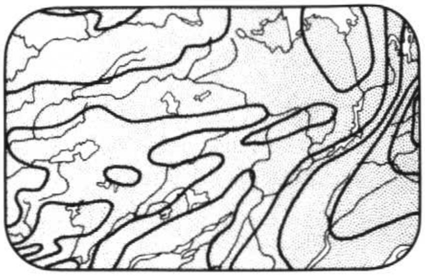

Gravity Mapping in Canada: A Review of Progress

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Summary
We review progress made in the gravity survey of Canada from its inception in the early part of this century to the present time. We briefly describe the National Gravity Network of control stations and its relationship to the International Gravity Standardization Net of 1971. Gravity data services offered to the private and public sectors by the Gravity and Geodynamics Division of Earth Physics Branch are also described briefly.

Introduction
Each year EMR's Gravity Service extends gravity coverage over Canada's landmass, inland seas, and continental shelves. During 1976, 4600 new gravity stations and 15,000 line kilometres of continuous shipborne gravity measurements were added in the national gravity mapping program. Helicopter-supported surveys were made on sea-ice in the Beaufort Sea, Amundsen Gulf and James Bay, on the ice of Great Slave Lake, and over Cape Breton Island and other parts of Nova Scotia. At sea, an underwater gravimeter survey was undertaken west of Vancouver Island and the Queen Charlotte Islands and shipborne gravimeter cruises were completed off the northwest coast of Vancouver Island and in Hudson Bay.

The national gravity mapping program is organized and directed by the Gravity Service of the Earth Physics Branch (formerly the Dominion Observatory), Ottawa, which has a history in gravity measurements dating back to the beginning of the century. Most gravity measurements on land and ice surfaces have been made by the Gravity Service, but a large proportion of those acquired on the open sea has been collected by the Atlantic Geoscience Centre of the Geological Survey of Canada, Dartmouth. Gravity and related data collected by these agencies are stored in the National Gravity Data Base at the Earth Physics Branch. Throughout the years, contributions to this data base have also been made by various provincial government departments, universities, and mineral and petroleum companies.

The objectives of the gravity mapping program are: to collect and disseminate data and information on spatial and temporal variations in the gravity field; to develop instrumentation and methodology for acquiring these data; and to provide storage, retrieval, display and management services for these data.

Review of Progress
As far as can be determined, the first gravity measurement in Canada was made in 1820, near Winter Harbour, Melville Island, by Lieutenant Edward Sabine, a member of Sir William Parry's expedition in search of the northwest passage (Sabine, 1821). He used Kater pendulums to obtain his results which were subsequently used in studies of the figure of the earth. It was not until 1891, however, that a gravity measurement was made in Canada with a relatively modern apparatus, which was to play an important role in gravity measurements in Canada for approximately another half century. The apparatus was the Mendenhall invariable half-second pendulum (Fig. 1) developed by the United States Coast and Geodetic Survey (Mendenhall, 1892). This pendulum was tested during an expedition to Alaska, and one of the measurements was made at Port Simpson, British Columbia. Canadian interest in the measurement of gravity was heralded in 1902 when a half-second pendulum modelled after the Mendenhall apparatus was obtained from the United States Coast and Geodetic Survey by the Observatory Division of the Astronomical Branch, Department of the Interior. That same year, O. J. Klotz, later to become director of the Dominion Observatory, measured gravity at Ottawa, Montreal and Toronto (Klotz, 1908). Apart from one measurement in Labrador in 1905, no further gravity observations were made in Canada until 1914 when 18 observations were made as part of a planned coverage of the whole country and Ottawa was selected as the base for all Canadian work (McDiarmid, 1915). Presenting reasons for covering the

