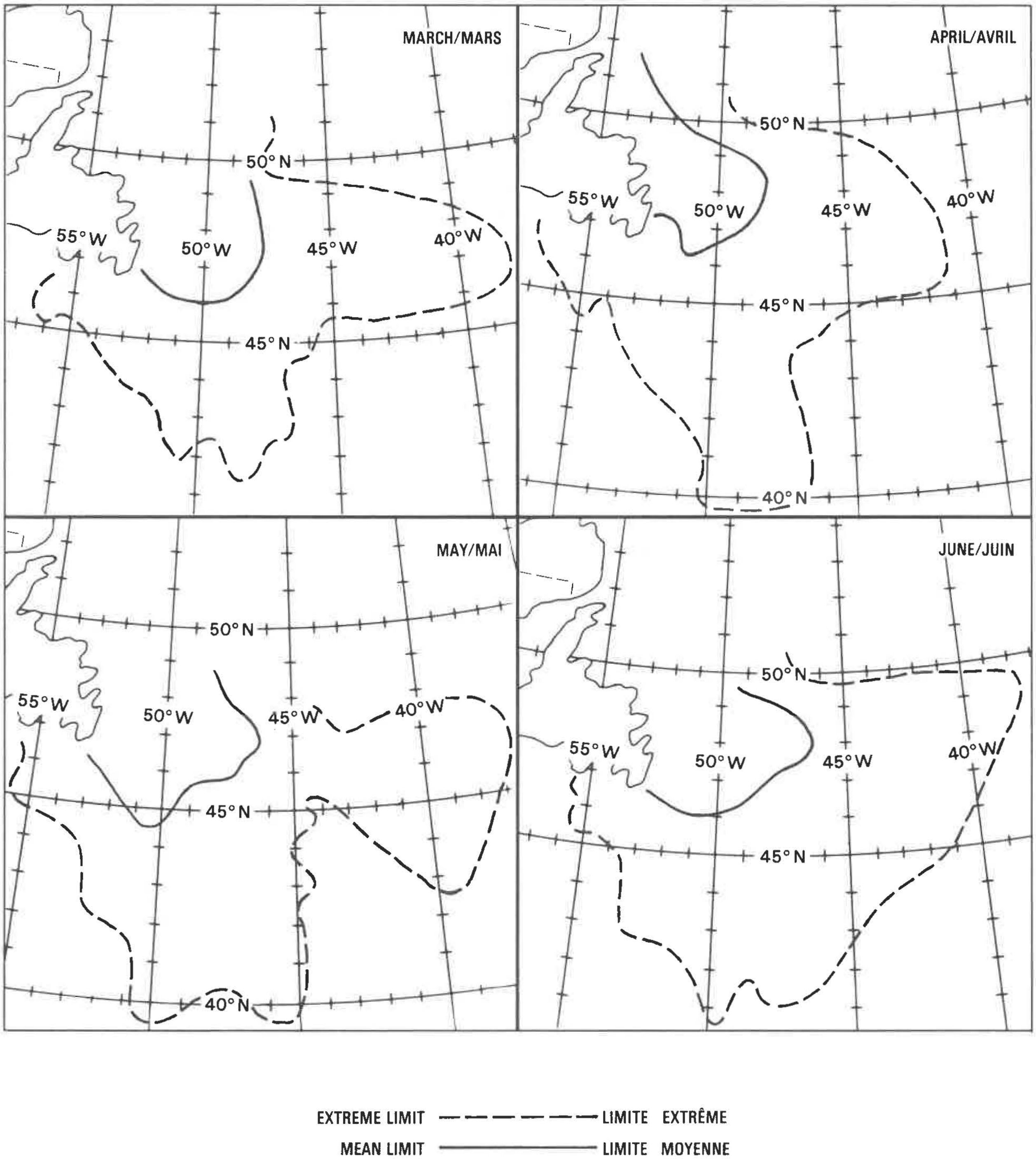


Figure 53

Extreme and Mean Limits of Icebergs Offshore from Newfoundland, 1959-75

Icebergs float with seven-eighths of their mass under water; however, this does not mean that their draught is seven times their height, since shape is very important. From actual measurements it has been found that the average height/draught ratio varies from a 1:1 proportion in "dry-dock" types of bergs, to 1:5 in tabular, steep-sided bergs.

Icebergs have been reported south of Newfoundland in all months of the year, but they are most numerous in April, May and June and least numerous in the months from September until January inclusive.

The first icebergs are usually sighted on the eastern edge of the Grand Banks of Newfoundland in late February or in early March. Greenland produces 10 000 to 20 000 icebergs each year but the number that reach the waters south of 48°N varies considerably from year to year. Few icebergs drift south of 40°N and these do not penetrate far, as is evident on the charts of monthly iceberg limits (see Figure 53).

The drift of icebergs is related to both current and wind. Since seven-eights of its mass is under water, an iceberg is affected by water currents from the surface down to its draught. The resultant force carries the iceberg along with the integrated current. Since it is also exposed to wind, an additional but smaller drift vector is added which tends to move the iceberg downwind. The final result is a motion which takes both these forces into account, and icebergs can move against or across the wind as well as down wind or at small angles to it.

Ships equipped with radar in good working order, should be able to pick up an iceberg at a sufficient distance to avoid a collision. However, in certain sea conditions, small icebergs and growlers, of sufficient size to damage a ship, may be missed.

Ice Scouring

The effect of wind on sea ice causes it to move and to form ridges and hummocks. The thickness of the ice is then increased not only above the surface but also in the depth under water. The wind pushes these ridges as well, and when shallow water is reached, the ice then ploughs furrows in the bottom, often called scours. The normal procedure in drilling from drill ships in the Beaufort Sea, where scouring is very evident, is to dredge out a "glory hole" a few metres deep and several metres across, so that the bottom mounted equipment is below the level of the surrounding sea bottom.

The icebergs that float down the east coast of Canada also produce scours. Damage to cables from icebergs off Greenland has occured at depths of 230 metres. Therefore, precautions must be considered for sea floor-mounted equipment and plugging drill holes at that depth and less. A large part of the continental shelf along the Canadian east coast is subject to iceberg scours.

Arctic Shipping Regulations

The thickness of the ice at any one location varies throughout the year. The ice moves in response to wind and currents to form leads or converse ridges or hummocks. Ice can be of different qualities, young or first year ice that is easy to break, or the much harder second or multi-year ice. To identify the types of ice, the waters of the Canadian Arctic, north of 60°N, are divided into 16 control zones (see Figure 54). The number of the zone is the approximate rank of ice severity. The Shipping Safety Control Zones Order, the Arctic Shipping Pollution Prevention Regulations and the Arctic Waters Pollution Prevention Regulations specify what class of ship may enter each zone during specific periods of the year. Most of the Canadian Coast Guard heavy icebreakers may enter the Canadian Arctic Waters as early as June 5 (Zone 16) and leave as late as January 31 (Zone 15), but may be in Zone 1 from August 20 to September 15 only.

Icebreakers

The Canadian Coast Guard has a fleet of icebreakers of various sizes used to maintain shipping lanes in southern areas of Canada during the winter and to maintain lanes for re-supply vessels for northern communities in the summer months. The ships also have the duty of maintaining navigational aids and are responsible for search and rescue operations. Seldom are the ships dedicated to a single user's purpose. For this reason, Dome Petroleum initially leased the CCGS John A. MacDonald and then had the Canmar Kigoriak, built so that they would have a dedicated icebreaker for their requirements in the Beaufort Sea.

TABLE XI

Heavy and Medium Icebreakers of Canadian Registry
(abstracted from Canadian Merchant Fleet 1981 Annual List)

	Gross Tons
Heavy Icebreakers	
CCGS Louis S. St. Laurent (Arctic Class 4)	10908
CCGS John A. MacDonald	6186
CCGS John Franklin (Arctic Class 3)	5910
CCGS Pierre Radisson (Arctic Class 3)	5910
CCGS d'Iberville	5678
CCGS John Cabot	5234
CCGS Norman McLeod Rogers	4179
CCGS Labrador	3823
CANMAR Kigoriak (Arctic Class 3)	3642
Medium Icebreakers	
CCGS J.E. Bernier	2457
CCGS Griffon	2212
CCGS Sir William Alexander	2154
CCGS Camsell	2022
CCGS Montcalm	2017
CCGS Sir Humphrey Gilbert	1931

The Canadian Coast Guard has designed and intends to build an Arctic Class 8 icebreaker (39 000 tonne, full load). The earliest commissioning of such a ship would be 1989 if approval is obtained now to build it. Such a ship could operate in Zones 2 to 16 (Figure 53) all year and in Zone 1 from July 1 to October 15 only.

As a comparison, the United States Coast Guard has two icebreakers that are slightly larger than the CCGS Louis S. St. Laurent, and 13 of the USSR's fleet of over 50 icebreakers are larger than the CCGS Louis S. St. Laurent. Two of these are almost twice her tonnage and three are nuclear powered. Table XI lists many of the large icebreakers of Canadian Registry.

Ice Drilling Platforms

About a dozen wells have been drilled in the Melville Island area since 1976, by mounting the drilling rig on fast ice. Because of the mass of the rig, the thickness of the ice had to be built up, by flooding, to six to eight metres to achieve sufficient buoyancy. An area of several hectares is usually flooded for the rig site and areas of less thickness are flooded for the accommodation and the fuel cache, etc. Work usually starts in early December and ceases by early June.

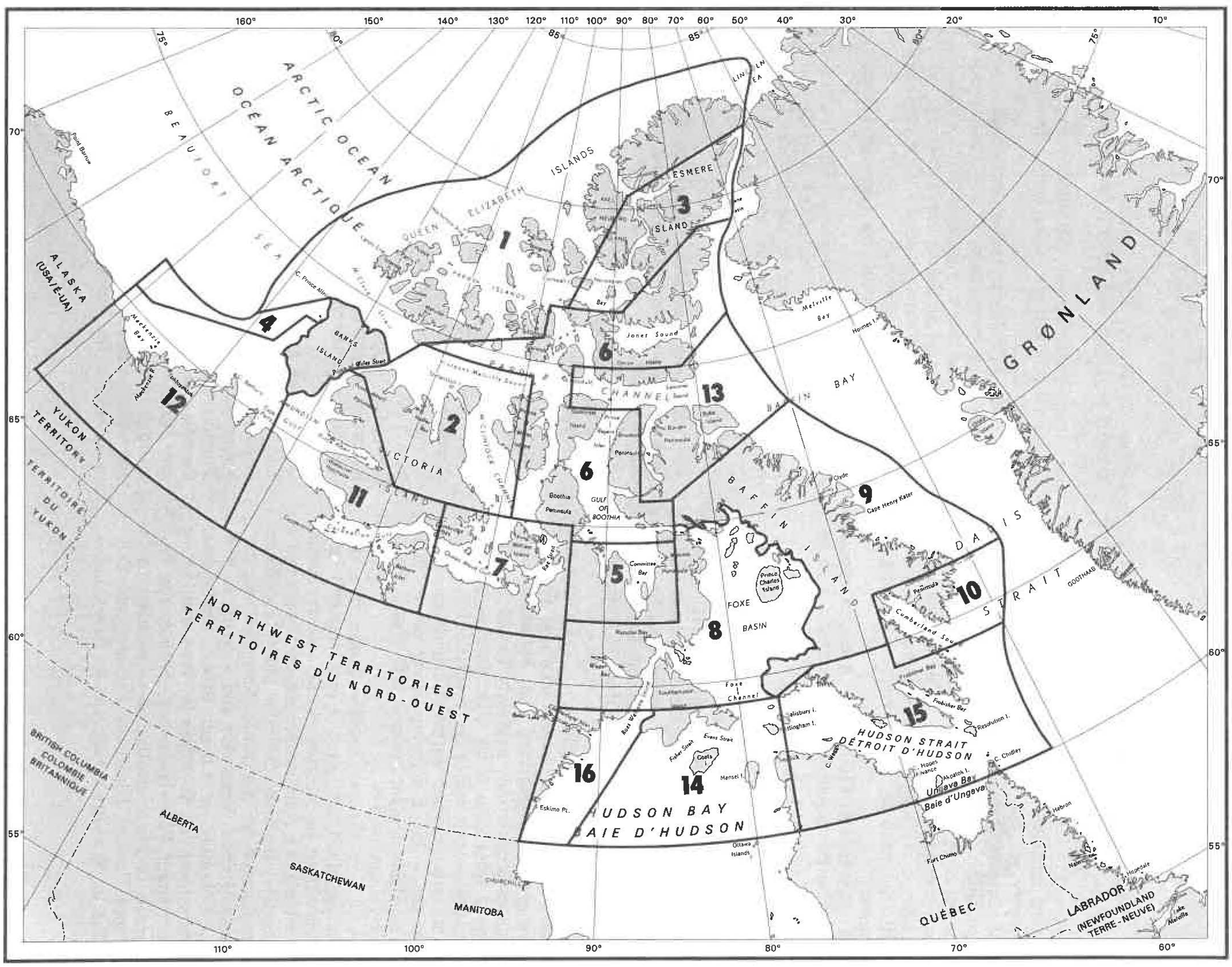


Figure 54

Arctic Shipping Safety Control Zones (North of 60^0)

Appendix A

Offshore Surveying for Petroleum Developments Outside North America

by
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Offshore Survey Regulations

While survey regulations have long been a feature of cadastral surveying activity in many countries of the world, rarely has it been thought necessary to extend them to cover the offshore, or even the close inshore. So called legal surveys for the offshore do not exist outside North America. Despite the considerable offshore exploration and engineering development activity which nowadays characterises the petroleum industry, only a handful of nations seek to apply any regulation to the conduct of survey work offshore or, more particularly, to the definition of positions at sea. Indeed survey is accorded so little consideration by the petroleum exploration administrations of national governments that seldom is there any rigorous definition of offshore licence boundaries. The operating companies are left to assume what they will about the bare latitudes and longitudes or grid values which feature in legal documents related to such areas. Further, the quality of the hydrographic, geophysical and positional survey work subsequently undertaken in licenced blocks is left entirely to the discretion of the operating company, which then undertakes the survey work which it feels it needs to further only its immediate work requirements. Shortcomings may be further compounded by the absence within the operating companies themselves of any survey expertise, with the administration of work undertaken by contracted survey companies being merely the part time occupation of an interested, though usually only partially informed staff member from another discipline. Such a situation causes the operating company few immediate operating problems. No effort or expenditure need be made which (in ignorance perhaps) it feels is not absolutely necessary.However, there are undoubtedly, losses to the company itself, other companies which may subsequently become involved, and to the host country. The data acquired by the host country relating to its offshore is not consistently reliable. It cannot maintain an orderly and fully documented record of the survey and positioning aspects of the exploration activity.

Offshore Survey Data

Offshore survey work within the field of the land and hydrographic surveyor embraces both the acquisition of data pertaining to the seabed and water body, where it overlaps the role of the oceanographer, and the more predominant activity concerned with the determination of position, which mutually relates every stage of mineral exploration and production operation. The quantity of data in both categories accumulates within the archives of the operating companies at a great rate. This has been particularly so over the last decade when host governments have, through ever more stringent licencing conditions, exerted considerable pressure on the companies to perform heavy work commitments within a restricted time scale.

The survey data, both physical and positional, generally remains with the operating company. Some physical data relating to the sea bed and oceanographic conditions may be passed to interested national research agencies if they are active in pursuing it or, occasionally, in participating in the work done to acquire it. In a few countries, for example Norway and Britain, environmental considerations require sidescan surveys before and after drilling work. Other countries without active fishing interests or lobby groups are less concerned but usually require the removal of major obstructions.

Positional data may be transferred in map or condensed digital tape form to partners, traded or sold to other companies along with the seismic or well data to which it relates, and passed to the national body regulating the offshore mineral exploration/exploitation activity. Unlike the situation in Canada, rarely does this body also have national responsibility for survey, so seldom are any survey regulations applied in the conduct of survey and positioning work offshore. Unless and until the national survey body becomes interested and is given statutory responsibility, this situation is likely to continue in most countries of the world.

Various other bodies may require notification of positional data relating to navigational, fishing or anchoring hazards, such as drilling rigs, platforms, or sea bed hardware of various types, but this need not consist of more than bare geographical co-ordinates or a small scale chart and is required merely to advise other ocean users of their need for caution in the vicinity of such structures. All well co-ordinates have to be provided to the mineral exploration authority – normally in the form of a report on the positioning of the drilling vessel by the positioning contractor. But, the nature of the positioning method or the geodetic criteria applicable to the coordinates is seldom predetermined. The operating company is left to undertake what it feels to be necessary. The following are some examples of offshore petroleum surveying procedures in various areas outside North America.

The North Sea

In Northwest Europe, particularly the North Sea, there was early agreement by the maritime nations in the 1960's that all offshore boundaries and positions should be defined on the International Ellipsoid related to European Datum 1950

(ED50). The realisation of that coordinate framework offshore then depended on radio positioning systems — principally Hi-fix — the shore stations of which were, as well as could be determined at the time, expressed in ED50 terms. Seismic survey positional data, well locations and pipelines were all surveyed, often with only two lines of position, and expressed in these terms. As exploration activity was extended beyond the areas with acceptable 2 Mhz radio positioning coverage. Alternative methods of position determination were used. It was also realised that shortcomings in the primary triangulation networks did not adequately permit consistent definition of ED50 on the perimeters of the North Sea, thus leading to consequent inconsistencies in the positioning effected from both sides. Doppler satellite position determination became available and its use to confirm drilling locations and to identify systematic radio positioning errors became and still is standard practice. Recommended specifications for this work were defined by the United Kingdom Offshore Operators Association. More recently, the Ordnance Survey has been invited to participate and has contributed to an updated modification of the suggested procedures. One confidently anticipates that this industry/national survey agency cooperation will lead to further recommended standard procedures along the lines of those prevailing in Canada. The Ordnance Surveys have recently undergone a comprehensive review and amongst other things the Review Committee stated:

> "We conclude that there is a long-term need, arising mainly but not exclusively from the growing interest in exploitation of undersea resources, for an offshore geodetic network. The approximate positioning now being undertaken by the offshore industry will not be sufficiently accurate in the longer term for this purpose, although it may well provide a useful base on which to build. Prima facie there is a case for the Ordnance Survey, as the custodian of national geodetic archive, to undertake this compilation of an offshore geodetic archive as an extension of its existing land-based geodetic work, but further discussions will be required among the various parties involved as to the allocation of responsibilities. We recommend that the Ordnance Survey initiate such discussions."

The recommendations of the Review Committee have not yet been fully accepted by the Government and it is by no means certain that the degree of commercial performance that Government appears to be seeking from the Ordnance Survey will permit it to extend its activities into a new area without ensuring that the cost of doing so can be covered, presumably by the oil industry. The industry has so far managed its operations without direct Ordnance Survey involvement though reliant on the Ordance Survey for land station co-ordinates and advice on Doppler transformations. While the industry may continue to operate quite satisfactorily under such ad-hoc arrangements there are signs that closer liaison between the exploration operators, the Ordance Survey and the Department of Energy may lead to a set of recommended survey procedures and a well defined geodetic position reference system for the United Kingdom Continental Shelf.

Meanwhile in Dutch Waters, the Hydrographic Services of the Royal Netherlands Navy has taken the lead in Holland in collating a comprehensive report on the definition of offshore positions in the Dutch North Sea. This may also lead to suggested proccedures and regulations for future activity by exploration operators.

There is at present no obligation on the part of any operator to follow the United Kingdom Offshore Operators' Association guidelines or even to use a Doppler receiver at all if it is satisfied it has an adequate definition of well position through the radio position system. Nowadays this is usually Pulse 8, or in the southern North sea and English Channel, Syledis. Seldom are two radio positioning systems employed and this no requirement that two should be used. However there is now a normal specification of redundancy of lines of position from the system used.

Once fixed, an exploration well does not necessarily retain the coordinates then derived but in the light of new transformation data or revised shore radio beacon coordinates, these may be revised to what it is expected to be nearer the truth. Such changes will usually be small and the final, more accurate values have so far been of interest only to the oil companies themselves. So far the Ordnance Survey has not required that they be notified of any offshore coordinates; the Hydrographic Department requires them only to an accuracy to enable their depiction on the 1:200 000 chart. The Military Survey has only acquired them indirectly and without any concern over their reliability. Indeed, these bodies have only been closely involved in offshore position derivation when assisting in the definition of the position of a platform adjacent to the UK-Norway median line some years ago.

Further, platform positions in the North Sea are determined according to operating company requirements, the main encouragement to accuracy and consistency being the need to use them as base stations for microwave positioning systems, in turn used for precise 3D seismic surveys, further engineering development operations, and for dynamic positioning input to local deep saturation diving operations. There is no standard for marking or defining survey stations on platforms and no consistent method for establishing their coordinates, though for a group of intervisible platforms such as those of the East Shetland basin, a terrestrial network of distances and directions has been observed by Shell, the predominant operator, to augment the Doppler points, and an adjustment performed. Here, the initial network remained static and based on a single 3D Doppler fix. Additional platforms set in 1981 may possibly lead to a reappraisal of the survey point positions but it is not expected that such a reappraisal will result in changes of significance for the Syledis and Miniranger positioning systems. One may speculate on the significance of positional shifts of a few meters on utilisation agreements affecting fields which stradle licence boundaries, but this is not generally a problem which greatly exercises oilfield negotiators. In other areas of the North Sea, other small Doppler networks have been observed through combined operator action, usually to improve the accuracy of platform mounted base stations of microwave positioning systems. The Ordnance Survey and other European Survey agencies have participated in some of these projects.

Gabon Coast

Gabon has no overall national geodetic network, but rather, a series of separate but connected networks. Offshore positioning on its continental shelf depends on a line of coastal stations established every 5-10 km by second order tellurometer traverse, linking these together and providing the base stations for Miniranger, Syledis or Maxiran systems. This work was undertaken at the outset of offshore exploration by the Elf Oil Company at the time they held the entire Gabon offshore under exploration licence. Subsequently, as Elf relinquished acreage, other operating companies have arrived to work and have been happy to utilise the Elf control stations all of which were well marked by robust concrete pillars, some 10 feet tall. Thus all survey positions offshore Gabon, and radio positioning base stations on many platforms are related to this traverse, itself given absolute position from an intial astro-fix which is adopted as the national datum point (Shell subsequently employed Doppler satellite fixes for land operations and may have included stations of the coastal traverse). Positions offshore are reported to the Ministry of Petroleum but no survey regulations pertaining to work offshore are in force.

Tunisian Coast

Tunisia has a well conditioned country-wide primary triangulation network with listed coordinates evaluated by IGN Paris on a local Carthage Datum and modified Clarke 1880 ellipsoid. The mapping projection onshore is a 3 zone Lambert, each with two standard parallels.

No survey regulations apply to the offshore, and operating companies are free to determine positions and display data in map form by whatever means each considers best. In the past, some operators used Doppler satellite and sonar as the sole means of positioning seismic surveys, mapping the data on Broadcast Doppler datum or making an arbitrary transformation to European datum by the standard three translation shifts then published. However, current practice by all operators is to insist that their positioning contractors use shore based radio positioning systems whose base stations are surveyed from the primary or secondary triangulation network, and are thus evaluated in terms of Carthage Datum. By means of Doppler satellite observations at a few primary triangulation points adjacent to the offshore operational areas, datum shifts have been evaluated with which to correct earlier seismic mapping and drilling rig fixes. Now, most offshore positioning is by Syledis using a selection of coastal base stations whose coordinates are consistent and quoted in terms of Carthage Datum.

The map projection used to display the offshore data is again left to the operator — those working inshore, like BP, staying with the Lambert of the land maps but others working further offshore where the Lambert graticule is quite convergent, preferring to use the UTM.

Licence boundaries are expressed in the operating contracts with the oil companies in terms of 2 minute latitude and longitude steps but it is again left to oil companies to assume that the coordinates are to be referred to the Clarke 1880 ellipsoid and Carthage Datum of the land geodetic system. There are still no regulations in respect of either methods or presentation of surveys offshore.

United Arab Emirates (Persian Gulf)

The UAE is as yet without a national survey, unified control network, or recognisable national survey department. Such survey control as exists on land, offshore islands and platforms, is the result of effort by the oil companies and mapping contractors to provide for their immediate needs with a moderate consideration for the longer term. The military and major towns have survey units. The military is slowly assuming the role of a national survey agency and is in the process of organising contracts to produce a national control network and a basic map series. However, the lack of coordination of survey activities within the Emirates results in duplication of effort, for both localised mapping and control.

The principal control is a Trucial Coast chain of third order triangulation originally laid out and observed in the 1960's by a dedicated solitary oil company surveyor. The chain was subsequently strengthened by EDM observations and re-adjusted to an Iraqi (Nahrwan) datum of the Iranian Oil Services Triangulation network, using a cross-gulf link at the Straits of Hormuz, and thence also tied to European Datum. Present plans are to augment, extend and reobserve this Trucial Coast chain, establish some dozen Doppler satellite points as zero order control and link the whole system to the Saudi Ain el Abd datum which probably will become the adopted datum for the whole Arabian peninsula.

Offshore Abu Dhabi, the principal operating oil company, serviced by BP surveyors, carried the triangulation through a series of offshore islands and producing fields and, by rudimentary translocation, established additional Doppler control to support the hanging triangulation chain. By various means, ranging from Decca Navigator to the currently predominant Syledis and localised in field Trisponder and Miniranger, all positioning offshore has been related to the Trucial Coast triangulation and expressed in terms of Nahrwan Datum (Clark 1880). The main onshore oil company, also serviced by BP surveyors, has also maintained a consistent predilection for this system. By virtue of their joint influence, companies which arrived on the scene later have followed suit and used the control data established earlier. In this way, a consistent basis for the definition of offshore positions has been maintained in the absence of any national control or interest in the problem. It is equally apparent that no regulations have had to be satisfied in the conduct of survey operations and all records of the work reside only with the operating company and its parents. The implications of the new survey control network on offshore operational survey work are likely to remain uncertain for several more years, but it is probable that the positions of all permanent structures there may ultimately have to be redefined.

Brazilian Coast

As befits a large wealthy country with an expanding economy, Brazil has a well established national survey institute and except for the Amazon Basin, an overall network of triangulation chains, some not very well preserved but including one running the length of the Atlantic coast. This allows a ready basis for establishing coordinates for radio positioning chains to be used offshore. However, neither the national geodetic survey institute nor hydrographic institute plays a part in Brazil's offshore oil exploration which is wholly administered by the state oil company Petrobras. Prior to the arrival of the foreign oil company explorers, Petrobras conducted all its own exploration work and established all provisions for survey. Beginning land work in the Northeast of the country they established their own datum point (Aratu) for surveys, independent of the then used control and mapping datum of the national survey, and have extended its application to the rest of their operations both on and offshore. Foreign oil companies have been obliged to adopt the same system and the coordinates of a series of shore base-stations which Petrobras had previously employed for their radio positioning chains and which were fixed by a long coastal tellurometer traverse. The relationship of some of these stations to both the national network and broadcast Doppler is sometimes obscure and somewhat inconsistent. The latter depends on a series of early 3D Doppler fixes on the primary network which do not demonstrate a very high degree of consistency.

All reporting of survey activity by the operating companies is given to Petrobras which, though having its own small operational survey unit, merely takes note and leaves the operational methods to the discretion of the companies. Their primary survey concern is to ensure adequate positional consistency between the various stages of exploration effort. Data inherited from Petrobras itself, sometimes for historical reasons, is of uncertain positional derivation and integrity.

China's Coast

As for many other aspects of China, its survey remains inscrutable. When western oil companies were permitted to begin offshore exploration activities in 1979, the operating groups made program proposals, including those for positional control, to the various Chinese bodies concerned with oil exploration. In early discussion it was apparent that, despite the existence of a unified geodetic control system covering most of the country (Peking Datum, Krassowski ellipsoid), there had been very little survey work offshore and thus little appreciation of modern radio positioning systems and possibilities. A Toran system had, however, been in use in the Gulf of Pohai and it was believed that other military systems were present elsewhere but unavailable for civilian use. The operating companies, BP and Total in the Yellow sea and six American companies in the South China Sea, were therefore free to adopt working methods to suit their essentially reconnaissance programme. Those in the north chose a 4 station 3 pattern Pulse 8 system, while the southern groups selected Argo and Maxiran. The companies had to negotiate for base station sites and then determine their coordinates but without any access to descriptions or coordinate values for nearby triangulation points. The Chinese were requested to survey the sites and provide coordinates of 5 Yellow Sea coast stations while, to ensure internal consistency and a reliable connection to the large Chinese geodetic network, Doppler satellite translocation between stations was employed as a check. The southern Argo and Maxiran stations were initially fixed only by 3D single point Doppler fixes. Subsequently, the southern operators were obliged to convert all coordinates to the Chinese national geodetic system by datum shift translations which the Chinese provided. All companies who participated in the 1979-80 seismic reconnaissance now await the Chinese intentions and regulations for further exploration work. It is not expected that these will be explicit in respect of survey procedures and requirements which will again be left to the discretion of the operating oil companies.

Conclusion

It is apparent from these few examples that the rest of the world has little to teach Canada in the administration of offshore survey work to define position.

Canada's regulations and the guidance provided in the 1975 edition of *Surveying Offshore Canada Lands for Mineral Resources Development*, are unique.

This writer has not encountered similar documents in any other country in which his company has undertaken petroleum exploration operations. The regulations may well be revised to suit changing circumstances in Canada. However, if promulgated to the appropriate regulatory bodies in other countries, they could serve as a pattern for providing recognition of the relevance of proper survey definition and conduct to orderly offshore operations, and also for ensuring that, through an active professional survey unit, all operating companies would follow a nationally determined set of procedures based on a consistent survey system. However, recalling the tyranny which ill-conceived regulations may have imposed on cadastral surveyors in certain former colonial territories, it is equally important to ensure that offshore survey regulations do not unnecessarily extend land systems and accuracy requirements to the offshore. It is important to define the geodetic parameters to be used (normally the same as those on the national land territory); to regulate positional definition procedures (not instrumentation or systems); and to provide a standardised comprehensive method of reporting to one or more national survey institutions where reports can be understood and checked; and the data used for other national purposes.

The thoughts expressed above are those of the author and must not be construed as representing the position of The British Petroleum Company.

Appendix B

Canadian Coast Guard Position Requirements for Marine Aids in the Arctic

To date, Arctic marine activity has been confined to community re-supply, Churchill grain traffic, and some mineral development cargoes. Thus, traffic has been almost exclusively carried in vessels of low ice class within the summer navigation seasons.

The anticipated oil and gas developments at a number of areas throughout the Arctic will require carrier traffic to operate through the Northwest Passage route on a year-round basis.

Planning for the provision of marine services to accommodate this traffic has been complicated by uncertainty in two aspects: the actual level of shipping activity which will ensue, and the date of the introduction of the traffic.

This discussion paper applies to all waters north of the 60th degree of latitude to which the *Arctic Waters Pollution Prevention Act* applies, and to Hudson Bay, James Bay, Ungava Bay, and the Mackenzie River system.

Premises of Planning

1. Subject to paragraphs 2 and 3 below, planning for the necessary resources for marine aids is being developed to respond to the marine transportation activity scenario based on an expectation of:

a) Year round operation of liquified natural gas (LNG) carriers from Bridport Inlet on Melville Island to Eastern Canada commencing early 1986.
b) Year round operation of large crude oil carriers from the Beaufort Sea to Eastern Canada via the Northwest Passage commencing late 1987.
c) Year round operation of LNG carriers from King Christian Island to eastern Canada commencing about 1990.
d) Continuation of seasonal movements of grain out of Churchill at approximately present levels.
e) Moderate growth from present levels in the seasonal movements of minerals.
f) Moderate growth from present levels in seasonal re-supply movements.

2. The program for marine aids shall incorporate sufficient flexibility to enable adjustment to the allocation of proposed resources, if Arctic development occurs more slowly than assumed in the marine transportation activity scenario outlined above.
3. Legislation, requiring ships to fit and use navigational aids, should be coordinated with the establishing of marine aids.

Scope of Service

1. The level of marine aids provided shall be sufficient to meet the objectives of safety, system efficiency and contribution of Federal government objectives. Establishment of the appropriate level shall take into account the cost of provision and maintenance of such marine aids.
2. Those marine aids necessary for navigation to or from any re-supply port, including conventional and electronic, shall be provided to a standard sufficient to ensure an adequate level of safety to shipping.
3. Marine aids for commercial ports shall generally be financed, managed and operated by the primary commercial interest at that port.

Policy on the Provision of Marine Aids

1. Marine aids shall be provided where necessary to ensure an adequate level of safety to shipping or the environment and may also be provided where appropriate for the improved efficiency of marine operations.
2. The provision, operation and maintenance of marine aids shall be the responsibility of the Marine Administration except in the approaches to, and within the limits of, private commercial ports; where the provision, operation and maintenance shall normally be the responsibility of the major private marine interest at that port.
3. Private interests may, where appropriate, contract with the Marine Administration for the provision or operation and maintenance of the marine aids at private commercial ports in accordance with approved Arctic cost recovery policies.
4. Marine aids provided, operated and maintained by private interests shall be in accordance with standards established by Transport Canada.
5. Marine aids shall normally be established only in properly charted areas.
6. Marine aids coverage and service shall be continuous over each designated Arctic shipping corridor during its respective shipping season.
7. The provision of aids to navigation should be conditional upon legal requirements to fit and use complementary navigational aids.

Canadian Coast Guard Position

General Overview of Requirements

Planning for shipborne navigational aids north of 60° north latitude should be directed at making ships as self sufficient as possible using existing systems or systems presently being improved or developed.

It is believed that high performance conventional equipment can meet most of the navigational needs, provided such supplementary appliances as charts, publications and radio communications are adequate and dependable.

This opinion does not cover special ice detection needs which may be partly met by some existing, high performance navigational type of equipment such as radar.

In cases where special navigational accuracy is essential because of known hazards and limited manoeuvering room, conventional aids will have to be supplemented or new systems established. At present there is not sufficient information to determine system accuracy requirements in such areas as the Beaufort Sea where pingos are known to exist. Further hydrographic surveys will provide this information.

The most important high performance aids will be a combination of gyro, log, radar and Satnav. In areas where very accurate navigation is required, these aids may be coordinated into a system or systems that provide good DR positions between Satnav fixes. Bottom-tracking doppler, differential Omega, racons, etc. may provide sufficiently accurate updates to navigate safely within known safe "channels".

The future Global Positioning System (GPS) navigational satellites should more than adequately meet all but the most exacting position fixing requirements.

Special very accurate systems may be required for harbour entrances. However, these should be primarily the responsibility of the proponent to provide.

Detailed General Planning

Based on the above Transport Canada approved Policy on the Provision of Marine Aids, and numerous in-house and Coast Guard/industry discussions, the Coast Guard is planning the following scenario for Arctic aids. It must be recognized that good hydrographic surveys and early availability of charts are a necessary prerequisite to the use of all marine aids and shipborne navigational systems.

Radar supported by enhancing devices (RACONs, radar reflectors) will be the prime aid when within its normal range – 25 nautical miles or less. Beyond this range, the accuracy requirements for position fixing need not be better than about 1 nautical mile. At that range, the prime aids will be Satnav supplemented by various shipborne devices such as depth sounder, gyrocompass, and others.

Omega/VLF is being evaluated to determine if it can perform the dead reckoning function between satellite fixes. The potential of Loran-C in the Arctic is being studied. However, it is anticipated that the aforementioned navigational aids will suffice.

In the Beaufort Sea, beyond radar coverage and for the existing vessels, an accuracy of about 1 nautical mile is adequate. However, if the survey of the proposed traffic lane to be used by deep draft vessels shows a great frequency of pingoes, an accuracy of about 1/4 nautical mile may be required. In this case, it may be necessary to establish a mini-Loran-C chain to provide this accuracy. Before a final decision is made, further Omega evaluations will allow the Coast Guard to determine if differential Omega can fulfill this requirement of about 1/4 nautical mile accuracy.

For the entrance into the Hudson Strait a high-powered radio beacon will be established at Button Island. RACONs are being established at important points along the Husdon Strait and in Ungava Bay.

Appendix C

UNITED NATIONS

THIRD CONFERENCE ON THE LAW OF THE SEA

Resumed Tenth Session, Geneva, 3-28 August, 1981

Draft Convention on the Law of the Sea

Part VI — Continental Shelf

Part VI
Continental Shelf

Article 76
Definition of the Continental Shelf

1. The continental shelf of a coastal State comprises the sea-bed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance.

2. The continental shelf of a coastal State shall not extend beyond the limits provided for in paragraphs 4 to 6.

3. The continental margin comprises the submerged prolongation of the land mass of the coastal State, and consists of the sea-bed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof.

4. (a) For the purposes of this Convention, the coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by either:

(i) a line delineated in accordance with paragraph 7 by reference to the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 percent of the shortest distances from such point to the foot of the continental slope; or

(ii) a line delineated in accordance with paragraph 7 by reference to fixed points not more than 60 nautical miles from the foot of the continental slope.

(b) In the absence of evidence to the contrary, the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base.

5. The fixed points comprising the line of the outer limits of the continental shelf on the sea-bed, drawn in accordance with paragraph 4 (a)(i) and (ii), either shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 nautical miles from the 2,500 metre isobath, which is a line connecting the depth of 2,500 metres.

6. Notwithstanding the provisions of paragraph 5, on submarine ridges, the outer limits of the continental shelf shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured. This paragraph does not apply to submarine elevations that are natural components of this continental margin, such as its plateaux, rises, caps, banks and spurs.

7. The coastal State shall delineate the outer limits of its continental shelf, where that shelf extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by co-ordinates of latitude and longitude.

8. Information on the limits of the continental shelf beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured shall be submitted by the coastal State to the Commission on the Limits of the Continental Shelf set up under Annex II on the basis of equitable geographical representation. The Commission shall make recommendations to coastal States on matters related to the establishment of the outer limits of their continental shelf. The limits of the shelf established by a coastal State on the basis of these recommendations shall be final and binding.

9. The coastal State shall deposit with the Secretary-General of the United Nations charts and relevant information, including geodetic data, permanently describing the outer limits of its continental shelf. The Secretary-General shall give due publicity thereto.

10. The provisions of this article are without prejudice to the question of delimitation of the continental shelf between States with opposite or adjacent coasts.

Article 77
Rights of the Coastal State Over the Continental Shelf

1. The coastal State exercises over the continental shelf sovereign rights for the purpose of exploring it and exploiting its natural resources.

2. The rights referred to in paragraph 1 are exclusive in the sense that if the coastal State does not explore the continental shelf or exploit its natural resources, no one may undertake these activities without the express consent of the coastal State.

3. The rights of the coastal State over the continental shelf do not depend on occupation, effective or notional, or on any express proclamation.

4. The natural resources referred to in this Part consist of the mineral and other non-living resources of the sea-bed and subsoil together with living organisms belonging to sedentary species, that is to say, organisms which, at the harvestable stage, either are immobile on or under the sea-bed or are unable to move except in constant physical contact with the sea-bed or the subsoil.

Article 78
Legal Status of the Superjacent Waters and Air Space and the Rights and Freedoms of Other States

1. The rights of the coastal State over the continental shelf do not affect the legal status of the superjacent waters or of the air space above those waters.

2. The exercise of the rights of the coastal State over the continental shelf must not infringe or result in any unjustifiable interference with navigation and other rights and freedoms of other States as provided for in this Convention.

Article 79
Submarine Cables and Pipelines on the Continental Shelf

1. All States are entitled to lay submarine cables and pipelines on the continental shelf, in accordance with the provisions of this article.

2. Subject to its rights to take reasonable measures for the exploration of the continental shelf, the exploitation of its natural resources and the prevention, reduction and control of pollution from pipelines, the coastal State may not impede the laying or maintenance of such cables or pipelines.

3. The delineation of the course for the laying of such pipelines on the continental shelf is subject to the consent of the coastal State.

4. Nothing in this Part affects the right of the coastal State to establish conditions for cables or pipelines entering its territory or territorial sea, or its jurisdiction over cables and pipelines constructed or used in connection with the exploration of its continental shelf or exploitation of its resources or the operations of artificial islands, installations and structures under its jurisdiction.

5. When laying submarine cables or pipelines, States shall have due regard to cables or pipelines already in position. In particular, possibilities of reparing existing cables or pipelines shall not be prejudiced.

Article 80
Artificial Islands, Installations and Structures on the Continental Shelf

Article 60 applies mutatis mutandis to artificial islands, installations and structures on the continental shelf.

Article 81
Drilling on the Continental Shelf

The coastal State shall have the exclusive right to authorize and regulate drilling on the continental shelf for all purposes.

Article 82
Payments and Contributions with Respect to the Exploitation of the Continental Shelf Beyond 200 Nautical Miles

1. The coastal State shall make payments or contributions in kind in respect of the exploitation of the non-living resources of the continental shelf beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured.

2. The payments and contributions shall be made annually with respect to all production at a site after the first five years of production at that site. For the sixth year, the rate of payment or contibution shall be 1 per cent of the value or volume of production at the site. The rate shall increase by 1 per cent for each subsequent year until the twelfth year and shall remain at 7 per cent thereafter. Production does not include resources used in connection with exploitation.

3. A developing State which is a net importer of a mineral resource produced from its continental shelf is exempt from making such payments or contributions in respect of that mineral resource.

4. The payments or contributions shall be made through the Authority, which shall distribute them to States Parties to this Convention, on the basis of equitable sharing criteria, taking into account the interests and needs of developing States, particularly the least developed and the land-locked among them.

Article 83
Delimitation of the Continental Shelf Between States with Opposite or Adjacent Coasts

1. The delimitation of the continental shelf between States with opposite or adjacent coasts shall be effected by agreement on the basis of international law, as referred to in Article 38 of the Statute of the International Court of Justice, in order to achieve an equitable solution.

2. If no agreement can be reached within a reasonable period of time, the States concerned shall resort to the procedures provided for in Part XV.

3. Pending agreement as provided for in paragraph 1, the States concerned, in a spirit of understanding and co-operation, shall make every effort to enter into provisional arrangements of a practical nature and, during this transitional period, not to jeopardize or hamper the reaching of the final agreement. Such arrangements shall be without prejudice to the final delimitation.

4. Where there is an agreement in force between the States concerned, questions relating to the delimitation of the continental shelf shall be determined in accordance with the provisions of that agreement.

Article 84
Charts and Lists of Geographical Co-ordinates

1. Subject to this Part, the outer limit lines of the continental shelf and the lines of delimitation drawn in accordance with article 83 shall be shown on charts of a scale or scales adequate for ascertaining their position. Where appropriate, lists of geographical co-ordinates of points, specifying the geodetic datum, may be substituted for such outer limit lines or lines of delimitation.

2. The coastal State shall give due publicity to such charts or lists of geographical co-ordinates and shall deposit a copy of each such chart or list with the Secretary-General of the United Nations and, in the case of those showing the outer limit lines of the continental shelf, with the Secretary-General of the Authority.

Article 85
Tunnelling

This Part does not prejudice the right of the coastal State to exploit the subsoil by means of tunnelling, irrespective of the depth of water above the subsoil.

Appendix D

Local Datum Shifts (NAD27)

The values of local datum shifts given in Table D-1 and Figures D-1, D-2, and D-3 for points across Canada were derived by subtracting the NAD27 Cartesian coordinates for the point from the corresponding earth-centred Cartesian coordinates, derived from Doppler satellite observations.

The NAD27 Cartesian coordinates were derived (using equations (2) to (4), Chapter 5) from the most recently published values for NAD27 latitude and longitude. For the height coordinates, the best available height above sea level was added to the geoid height above the Clarke 1866 (NAD27) ellipsoid. These geoid heights were derived from a model of the earth's gravity field (the geoid) designated GEM10B (for Goddard Earth Model 10B) refined by local gravity measurements. GEM10B consists of a spherical harmonic expansion devised by the United States Goddard Space Centre. It is based on 700 coefficients and gives a smoothed geoid model for the world. Figure D-4 shows the Canadian part of GEM10B geoid contours relative to the Clarke 1866 (NAD27) ellipsoid. Refinements to GEM10B were devised by the Geodetic Survey of Canada taking into consideration Canadian local gravity measurements to model local variations (Lachapelle and Rapp, 1982).

TABLE D-I
DATUM SHIFTS OF PUBLISHED NAD27 COORDINATES AT VARIOUS LOCALITIES IN CANADA

LOCALITY	STATION NAME	STATION NUMBER	NAD27 PUBLISHED COORDS. LATITUDE	NAD27 PUBLISHED COORDS. LONGITUDE	HEIGHT ABOVE SEA LEVEL (M)	GEOID HEIGHT USED (M)	LOCAL DATUM SHIFT X (M)	LOCAL DATUM SHIFT Y (M)	LOCAL DATUM SHIFT Z (M)
NEWFOUNDLAND									
GRAND BANK	GRAND BANK A	51063Z	47 04 05.361	55 50 50.584	93.9	26.4	-45	148	180
ST.JOHN'S	SATANT	730100	47 34 17.628	52 41 42.060	71.1	32.0	-41	147	181
ROBINSON	ROBINSONS	36005	48 15 32.534	58 47 59.887	95.9	21.4	-47	150	180
GANDER	GANDER	38000	48 54 48.552	54 42 25.348	216.9	32.1	-43	149	180
WHITE BAY	COW HEAD	39006	49 55 13.020	57 49 15.784	66.8	24.1	-43	153	180
STRAIT OF BELLE	SAVAGE	44000	51 19 13.428	56 42 06.187	18.3	26.2	-41	154	184
DOMINION LAKE	ALDER NB	54008	52 59 24.708	62 02 42.871	430.9	18.0	-40	158	180
WABUSH-LABRADOR	PETITE	48019	53 02 11.895	66 28 35.318	767.9	14.0	-36	159	177
GOOSE BAY	GOOSE BAY SA	650001	53 18 30.075	60 21 53.189	33.5	20.8	-38	158	182
HAMILTON INLET	SNOOK	55023	54 12 31.330	57 46 47.259	78.2	26.9	-40	156	180
NAIN INLET	PAUL	57000	56 31 55.877	61 31 04.024	482.3	21.5	-37	157	179
NOVA SCOTIA AND NEW BRUNSWICK									
SABLE ISLAND	RED (4903)	631103	43 57 42.736	59 47 14.096	14.4	15.9	-39	154	180
HALIFAX	SHEARWATER	651050	44 38 17.063	63 30 36.720	50.9	11.1	-40	159	182
INGONISH	SMOKEY	23102	46 35 48.206	60 23 51.895	367.2	17.2	-40	158	184
GRANDE ANSE	GRANDE ANSE	24126	47 48 07.109	65 12 28.655	30.9	13.4	-38	159	178
QUEBEC									
LAUZON	LAUZON	682007	46 48 52.605	71 09 27.564	121.2	8.8	-34	158	175
MITCHINAMECUS	MACARTHUR	30202	47 28 57.154	75 48 29.582	549.2	4.8	-32	163	176
ROBERVAL	POINTE BLEUE	22214	48 32 39.001	72 13 59.191	168.4	5.5	-35	159	176
MATANE, GASPE	MATANE	20204	48 49 15.318	67 33 14.377	88.5	10.2	-36	157	179
OBATOGAMAU LAKE	EXPLORER	55215	49 30 14.767	74 23 02.247	448.2	3.2	-31	161	177
SEPT-ILES	BOULE	21203	50 08 20.543	66 17 16.423	209.7	12.6	-40	160	175
NATASHQUAN	NATASHQUAN N	41210	50 16 57.614	61 49 25.747	96.9	14.3	-42	157	182
LAKE MISTASSINI	PAPA	56211	51 25 55.919	72 52 19.146	446.0	4.9	-34	158	179
ROMAINE RIVER	WHITE	53208	51 29 50.542	63 31 12.636	760.2	16.1	-37	159	179
NITCHEQUON LAKE	ROCK	58200	53 12 33.879	71 20 01.760	622.7	8.3	-34	160	179
FORT GEORGE	FORTGEORGE S	682146	53 50 02.320	78 59 34.153	5.5	-4.3	-34	161	177
SCHEFFERVILLE	SQUAW	49202	54 50 17.873	66 46 46.626	602.5	15.0	-33	159	176
LAKE MINTO	DEC	632000	57 06 42.252	74 35 17.267	306.6	2.6	-31	162	179
FORT CHIMO	CHIMO DOPPLE	742000	58 06 37.073	68 24 52.574	58.7	12.1	-28	159	178
PURTUNIQ	DODIE	652216	61 47 49.844	73 56 55.685	602.9	12.1	-27	163	174
ONTARIO									
WALKERTON	BERVIE	743022	44 07 11.813	81 28 25.632	288.4	3.4	-31	159	174
OTTAWA	GEOLAB	753229	45 23 39.037	75 42 50.096	88.0	5.6	-31	158	176
SUDBURY	N SUDBURY	29316	46 30 15.918	80 58 04.837	347.8	3.5	-31	159	174
SAULT STE MARIE	REPAIR	703315	46 32 12.341	84 18 57.460	246.9	2.4	-30	159	174
TIMMINS	TIMMINS SAT	653050	48 33 56.350	81 22 15.599	292.0	1.9	-34	162	177
THUNDER BAY	MCKENZIE EB	52303	48 34 13.096	88 50 03.284	251.2	2.1	-22	162	175
WHITE RIVER	WHITE RIVER	49315	48 37 46.867	85 11 25.444	597.7	1.2	-23	161	174
FORT FRANCES	HENRI	673221	48 43 21.872	94 21 01.698	336.0	8.6	-21	159	172
LAKE ABITIBI	MACE	28304	49 01 05.784	79 56 39.345	440.6	0.9	-34	161	177
KAPUSKASING	LOWTHER	723007	49 33 15.183	83 00 35.569	253.9	1.7	-22	160	174
SIOUX LOOKOUT	SIOUX	57319	50 05 21.494	92 00 01.082	444.7	5.0	-19	160	173
LAKE NIPIGON	CARIBOU	54304	50 20 11.497	89 08 36.088	437.4	3.1	-21	160	177
MOOSONEE	MOOSONEE	723002	51 16 33.522	80 37 59.893	7.8	-2.4	-26	162	177
ATTAWAPISKAT	ATTA	723022	52 55 24.423	82 25 40.997	9.0	-5.6	-20	161	173
WINISK LAKE	LAST	673211	52 59 13.887	87 21 33.168	214.9	-4.4	-18	160	174
BIG TROUT LAKE	BEARSKIN	673218	53 57 43.370	90 22 55.641	224.6	-3.3	-17	161	171
FLAGSTAFF PT.	WINISK	723026	55 13 47.339	85 07 32.652	18.0	-7.8	-15	157	173
HUDSON BAY	BDY 457A	593457A	56 50 24.271	89 00 06.622	2.4	-9.6	-17	159	177
MANITOBA									
ST.JEAN BAPTISTE	PLUM COULEE	25402	49 08 30.221	97 45 10.787	256.2	11.2	-20	160	173
KILLARNEY	FAIRHALL SEB	25415	49 17 14.897	99 39 23.626	485.7	13.4	-19	162	174
DUCK MTN.	GILL	61407	51 36 34.935	101 18 26.401	692.2	10.2	-15	159	174
LAKE WINNIPEG	STONEY	674104	52 07 37.934	97 29 52.805	221.3	3.8	-19	158	173
REINDEER	REINDEER	754010	52 33 08.554	97 58 22.954	219.0	3.8	-19	159	172
THE PAS	MURPHY	734011	53 44 44.020	101 46 15.661	272.6	5.4	-9	161	175
ISLAND LAKE	ISLAND LAKE	674100	53 57 54.194	93 55 03.123	249.9	-.6	-18	161	176
THOMPSON	THOMPSON	714007	55 44 08.883	97 50 58.991	253.2	-.5	-8	161	176
LYNN LAKE	LYNN SAT	644000	56 51 38.890	101 03 57.780	350.5	1.0	-3	162	175
YORK FACTORY	YORK ASTRO	734020	57 00 17.744	92 18 01.596	10.4	-8.9	-11	164	175
CHURCHILL	DAK	664002	58 45 32.461	93 59 24.050	34.8	-11.7	-5	164	178
BARALZON LAKE	LYE	664031	59 57 22.599	97 53 42.680	295.5	-9.2	-7	163	178
SASKATCHEWAN									
MAPLE CREEK	WINDY	765047	49 52 22.654	109 58 13.485	845.0	12.2	-16	172	183
CUTHBERT	GULLY	765046	51 05 45.162	109 57 14.692	710.3	10.6	-16	172	183
WATROUS	WATROUS 2	705026	51 41 46.896	105 32 48.152	566.1	11.1	-11	165	178
NORTH BATTLEFORD	LIND	665007	52 44 28.543	108 25 20.117	557.1	9.8	-8	168	180
PRINCE ALBERT	RED DEER HIL	30513	53 03 23.007	105 50 28.674	531.6	9.0	-5	162	177
NORTH BATTLEFORD	COCHIN	765043	53 06 24.579	108 21 20.948	573.2	8.9	-5	179	165
MIDNIGHT LAKE	MIDNIGHT	765050	53 27 12.952	108 22 33.712	683.2	8.1	-5	179	165
TURTLE LAKE	TURTLE	765060	53 46 26.180	108 23 05.993	669.2	7.4	-5	179	166
MEADOW LAKE	MEADOW	765070	54 07 30.642	108 30 12.645	481.3	6.3	-6	179	165
GREEN LAKE	GREEN	765080	54 15 21.623	107 46 32.032	504.3	5.9	-6	178	163
DORE LAKE	WATERHEN	765090	54 36 51.233	107 48 52.191	468.4	5.5	-6	178	163
CANOE LAKE	KEELEY	665201	54 43 12.528	108 30 36.380	694.3	5.7	-9	171	177
DORE LAKE	MILL	765100	54 56 25.702	107 47 31.629	454.3	5.0	-6	177	163
FORT BLACK	CURVE	765110	55 15 02.917	107 48 24.019	442.6	4.3	-5	175	164
LAC LA RONGE	WADEN	57509	55 16 32.628	105 03 43.900	434.6	4.1	-2	161	177
ILE A LA CROSSE	INTER	765120	55 33 54.179	108 06 58.077	436.6	3.6	-5	174	164
BUFFALO	BUFFALO	765130	55 50 31.730	108 28 18.247	420.5	3.1	-5	174	164
CHURCHILL LAKE	GRAVEL	765140	56 11 22.510	108 50 32.437	458.5	2.8	-8	164	181
TURNOR LAKE	TURNOR LAKE	765150	56 28 07.310	108 41 44.193	436.3	2.2	-4	173	164
TURNOR LAKE	TURN	665200	56 44 35.027	108 46 27.199	436.8	2.1	-7	165	179
REINDEER LAKE	HUGH	59504	56 58 44.401	102 15 46.756	394.3	1.2	-1	161	174

TABLE D-I CONTINUED
DATUM SHIFTS OF PUBLISHED NAD27 COORDINATES AT VARIOUS LOCALITIES IN CANADA

LOCALITY	STATION NAME	STATION NUMBER	NAD27 PUBLISHED COORDS. LATITUDE	NAD27 PUBLISHED COORDS. LONGITUDE	HEIGHT ABOVE SEA LEVEL (M)	GEOID HEIGHT USED (M)	LOCAL DATUM SHIFT X (M)	LOCAL DATUM SHIFT Y (M)	LOCAL DATUM SHIFT Z (M)
			ALBERTA						
CARDSTON	BEAZER	23600	49 05 40.363	113 27 49.234	1474.1	11.8	-19	170	179
COMREY	SAGE	23611	49 09 18.394	110 24 03.774	988.7	12.8	-16	168	180
TABER	TABER	766251	49 52 23.671	112 20 07.776	828.6	10.4	-17	171	182
IDDESLEIGH	IDDESLEIGH	26611	50 40 03.753	111 15 56.490	867.6	10.0	-16	172	183
CALGARY	ASTRO A	656025	50 52 16.774	114 17 32.997	1262.8	11.0	-15	176	185
BROOKS	FLAT	766250	51 05 44.742	111 50 59.697	740.4	9.6	-16	172	183
JASPER	SIGNAL	736108	52 52 01.272	117 59 04.449	2129.2	13.3	-13	176	180
EDMONTON	RESERVOIR	666002	53 29 11.130	113 26 33.345	716.6	7.4	-13	174	182
TANGENT	TANGENT	54609	55 54 46.009	117 42 29.088	590.5	7.3	-18	176	180
PELICAN PORTAGE	HOUSE	666200	55 55 00.483	112 04 48.007	695.9	5.7	-10	170	181
FORT CHIPEWYAN	FORT	686004	58 43 21.642	111 09 15.309	276.9	0.2	-8	166	179
INDIAN CABIN	LAST	58608	59 54 54.400	117 02 05.547	298.4	4.9	-13	170	179
			BRITISH COLUMBIA						
VICTORIA	SPEEDY	677016	48 24 49.406	123 19 26.278	66.5	-4.0	-24	169	176
OLIVER	KOBAU ASTRO	657004	49 06 57.758	119 40 29.334	1862.9	2.3	-23	168	178
QUEEN CHARLOTTE	KLUCKSIWI 2	757030	50 34 22.453	127 09 44.378	359.9	-4.3	-26	176	180
SALMON ARM	IDA	35706	50 38 46.557	119 16 27.030	1501.4	3.9	-20	169	178
FIELD	VAUX	697001	51 17 51.377	116 32 43.706	2502.2	12.3	-16	173	179
WILLIAMS LAKE	FRASER	36704	51 58 27.210	122 13 43.874	1330.1	2.6	-22	173	181
PRINCE GEORGE	PR GEORGE NB	36717	53 54 09.037	122 42 16.967	731.1	5.8	-21	177	181
PRINCE RUPERT	OLDFIELD	15701	54 17 03.573	130 18 49.065	704.1	1.8	-24	166	173
BABINE LAKE	OLDFORT (103	737025	55 05 18.756	126 23 00.565	1568.1	7.4	-21	175	178
DAWSON CREEK	ROLLA EB	50705	55 53 52.697	120 07 18.173	692.7	8.2	-20	171	177
KINASKAN	4 HIGH	747010	57 22 40.841	130 08 29.720	1737.3	14.0	-17	162	171
FORT NELSON	NELSON 2	647000	58 51 05.849	122 50 00.175	666.6	8.6	-17	157	170
LOWER POST	CANYON	50711	59 59 02.031	128 32 58.850	866.3	12.6	-13	150	172
			NORTHWEST TERRITORIES						
SELWYN LAKE	BOUSKILL	60976	60 11 16.705	104 13 02.597	526.6	-4.1	-7	165	178
CAPE BURWELL	BURWELL DOPP	749194	60 25 28.158	64 50 33.343	35.1	25.2	-32	144	175
RESOLUTION IS.	PHONE-2	749193	61 35 46.670	64 38 24.224	364.9	27.6	-15	159	173
FORT SIMPSON	SIMPSON	689004	61 44 48.953	121 14 00.904	168.5	7.4	-4	165	179
YELLOWKNIFE	YELLOWKNIFE	629102	62 28 28.863	114 26 21.415	209.2	-.6	-8	167	179
RELIANCE	RELIANCE	59928	62 45 20.248	109 04 59.978	278.8	-1.7	-6	165	178
RANKIN INLET	RANKIN DOPPL	749192	62 48 41.204	92 05 16.505	25.3	-9.8	-5	163	177
DUBAWNT LAKE	DUB	61967	62 50 44.776	101 56 14.398	311.2	-7.8	-6	165	178
WRIGLEY	WRIGLEY	759200	63 12 36.335	123 25 55.254	148.9	9.0	-3	162	178
FROBISHER BAY	FROBISHER DO	659250	63 45 28.474	68 32 30.547	26.9	22.5	-17	163	175
CORAL HARBOUR	CORAL DOPPLE	749191	64 11 12.373	83 20 36.051	51.3	1.6	-17	168	174
CAPE DORSET	DORSET ASTRO	749008	64 14 01.680	76 32 36.991	11.7	8.2	-16	166	174
BAKER LAKE	BAKER	639509	64 18 22.184	96 07 11.716	131.5	-8.5	-5	164	176
TOURGIS LAKE	DRAW	629002	64 54 02.973	106 05 22.650	370.4	-3.4	-6	167	175
HOTTAH LAKE	ZEBULON	639022	65 12 12.818	117 04 39.179	431.6	4.3	-6	168	179
NORMAN WELLS	NORMANWE	759201	65 16 42.166	126 47 22.557	70.1	5.6	-2	158	180
LOWER MACDOUGALL	BACK RIVER	749372	65 57 30.500	98 03 27.252	167.7	-7.3	-6	168	175
WAGER BAY	739100	739100	65 58 51.344	90 01 48.963	286.1	-2.1	-5	167	180
REPULSE	REPULSE BAY	749178	66 31 22.259	86 14 02.237	20.8	1.5	-2	166	173
CAPE DYER	DYER DOP	749187	66 35 49.337	61 34 40.890	371.3	36.4	-15	162	176
MARTIN HOUSE	MARTIN	699024	66 58 56.148	132 47 52.878	179.2	7.6	-9	150	174
NETTILLING LAKE	BASIN SH 82	569082	67 04 35.581	71 46 32.464	106.2	16.3	-15	164	177
LAC MAUNOIR	MAN	709111	67 38 10.277	124 54 41.510	597.4	8.8	-5	162	172
COPPERMINE	COPPERMINE	639045	67 49 12.525	115 06 46.877	65.8	3.3	-5	168	179
CUMBERLAND PEN	HOOPER	749523	67 51 05.469	67 59 01.845	972.3	27.5	-14	164	177
HALL BEACH	HALL SH 128	569128	68 45 56.007	81 13 44.327	5.2	9.4	-4	166	174
HALL BEACH	HALL DOPPLER	749183	68 47 27.357	81 14 11.486	6.1	9.4	-4	169	167
SHEPHERD BAY	SHEPHERD BAY	749179	68 47 36.645	93 26 17.597	44.6	0.5	-4	167	174
CAMBRIDGE BAY	VICTORIA	649032	69 06 59.067	105 03 30.777	13.5	-3.9	-6	167	178
TUKTOYAKTUK	TUK	749151	69 26 15.177	133 01 52.648	4.5	4.6	-16	150	172
PEARCE PT.	PEARCE DOPPL	749153	69 48 28.206	122 39 46.694	6.6	7.2	-12	166	176
CLYDE INLET	CAPE CHRISTI	749186	70 31 32.796	68 17 42.696	22.4	29.0	-13	165	177
SACHS HARBOUR	749154	749154	71 59 35.787	125 16 47.398	82.0	6.8	-12	173	177
STORKERSON PENN	CLOUDY SH 11	569119	72 28 15.734	106 29 27.727	162.2	5.6	-13	170	179
CROOKED LK.	MAGNETIC SH	569122	72 35 55.521	98 46 58.598	42.7	10.0	-3	169	171
ARCTIC BAY	ARCTIC BAY	749180	73 02 02.018	85 09 32.646	9.3	16.9	-16	169	171
WALLACE PT.	RUSSELL	749155	73 28 08.735	115 23 52.121	28.4	6.9	-12	172	176
CROKER BAY	HOME	609835	74 32 34.339	83 35 57.116	3.1	23.8	-12	168	177
RESOLUTE BAY	RESOLUTE DOP	749159	74 43 05.364	94 59 12.503	65.5	15.7	-13	169	176
HEARNE PT.	WINTER HBR D	749162	74 48 12.328	110 30 35.794	23.2	7.8	-13	172	173
MOULD BAY	MOULD DOPPLE	749177	76 14 26.392	119 21 17.941	11.3	8.5	-11	171	178
GRISE FIORD	GRISE FIORD	749173	76 24 57.345	82 53 25.769	3.7	22.9	-11	166	178
LOUGHEED ISLAND	LOUGHEED SH	579234	77 23 42.298	105 01 21.204	33.2	11.9	-11	170	176
CORNWALL	CORNWALL DOP	749165	77 45 40.099	94 37 35.611	4.3	17.2	-11	169	176
BROCK ISLAND	BROCK (134)	619434	77 56 07.388	114 51 06.939	25.0	12.7	-10	173	166
ISACHSEN	ISACHSEN DOP	749163	78 47 08.270	103 30 52.170	27.7	15.9	-10	171	174
CAPE RUTHERFORD	ALEX FIORD	749171	78 52 51.656	75 47 05.655	12.5	26.5	-9	167	175
EUREKA SOUND	EUREKA DOP	749167	79 59 34.733	85 49 59.885	108.5	19.4	-9	173	148
ALERT PT.	ELLESMERE DO	629246	82 24 53.737	85 38 02.870	28.3	20.4	-8	169	176
CAPE RICHARDSON	ALERT	749169	82 29 50.381	62 21 23.337	81.1	24.9	-9	168	171
			YUKON TERRITORY						
WHITEHORSE	SATELLITE	648000	60 43 35.055	135 05 20.035	721.7	8.6	-14	147	177
ROSS RIVER	ROSS R	758001	61 58 56.844	132 26 53.321	698.5	10.4	-14	150	175
TUNGSTEN	TUNGSTEN	758000	62 01 58.080	128 21 08.924	1288.9	10.9	-14	151	176
BEAVER CREEK	BEAVER CR AS	44807	62 27 21.763	140 51 00.293	623.2	6.1	-13	146	182
KENO HILL	GALENAN	488108	63 55 00.998	135 23 23.238	1444.7	9.1	-17	148	175
CLINTON CREEK	MON 126G	078010	64 05 12.427	140 59 56.637	1291.7	6.9	-14	144	180
OGILVIE RIVER	DEMPSTER	728027	65 27 30.727	138 11 51.725	558.4	7.8	-15	145	177
OLD CROW	RAMPART IBC	708001	67 21 42.300	140 56 38.195	713.8	5.6	-16	148	171
DEMARCATION PT.	BUG TOPO	708007	69 28 37.836	140 54 50.142	439.3	4.0	-9	138	173
			UNITED STATES						
SANDPOINT	BONNERS	36733US	48 40 32.905	116 19 57.833	561.7	6.8	-20	168	179
POPLAR RIVER	MADOC	23527US	48 48 27.902	105 19 05.250	853.1	15.5	-13	165	179

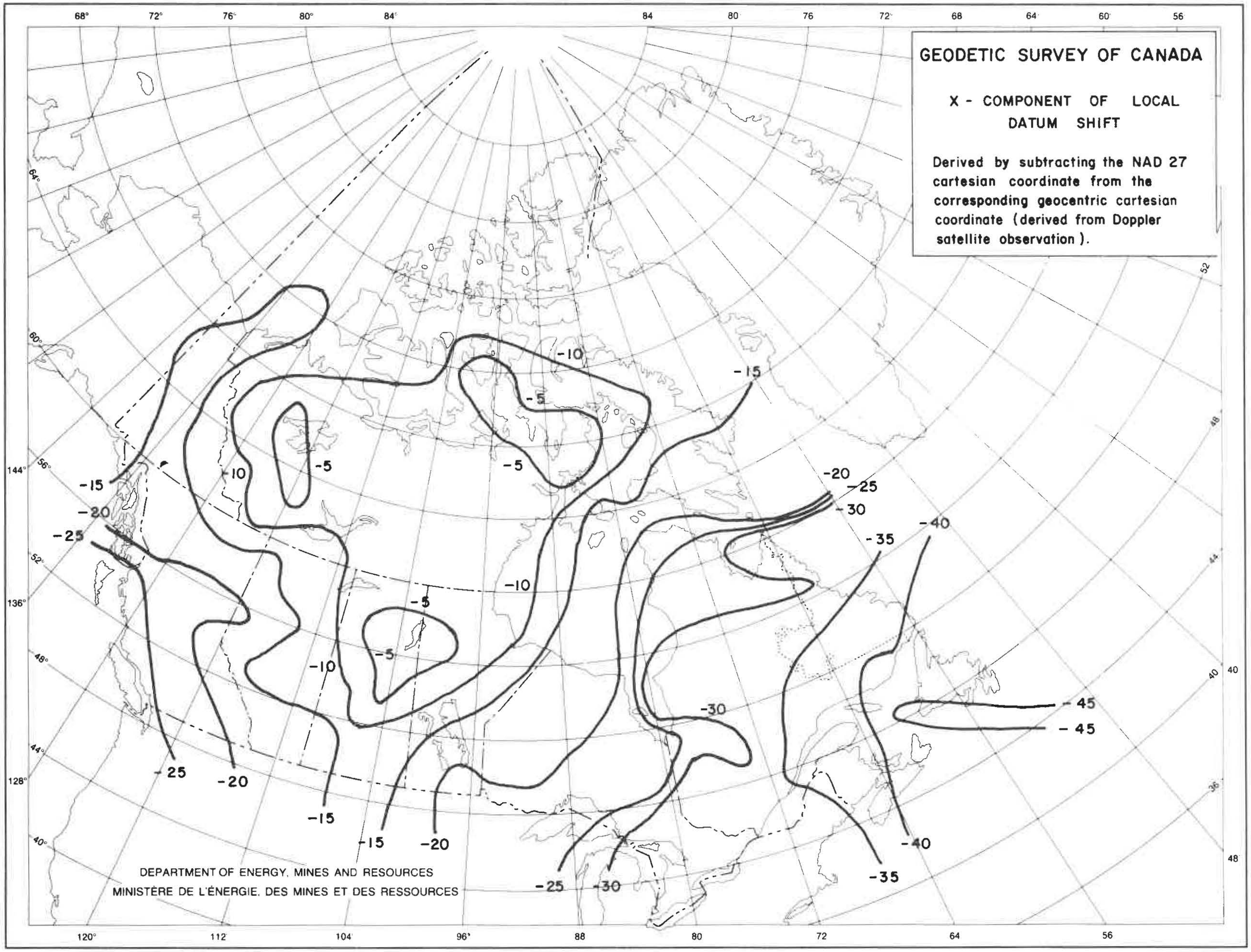


Figure D-1

X-Component of NAD27 Local Datum Shift

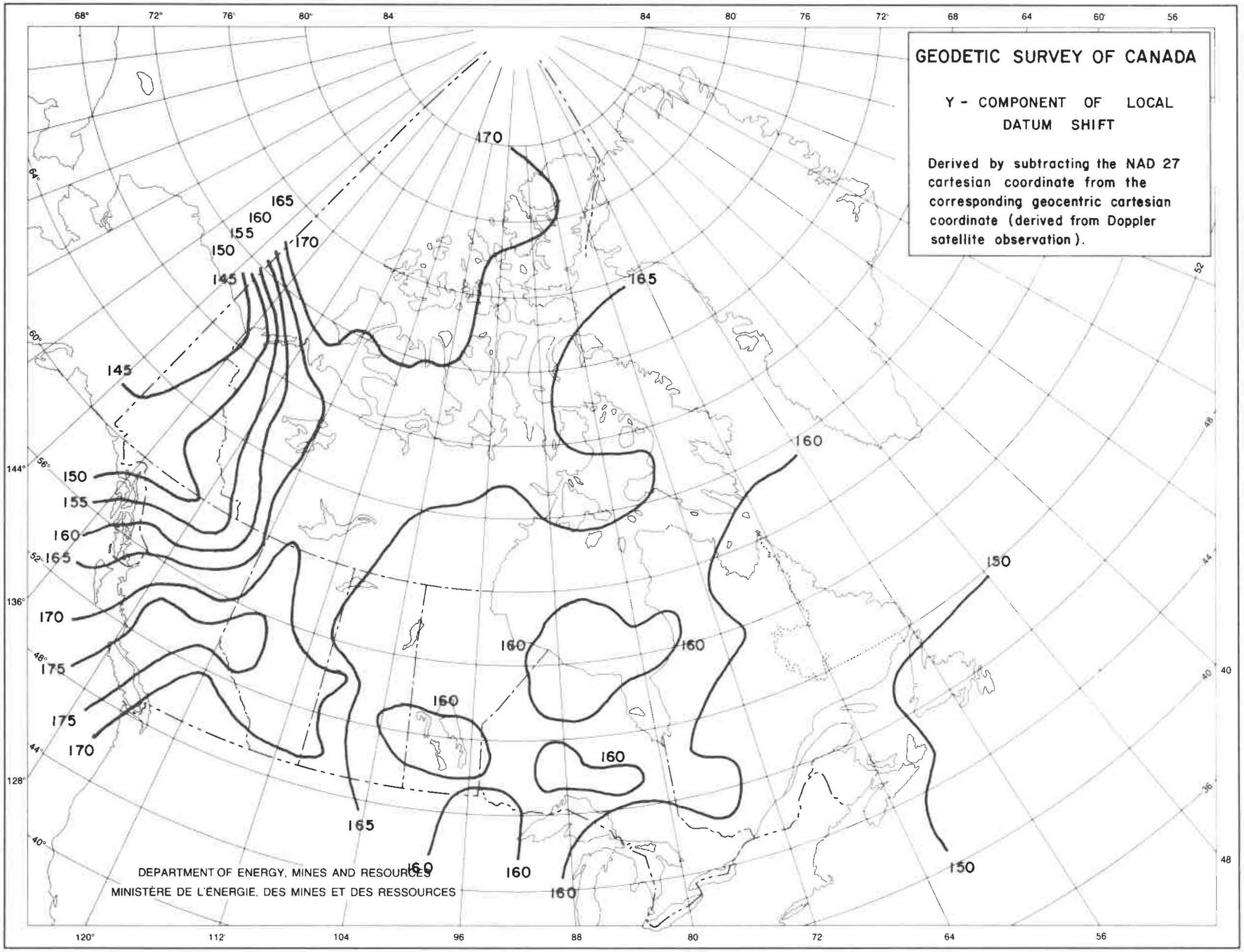


Figure D-2

Y-Component of NAD27 Local Datum Shift

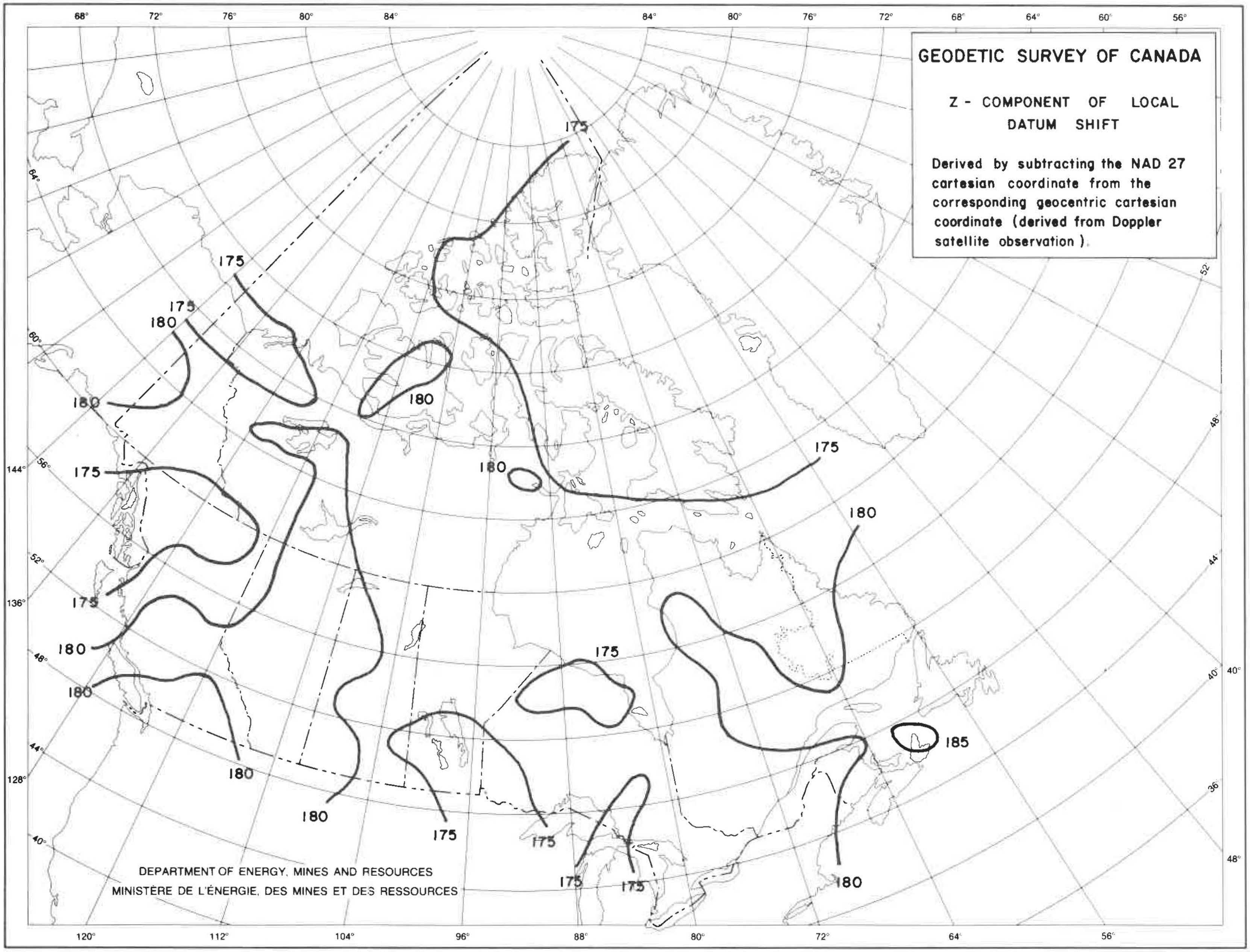


Figure D-3

Z-Component of NAD27 Local Datum Shift

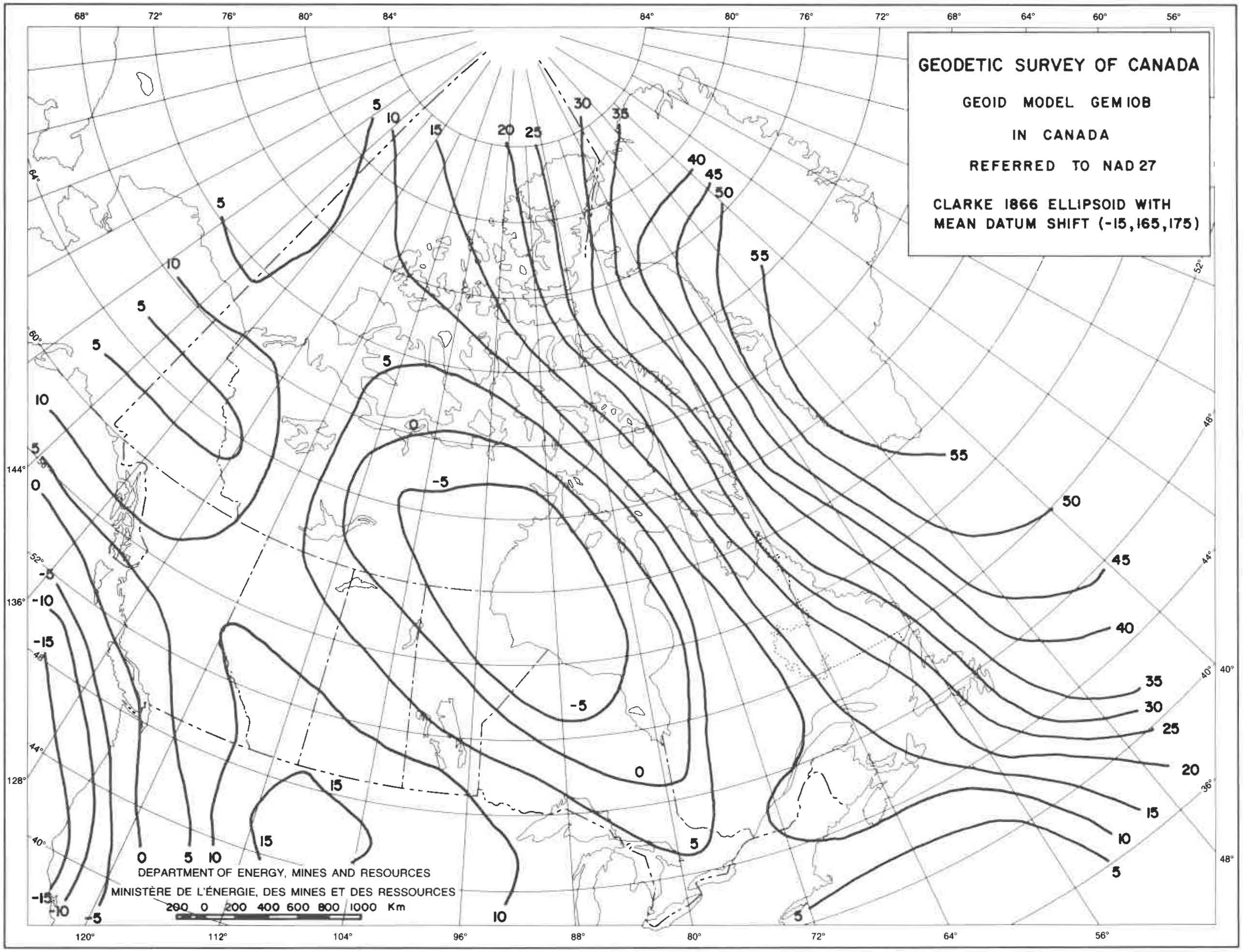


Figure D-4

Geoid Height above NAD27 Ellipsoid

Appendix E

a reprint of

Specifications for Positioning Reports for Offshore Exploratory Wells

published by

Canada Oil and Gas Lands Administration

January 1983

Specifications

The subject matter outlined below covers the specifications for the final well survey submission for all exploratory wells in the Canadian offshore. This includes wells drilled on artificial and ice-reinforced islands.

Submission

Positioning reports for offshore exploratory wells should be submitted to:

Administrator.
Canada Oil and Gas Lands Administration,
355 River Road,
OTTAWA, Ontario,
K1A 0E4.

For review and other purposes, two copies will be forwarded to the Office of the Surveyor General, Department of Energy, Mines and Resources. One of these two copies will be recorded in the Canada Lands Surveys Records.

Survey System

The survey system used should be sufficient to ensure a survey connection to the nearest geodetic shore control with at least fourth order accuracy as defined in *Specifications and Recommendations for Control Surveys and Survey Markers* 1978.

Where the well is close enough to shore to permit the use of conventional land survey techniques, they should be used.

The method used should contain adequate checks against gross errors either by survey closures and redundant measurements or by an independent check using another method.

Shore stations should be described and permanently marked so that they could be reoccupied if necessary.

Report

The report may take the form of a plan alone or a plan appended to a textual report describing the survey system, observed quantities and final results, etc.

The report shall include, either on the plan or in separate text, a general description of the techniques including those which may be used for independent checking. It should include enough information to allow the system to be assessed (e.g. calibration, reduction and adjustment techniques and procedures and rejection criteria). Where the system used incorporates a computer program (such as a Doppler satellite reduction program) a reference should be given to where program documentation could be procured. It should include the basic determinations of the survey from which the final position is derived.

In the case of the Doppler satellite surveys the report should include the computer printout of the Doppler adjustment. Where the computer printed coordinates are not those of the well or monument on the plan, the derivation of the required coordinates must be clearly explained. The a-priori standard deviations, rejection criteria, datum parameters, pass by pass summary, derived standard deviations, etc. must be shown.

An analysis of the accuracy of the survey is required to indicate how the accuracy of the derived position differences between the newly established points and the neighbouring control compares to the required fourth order specification.

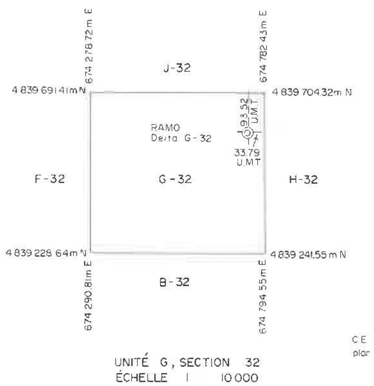
Plan

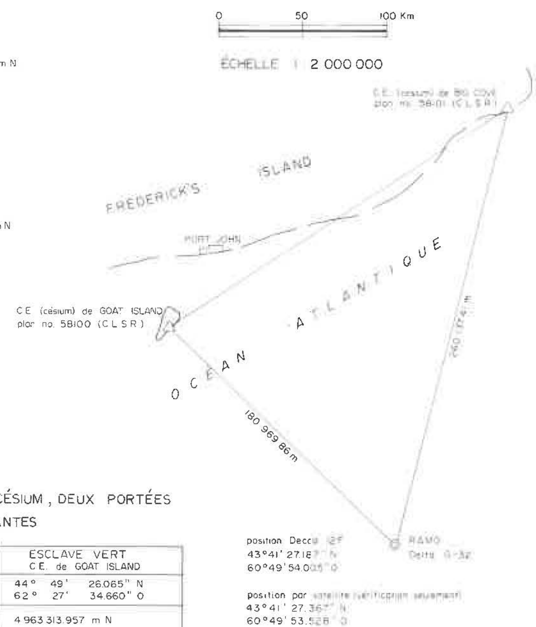
The plan should show:

- Well name, including the section and unit designation under the Canada Oil and Gas Land Regulations.
- Grid area designation under the Regulations.
- Lease or Permit number, if applicable.
- Positions and Universal Transverse Mercator coordinates (referred to the 1927 North American Datum) with zone number and central meridian of:
  - — the well
  - — all monumented stations of the survey
  - — corners of the unit within which the well is situated
- Water depth at location
- Measured distances (horizontal), angles or azimuths
- Geographical coordinates (1927 NAD) of:
  - — the well
  - — control monuments (with specified source of datum information e.g., Geodetic Survey of Canada, C.L.S.R. plan no.)
- Position of the well with respect to the unit boundaries.
- Table of Constants and Parameters pertinent to the survey system used.
- Source and value of any datum shift used to transform coordinates to 1927 NAD if the positioning system used is based on an earth centred datum (e.g. Doppler Satellite or Loran C).
- Brief note on primary and secondary system or in checks or redundant measurements made if only one positioning system is used.
- Scale(s)
- North point
- Date of Survey: year, month, day
- Surveyors statement, signature, and qualifications (with witness)
- Endorsement by permittee or lessee (optional)

A copy of a Specimen Plan is available for use as a guide. To facilitate filing and reproduction, outside dimensions of a survey plan should not exceed 50 × 35 cm in general. If a larger plan is essential the width should not exceed 60 cm.

L.V. Brandon	W.V. Blackie
Director General	Surveyor General
Engineering and Control Branch	Surveys and Mapping Branch
Canada Oil and Gas Lands Administration	Department of Energy, Mines and Resources





IL FAUT CONSERVER UN ESPACE DE 5cm x 20cm POUR PARTICULARITÉS DE DÉPÔT

P L A N T Y P E

PLAN

DE LOCALISATION DU PUITS DE SONDAGE

RAMO DELTA G-32

AU LARGE DES CÔTES

ÉTENDUE QUADRILLÉE 43°50', 60°45'

RÈGLEMENT SUR LES TERRES PÉTROLIFÈRES ET GAZIFÈRES DU CANADA

Permis : no. W-12345

Arpenté entre le 24 février et le 3 mars 1975

pour RAMO OIL CANADA LTÉE

par *(nom, titre)* ______________________

CHAÎNE No. 200 DECCA 12F MODE OPÉRATOIRE : CÉSIUM, DEUX PORTÉES

PARAMÈTRES ET CONSTANTES

	ESCLAVE ROUGE C.E. de BIG COVE	ESCLAVE VERT C.E. de GOAT ISLAND
latitude longitude	45° 56' 09.544" N 59° 54' 01.010" O	44° 49' 26.065" N 62° 27' 34.660" O
coordonnées U.M.T.	5 091 390.011 m N 740 298.616 m E	4 963 313.957 m N 542 721.110 m E
longueur de l'axe rouge - vert	235 457.74 m plan U.M.T. 235 484.67 m surface	235 457.74 m plan U.M.T 235 484.67 m surface
fréquence transmise standard de césium (maître = 175.410 kHz)	116 940 kHz	131.5575 kHz
fréquence de comparaison	350 820 kHz	526 230 kHz
vitesse de propagation nominale (trajet complet sur l'eau de mer)	299 650 km/s	299 650 km/s
longueur d'onde de comparaison	854.14173 m	569.42782 m
largeur du chenal (constant)	854.14173 m	569.42782 m

EMPLACEMENT DU PUITS		
lectures Decca non corrigées	304.62 chenaux (rouge)	317.86 chenaux (vert)
lectures Decca corrigées pour le retard de phase en théorie	304.56 chenaux (rouge)	317.81 chenaux (vert)
coordonnées U.M.T.	4 839 609.96 m N	674 751.09 m E
coordonnées géographiques	43°41'27.187" N	60°49'54.005" O

L É G E N D E

Toute coordonnée mentionnée se rapporte au système de référence géodésique nord-américain de 1927.
Les coordonnées U.M.T. apparaissant ici sont calculées pour le fuseau 20, méridien central 63° Ouest.
Les distances montrées sont en mètres et horizontales. A moins d'indication contraire, elles n'ont pas été redressées au plan U.M.T.
A l'emplacement du puits, la profondeur de l'eau était de cinquante et un mètres (51m)
Le repérage a été effectué au moyen du mode d'arpentage Decca 12F à deux portées
Il fut vérifié par observations du satellite Doppler (une énumération étant incluse avec les présentes). 23 passages acceptables du satellite furent pris à bord du navire de forage avant son départ des lieux. La documentation requise en rapport avec le programme de calculs de satellites Doppler est disponible à ......
Les valeurs (Xo = -27m, Yo = 153m, Zo = 188m) employées pour le décalage du système de référence (datum shift) à l'endroit donné entre le système de référence du satellite et le système de référence géodésique nord-américain de 1927 ont été fournies par les Levés géodésiques du Canada le 28 février 1975.

(voir remarque 5)

RAMO OIL CANADA LTÉE

(signature, fonction) ______________________

(signature) ______________________
témoin

______________ date

Je, soussigné, certifie que l'arpentage représenté par ce plan a été exécuté sous ma surveillance personnelle et qu'il est correct et vrai, au meilleur de ma connaissance.

(signature, titre) ______________________

(signature) ______________________
témoin

______________ date

REMARQUES

1. Les dimensions du plan, y compris les marges, ne sauraient excéder 35cm x 50cm comme règle générale. Cependant, s'il le faut, la moindre des deux dimensions ne devra excéder 60 cm.
2. Les écritures de plans ne sauraient être inférieures à 2mm (gabarit no. 80, C.L.).
3. Un travail accompli dans un système d'arpentage différent mais reconnu peut donner lieu à une présentation de ce genre.
4. Un tel plan peut tenir lieu d'un compte-rendu de positionnement en tout ou en partie.
5. La certification du plan par la compagnie intéressée est facultative.

Figure E-1

Specimen Plan of Survey of an Offshore Exploratory Well Location

Appendix F
Government Publications, Maps and Charts

Selected Legislation and Regulations Relevant to Surveying Offshore Canada Lands

Surveying personnel and consultants engaged in offshore surveying for geophysical or drilling operations should be cognizant of the following Acts and Regulations thereunder, which control and provide for approvals for carrying out offshore oil and gas operations on Canada Lands. Foreign operators should pay particular attention to the Immigration, Customs and Radio Acts.

available from:
Canadian Government Publishing Centre,
Supply and Services Canada,
Hull, Québec,
K1A 0S9.

Arctic Waters Pollution Prevention Act
- Arctic Shipping Polution Prevention Regulations
- Arctic Waters Pollution Prevention Regulations
- Shipping Safety Control Zones Order

Canada Lands Surveys Act

Canada Oil and Gas Act
- Canada Oil and Gas Land Regulations

Canada Shipping Act

Customs Act

Fisheries Act

Immigration Act

Land Titles Act

Northwest Territories Act

Oil and Gas Production and Conservation Act
- Canada Oil and Gas Drilling Regulations
- draft Canada Oil and Gas Diving Regulations
- draft Canada Oil and Gas Geophysical Regulations
- draft Canada Oil and Gas Offshore Structures Regulations
- draft Canada Oil and Gas Pipeline Regulations

Public Lands Grants Act
- Canada Mining Regulations

Radio Act

Territorial Lands Act

Yukon Act

International Agreements Establishing The Canada — United States Offshore Boundary

available from:
International Boundary Commission,
615 Booth Street,
Ottawa, Ontario,
K1A 0E9.

Title	Date	Area
Convention of Washington	21 April 1906	Beaufort Sea
Treaty of Washington	11 April 1908	Dixon Entrance, Strait of Georgia, Juan de Fuca Strait
Treaty of Washington	21 May 1910	Passamaquoddy Bay
Treaty of Washington	24 February 1925	Grand Manan Channel

Publications, Maps and Charts

PUBLICATIONS ON OFFSHORE EXPLORATION AND DEVELOPMENT

available, free of charge, from:
Canada Oil and Gas Lands Administration,
355 River Road, Tower "B",
Vanier, Ontario,
K1L 6S4.

Offshore Exploration
— information and procedures for offshore operators.

Offshore Report
— a periodical summary of industry's oil and gas activities.

Offshore Oil and Gas Permits
— publication of page-sized maps showing the disposition of permits, and lists of permittees.

Resources Under the Sea
— booklet of general interest on offshore exploration.

Oil and Gas Activities North of 60°
— periodical information on industry's activities.

OFFICIAL CANADA OIL AND GAS EXPLORATION PERMIT MAPS WITH INDICES

available from:
Canada Oil and Gas Lands Administration,
355 River Road, Tower B,
Vanier, Ontario,
K1L 6S4.

price per map: $3.00

Number	Scale	Area
100	1 inch = 16 miles	West coast
150	1 inch = 25 miles	East coast
151	1 inch = 25 miles	Labrador Sea and Hudson Strait
200	1 inch = 25 miles	Hudson Bay
1	1:1 000 000	Baffin Island — Davis Strait (60°N – 68°N, 57°W – 78°W)
2	1:1 000 000	Foxe Basin — Southampton Island (60°N – 68°N, 78°W – 99°W)
3	1:1 000 000	East Mackenzie (60°N – 68°N, 99°W – 120°W)
4	1:1 000 000	West MacKenzie (60°N – 68°N, 120°W – 141°W)
5	1:1 000 000	Delta — Beaufort (68°N – 76°N, 113°W – 141°W)
6	1:1 000 000	Victoria Island — Somerset Island (68°N – 76°N, 83°W – 113°W)
7	1:1 000 000	Baffin Island — Baffin Bay (68°N – 76°N, 56°W – 83°W)
8	1:1 000 000	Ellesmere Island (76°N – 84°N, 84°W – 100°W)
9	1:1 000 000	Sverdrup Basin (76°N – 84°N, 100°W – 141°W)

PUBLICATIONS ON SURVEY PROCEDURES

available from:
Canada Map Office,
Surveys and Mapping Branch,
Department of Energy Mines and Resources,
615 Booth Street,
Ottawa, Ontario,
K1A 0E9.
Telephone: (613) 998-3865

Specification and Recommendations for Control Surveys and Survey Markers, 1978
— designating accuracy standards and recommending procedures for making surveys and monumentating them, SMP 1254E.

The Mercator and Transverse Mercator Projections
— by L.M. Sebert, explaining the Mercator projection concept and outlining computing procedures, SMP-1001E

A Study of Claiming and Surveying Procedures in Relation to Mineral (Hardrock) Properties in Canada
— by D.W. Thomson, listing the 1970 regulations for all provincial and Canada Lands and discussing suitable revisions, SMP-1033E.

available from:
Canadian Government Publishing Centre,
Supply and Services Canada,
Hull, Québec,
K1A 0S9

Manual of Instructions for the Survey of Canada Lands, Second Edition

— giving the general requirements for surveys made under the instructions of the Surveyor General of Canada, $10.00 Canada, $12.00 other countries.

available from:
Geodetic Survey,
Surveys and Mapping Branch,
Department of Energy, Mines and Resources,
615 Booth Street,
Ottawa, Ontario,
K1A 0E9.

Guidelines and Specifications for Satellite Doppler Surveys

— by J.D. Boal, Geodetic Survey of Canada (being prepared for publication).

The following publications are manuals on computer programs developed the Geodetic Survey of Canada in order to process Doppler satellite survey data.

Program GEODOP, by J. Kouba and J.D. Boal, SMP-1213E.

Program PREPAR, by P. Lawnikanis, SMP-1216E.

GEODOP Utilities Program, by P. Lawnikanis, SMP-1215E

Program PREDOP, by P. Lawnikanis, SMP-1214E.

CHARTS SHOWING VARIOUS MARITIME ZONES AND LIMITS

available from:
Chart Distribution Office,
Canadian Hydrographic Service,
Ottawa, Ontario,
KIG 3A6.

Number	Scale	Area
Natural Resource Dividing Line between Greenland and Canada as defined by the Canada-Denmark agreement of December 17, 1973		
430	1:500 000	Kane Basin to Lincoln Sea
431	1:500 000	Cape Norton Shaw to Cape McClintock
432	1:2 000 000	Davis Strait and Baffin Bay
Fishing Zones of Canada as determined by Order in Council P.C. 1971-366 and P.C. 1977-1 as ammended by P.C. 1979-184		
399	1:525 000	Fishing Zone 3, Queen Charlotte Sound, Hecate Strait, Dixon Entrance
407	1:300 000	Fishing Zone 2, Bay of Fundy
408	1:300 000	Fishing Zone 1, Cabot Strait
409	1:250 000	Fishing Zone 1, Strait of Belle Isle
3000	1:1 250 000	Fishing Zone 5, Juan de Fuca Strait to Dixon Entrance
4001	1:3 500 000	Fishing Zone 4, Gulf of Maine to Strait of Belle Isle inlcuding Gulf of St. Lawrence
5001	1:3 500 000	Fishing Zone 4, Labrador Sea, Strait of Belle Isle to Davis Strait
7010	1:2 000 000	Fishing Zone 4, Davis Strait and Baffin Bay
Territorial Sea of Canada as determined by Order in Council P.C. 1972-966		
391	1:525 000	Vancouver Island
392	1:525 000	Queen Charlotte Sound to Dixon Entrance
401	1:1 000 000	South and East coasts of Nova Scotia
402	1:720 340	South and East coasts of Newfoundland
403	1:1 000 000	Coast of Labrador
412	1:300 000	Yarmouth to Halifax
413	1:350 000	Halifax to Cape Canso
414	1:300 000	Cape Breton Island (Atlantic Coast)
415	1:250 000	Cape Ray to St. Pierre
416	1:350 000	St. Pierre to St. John's
417	1:350 000	St. John's to Cape Freels
418	1:286 000	Cape Freels to White Bay
419	1:243 000	White Bay to Cape Bauld
420	1:250 000	Cape St. Charles to Domino Run
421	1:223 975	Domino Run to Hamilton Inlet
422	1:588 000	Hamilton Inlet to Nain
423	1:250 000	Nain to Saglek Bay
424	1:250 000	Saglek Bay to Button Islands

PUBLICATIONS ON ICE TERMINOLOGY

available from:
Atmosphere Environment Service,
Department of the Environment,
Ottawa, Ontario,
K1A 0H3.

MANICE — a manual of ice terminology, classification, standard ice reporting codes, and ice reconnaissance practices and procedures

PUBLICATIONS ON RADIO AIDS TO MARINE NAVIGATION

issued each March 1 and September 1
available (price: $.75 per single copy) from:
Canadian Government Publishing Centre,
Supply and Services Canada,
Hull, Quebec,
K1A 0S9.

Radio Aids to Marine Navigation (Atlantic and Great Lakes), TP 146E

Radio Aids to Marine Navigation (Pacific), TP 145E

PUBLICATIONS ON CANADIAN TIDES

available from:
Chart Distribution Office,
Canadian Hydrographic Service,
Fisheries and Oceans,
1675 Russell Road, P.O. Box 8080,
Ottawa, Ontario,
KlG 3A6.

Canadian Tidal Manual
— practical information for hydrographic surveyors, engineers, and an explanation of the theory of tide predictions. Ottawa, 1983.

Tide and Current Tables, Vol. 1-1V, Atlantic Coast and Arctic
— an annual publication of tide tables for ports and current tables for ports and their approaches.

Atlas of Tidal Currents, Bay of Fundy and Gulf of Maine
— describes tidal currents at hourly intervals relative to times of high and low water at St. John, N.B., Ottawa, 1981.

GENERAL BATHYMETRIC CHARTS OF THE OCEAN (GEBCO)

available from:
Chart Distribution Office,
Department of Fisheries and Oceans,
1675 Russell Road, P.O. Box 8080,
Ottawa, Ontario,
KlG 3R6.

Charts illustrating the general shape of the sea-bed by colour gradation and depth contours. Mercator projection from 72°S to 72°N, scale 1:10 million at the equator; polar stereographic projection to 64°N and S, scale 1:6 million at the poles. Numeric designation of sheets is shown in Figure F-1.

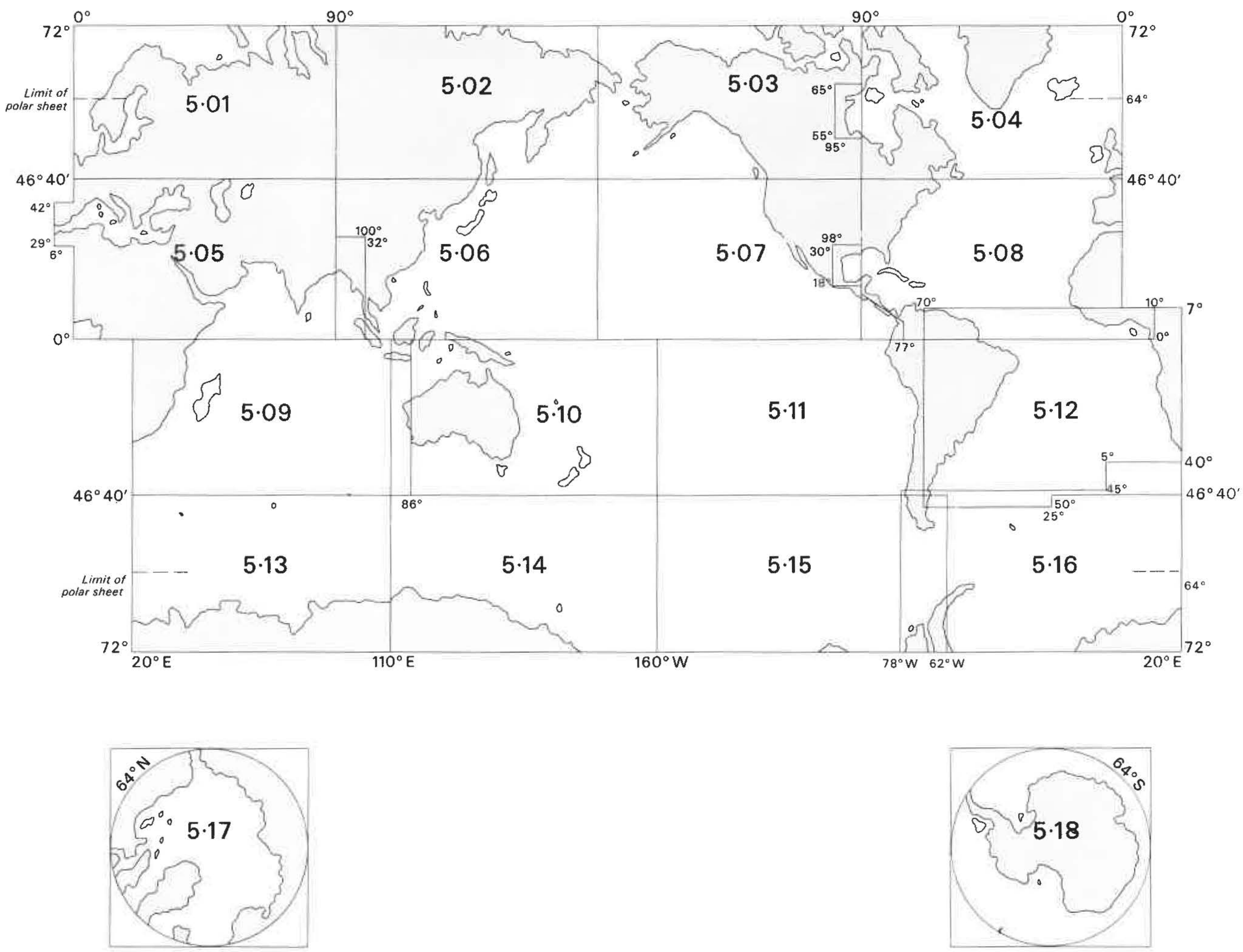


Figure F-1

Sheet Index for General Bathymetric Charts of the Oceans

OFFICIAL MAPS AND CHARTS OF THE CANADA-UNITED STATES INSHORE BOUNDARIES

available from:
International Boundary Commission,
615 Booth Street,
Ottawa, Ontario,
K1A 0E9.

Title	Sheet No.	Scale	Area
International Boundary from the Source of the St. Croix River to the Atlantic Ocean	15, 16, 17, 18	1:24 000	Passamaquoddy Bay, Grand Manan Chanel
Joint Chart of the International Boundary between United States and Canada from the 49th parallel to the Pacific Ocean		1:200 000	Strait of Georgia, Haro Strait, Juan de Fuca Strait.
International Boundary between United States and Canada from Cape Muzon to Mount St. Elias	1,2	1:250 000	Dixon Entrance
International Boundary along the 141st meridian	1	1:62 500	Beaufort Sea

Appendix G

Offshore Monumentation

The findings of the 1970 Workshop regarding monumentation are still relevant. They are repeated here with only minor changes, except for an extensively revised section on acoustic beacons and transponders.

Corrosion of metal structures is a major consideration for any offshore monumentation. Short-term protection can be provided in the form of inert or galvanic coating and increased cross-sectional areas to compensate for metal loss. Long-term protection can only be given by cathodic processes which require a permanent power supply to maintain a potential difference, or in which a constant replenishment of the sacrificial metal of an anode must be made.

Towers

Two types of towers may be used for survey monuments out of sight from land: permanent towers fastened to the bottom of the continental shelf (life expectancy, 20 to 50 years), and floating towers moored to the sea-bed (life expectancy, two years).

Permanent Towers

These towers are equipped for helicopter landing, and have been built in Canadian coastal waters for lighthouse purposes as well as elsewhere in the world for oil production at sea. An adaptation of these towers would be suitable for permanent referencing. They can be used for landing purposes whenever weather permits helicopter flight, and are sufficiently stable to meet the rigid requirements for astronomic observations.

The construction cost is very high depending on water depth, expected sea states, ice conditions and other factors; and, could not be justified for position information only. It is doubtful if it could be justified even considering shared use for aids to navigation or for scientific purposes.

Oil production platforms have been built in the North Sea, in the Gulf of Mexico and off the coast of California and in many other offshore regions of the world. Representative cost figures for 1975 were as follows:

30 m depth, \$3 to 5 million;
65 m depth, \$5 to 11 million;
130 m depth, \$11 to 15 million;
250 m depth (proposed), \$65 million.

Costs vary with depth and other design considerations such as the number of wells to be drilled (up to 48 from one platform), environment and oceanography. These platforms were designed to last as long as the calculated life of the oil and gas field, normally between 15 and 25 years depending on engineering and many other factors.

Floating Towers

Two types of floating towers have been built in Canada:

- Scientific Stable Platforms: built in Lake Superior, Gulf of St. Lawrence, and off Halifax, in relatively shallow water where divers could assemble moorings. In Lake Superior, the towers were removed in the fall and replaced in the spring to protect them from ice. Off Halifax, the tower remained for two years before being destroyed by a storm. These platforms have no helicopter platform and can be boarded only in a calm sea.
- Semi-Submersible Oil-Drilling Units: mobile (floating) offshore drilling units, such as the semi-submersibles referred to under Deepwater Drilling Techniques and in Figure1, are usually on a one-well location for periods of only one to three months. Their stability permits accurate location, but precise astronomic observations would not be possible without a gyro-stabilized platform.

Buoys

There are many types of buoys each having different characteristics. Common navigation buoys are described in a booklet published by the Department of Transport (1975), "The Canadian Aids to Navigation System". Basically they are moored in two ways: conventionally, which involves moorings of two to three times the water depth (Figure G-1 (B) (C)); and taut line, having the shortest mooring, consistent with keeping the buoy visible (Figure G-1 (A)). Buoys are recoverable under normal conditions of sea and weather, and are easily identifiable.

A relatively long life (two years or more) can be obtained with moorings approximately two to three times the water depth, but obviously this permits greater movement of the buoy and hence less accurate position (Figure G-2). Greater accuracy can be obtained by taut-line mooring (Figure G-1 (A)); however, with this method, buoy life is measured in terms of months, even with weak currents and good weather.

Maintenance at sea is normally a matter of replacement as determined by the mooring life of the buoy on station, and replacement requires that the complete buoy system be raised and a new system laid. Present buoy-laying technology makes it impossible to locate this new system on the identical spot. Therefore, we have virtually a new monument requiring reactivation of a positioning system to re-fix the buoy.

Further drawbacks is using buoys as monuments involve dragging their moorings in heavy weather, particularly taut-line moored buoys, a movement which may not be readily noticed. Buoys are susceptible to ice accretion and toppling, and may be dislodged off station by floating ice, or frozen in and crushed.

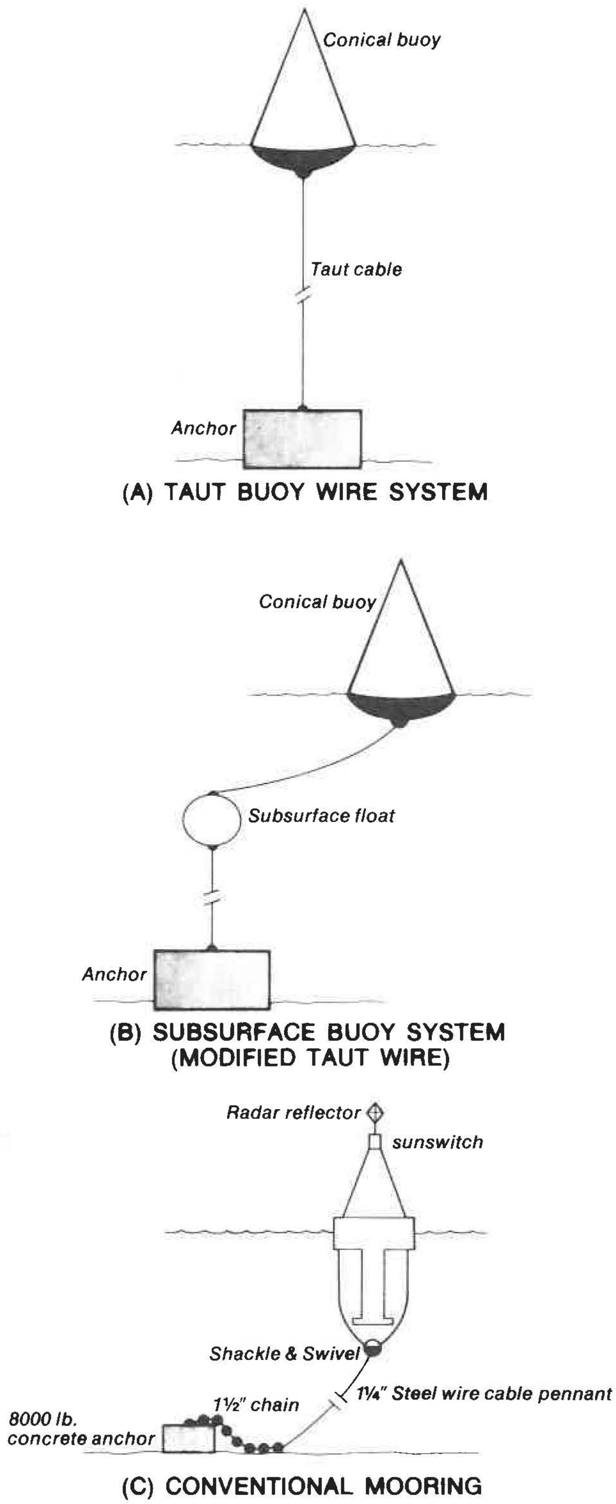


Figure G-1

Types of Buoy Moorings

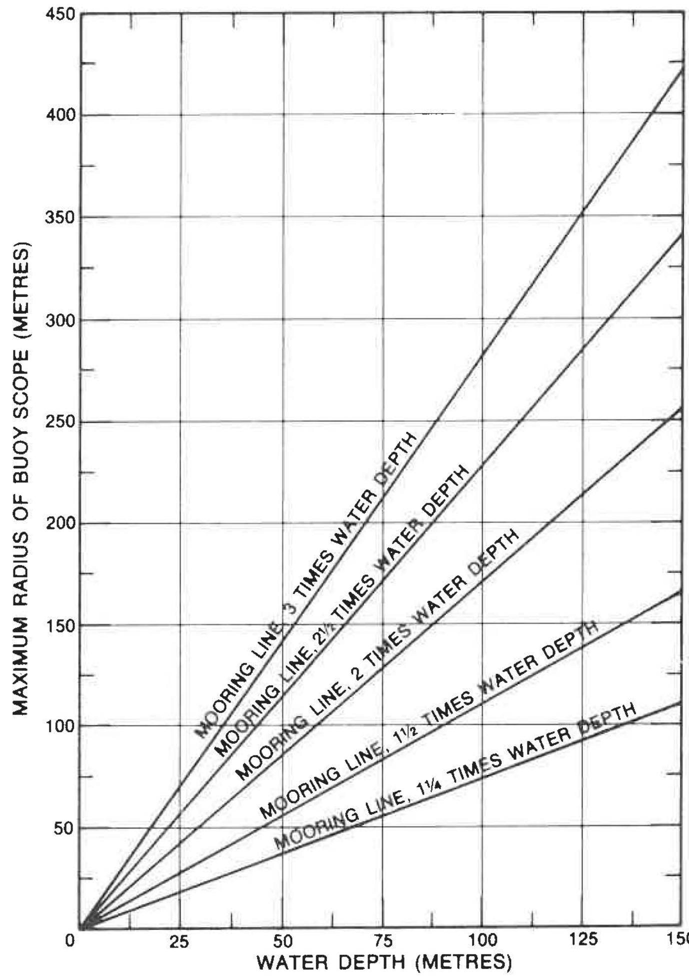


Figure G-2

Variation of Buoy Scope with Water Depth for Different Mooring Lines

There is also the possibility of their being moved or even removed by fishermen operating in the area.

The Department of Transport has had experience working with buoy anchorage to a depth of about 120 m. Mindful of the periodic checking necessary in any buoyage system, the Department of Transport operates on a one to two-year replacement schedule, and on an approximate four-month checking schedule.

Acoustic Beacons and Transponders

The acoustic beacon gives a continuous underwater signal which can be detected by sonar receivers. The transponder responds to a keyed sonar signal. The life of the acoustic beacon depends primarily on the life of the power pack, while the transponder is dependent on the number of interrogations and on battery shelf life. Passive transponders are commonly used as acoustic-release systems for ocean-instrument packages. The life of the power pack for these systems is typically one year, with a maximum of two years. Because of corrosion, it is unlikely that the assured life of the total system could be beyond five to seven years regardless of the power source. Transponders can be coded to provide definite identification to avoid confusion or ambiguity in any array.

Distances at which these devices may be detected by sonar receivers depend on acoustic noise, but the distances are generally in the two to three kilometre range. To achieve such range, the transponder should be buoyed above the sea bed, because range and accuracy decrease with depth and the transponder's proximity to the sea bed.

Positioning a vessel relative to the transponder presents problems which are discussed under Acoustic Positioning Systems. Maintenance of these instruments involves replacement, and entails the use of divers or submersibles, or redropping and refixing; the latter involving the reactivation of a positioning system.

The Department of National Defence has indicated that if such a system was considered, they would favour a type of transponder which could be readily deactivated.

A typical cost for a coded transponder with a one-year life power pack, and bottom-release system would be $10 000 per unit.

To summarize, these transponder locations cannot be occupied, and the transponders are of a variable life with cost of the power unit increasing substantially to achieve a life of useful duration. The transponders are subject to movement and are not reliable.

Research work on acoustic transponders is continuing, but emphasis is on their use as navigational or positional aids.

Wells

Abandoned offshore exploratory wells are useless as survey monuments.

Long life, stability and permanence of position are all desirable features for any survey monument, and abandoned wells qualify in those areas, and in addition, no maintenance is required for such a well.

Identification and the ability to be occupied are two essential criteria for any marker used as a survey monument; these features are extremely difficult to obtain with abandoned wells. Present methods of abandoning most wells at sea leave no physical evidence on the sea bed that a well has ever been drilled. The casing is usually sheared off from 5 to 10 m below the mudline and all equipment recovered. Within a short time, the hole fills in and no man-made evidence can be detected.

If any visual means, such as a TV camera, were used to relocate an abandoned well, some physical hardware would have to remain on the sea bed at the time of abandonment; however, anything left on the bottom is subject to destruction by icebergs and fishing draggers. Therefore, a new procedure for detection would have to be developed and this does not seem feasible at the present time.

Magnetic detection of the well casing was a method considered for finding an abandoned well. This might be accomplished by towing a magnetic-sensing head near the sea bed in the vicinity of the well. At best, this would give only a relative position for one instant, and one could never be positive of the sensing head's position relative to the well. Appendix C of the first edition (1970) of the Workshop report gives a more detailed appraisal of the method.

Both visual and magnetic-detection methods are considered to be cumbersome and difficult to use, and have the added objection that one can never be certain of the observer's position relative to the marker.

In summary, abandoned wells are difficult to find, cannot be occupied, and in some cases may not be identifiable; therefore, they are not considered useful as survey monuments at sea. On the other hand, production wells in the offshore are associated with permanent structures, above water or on the seabed (Figures 13 and 14). These structures have excellent characteristics for use as survey monuments (see monuments and underwater completions).

Cables

Cables were considered from two standpoints: first, as electronically-detectable line markers along the ocean floor so that intersecting lines would define a point; second, as a means of providing a permanent power source to active bottom transponders.

Cables are unsuitable as line markers because the shielding needed to protect them makes them virtually undetectable unless a break occurs. They are also very prone to movement and breakage wherever there is a dragging operation or where icebergs ground. As an example, icebergs near Greenland which rested on a cable at a depth of 230 m, broke the cable and prevented repairs for a period of six months.

Some protection is afforded, at great cost, by burying the cables. In fact, buried cables have not experienced any breaks to date. However, the cable companies have not devised a means of recovering buried cables.

Cables are inordinately expensive as a means of providing permanent power to acoustic transponders.

Wrecks

It is well known that the Canadian continental shelf is strewn with ship wrecks of various sizes at various depths. At present, the approximate locations of most of these wrecks are classified as military information. It is believed that this security restriction could be overcome, in specific instances, if these wrecks could be used as boundary reference marks.

At first glance it might appear that these sunken wrecks would be ideal markers if they were situated near the points being referenced, for their locations would not require any construction or maintenance expenditures.

In many cases, these approximate locations of wrecks are based on dubious information such as the last reported dead reckoning position of the vessel before it sank; often, the final resting place of the vessel is far from the reported position. Consequently, it is likely that an extensive search with special acoustical equipment would have to be undertaken to pinpoint the actual position of a particular wreck. In all probability, such acoustical equipment would have to be used each time a reference was made to a monument, although such a search would be facilitated by the previously determined coordinates of the wreck.

Sunken ships are subject to shifting due to underwater currents, their being covered by silt, and breaking up. Thus, only those ships of substantial size and in a reasonably good state of preservation could be classed as permanent enough for consideration as monuments.

Although limited use has been made of wrecks as positioning aids during offshore mineral exploration surveys (for example, wrecks have been used to check transponder movement), the use of sunken ships as survey monuments can be disregarded.

Potential Field Anomalies

The Ocean Science and Surveys Service, Department of Fisheries and Oceans, records continuous measurements of the earth's gravity and magnetic fields in conjunction with offshore bathymetric surveys. The contoured presentations of these measurements, showing their variability on a sea-level datum, are prepared in a manner similar to that of bathymetric charts.

Magnetic

Factors affecting the accuracy and repeatability of magnetometer measurements can be divided into three broad classes: instrument system errors, which are probably less than five nanoteslas, approximately predictable time-varying changes in the magnetic field, which are generally of the order of 25 nanoteslas, unpredictable transient disturbances called magnetic storms (which may exceed several hundred nanotesla).

Due to the numerous error sources, the exact position of a point, even on large-amplitude high-frequency magnetic anomalies, is not sufficiently well defined to serve as a survey monument.

Gravity

The accuracy and repeatability of shipborne gravimeter measurements are affected by instrumental and environmental factors. At present the accuracy of shipborne gravimeter measurements is approximately two to three milligals under carefully controlled surveys with good navigation.

As gravity anomalies are generally of less gradient than a few milligals per kilometre, contours of anomalies are not sufficiently definitive to serve as survey markers or monuments.

Physical Features

The Canada Oil and Gas Land Regulations refer to the use of a topographical feature identifiable on a map published by, or on behalf of, the government of Canada. Offshore, submerged topographical features are normally shown only on nautical charts. These charts have been designed as aids to marine navigation, and due to the inherent variables of chart usage and need, any two charts of the same area may not be identical in character and scope. The variety of seafloor relief is presented in a clear and practical manner, so that dangers and features useful as aids are identifiable, when navigating by echo-sounding or other sonar apparatus. Lines of depth sounding are widely spaced in deep water, but are more closely spaced on the continental shelf and in shoal water. Depth contours are used to clarify features relevant to navigation.

Physical features of the seafloor do not appear to be useful as monuments, but may serve as reference marks when relocating or recovering abandoned wells, wrecks, acoustic reflectors or other apparatus. These features fall into two categories. Bottom features include shoals, banks and canyons which have been identified during the course of hydrographic surveys and are shown on nautical charts; bottom characteristics are shown by appropriate abbreviations.

Identifiable sub-bottom features are usually rock formations or, in some cases, sunken wrecks covered by a layer of sediment. These features are frequently detected during the course of hydrographic surveys because the echo-sounding signals penetrate the sediment, are reflected back to the survey ship, and are recorded in the same manner as the bottom seafloor. These sub-bottom features are not normally shown on nautical charts.

Acoustic Reflectors

On the continental shelves, underwater positioning systems using an array of reflectors could be very useful in positioning a vessel. Distances measured to acoustic reflectors are affected by many factors: the quality of the transmitting-receiving equipment; the transmitting medium itself, which affects the velocity of sound; the signal frequency and target characteristics; and the ship's speed and bearing to the target.

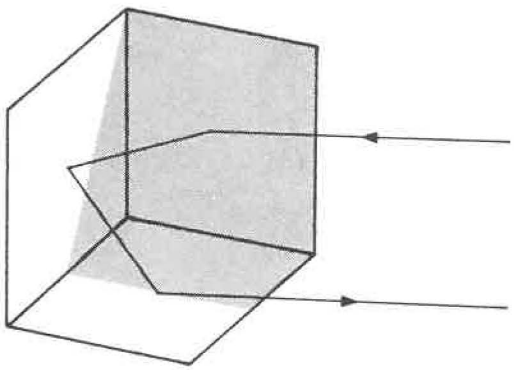
To detect a reasonably-sized target, the transmitting-receiving equipment must be highly directional and operate at high frequencies. This results in higher signal-to-noise ratio. Attenuation increases with frequency and reduces the effective range. Frequencies from 5 to 40kHz are commonly used in echo-ranging.

The transmitting medium, in this case sea water, has undergone considerable study as to its effect on the propagation of underwater acoustic signals. This information is readily available and is discussed at length in various texts (Ingham 1974). Conditions vary from one locality to another and, for accurate measurements of range, careful calibration must be carried out for every array of reflectors to determine the various parameters affecting propagation.

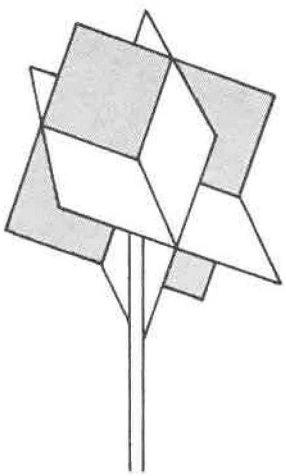
The strength of the reflected signal depends on the size, shape, orientation and position of the target, in relation to the transmitted signal and on the range from the signal source. All these factors combine to determine the target strength.

Target strengths of cylindrical objects vary with orientation. Spheres make good targets because their target strengths are relatively independent of orientation. Highly compressible spheres such as gas bubbles have greatly increased target strengths.

The greatest target strengths are obtained from flat surfaces perpendicular to the acoustic signal path. Corner reflectors and triplane reflectors (Figure G-3 (A)(B)), give an almost



(A) CORNER REFLECTOR



(B) TRIPLANE REFLECTOR

Figure G-3

Types of Acoustic Reflectors

constant reflected signal, regardless of the direction from which the signal is received.

Considerable increase in target strength is obtained by constructing the triplane target so that its reflecting plates contain air space.

The triplane target has undergone a series of tests to determine effective ranges compared with other targets of various shapes, and appears to be the most efficient type when size is considered. Most targets of this type use plane surfaces two metres to a side, and may be detected at ranges up to 1 000 m. The cost of such reflectors, including anchoring systems, is upwards of $2 000.

To make the target signal distinguishable from background reflections, the target must be held off the sea bed (usually about seven metres). This required buoys, anchors, and cables, thus introducing some attendant disadvantages.

There seems to be no doubt that a system of reflectors accurately positioned near the ocean floor could be used to position a surface of a sub-surface vehicle. The attendant problems are similar in many ways to those of buoys and, in addition, the target cannot be located visually.

The maintenance of the system, once established, would be similar to that of buoys and transponders. A regular series of checks on the stability of their positions would be required, and they would have to be repositioned after maintenance. Target strength would be lost due to sea growth on reflecting surfaces (to some extent), other deposits and chemical reaction.

The reflectors would be subject to the limited life of the anchoring system (cables, buoys, etc.) and would therefore be vulnerable to fishing draggers. All these disadvantages, plus the difficulty of accurately positioning them, give some indication of the problems which, although not insurmountable, would require serious consideration and study.

Appendix H

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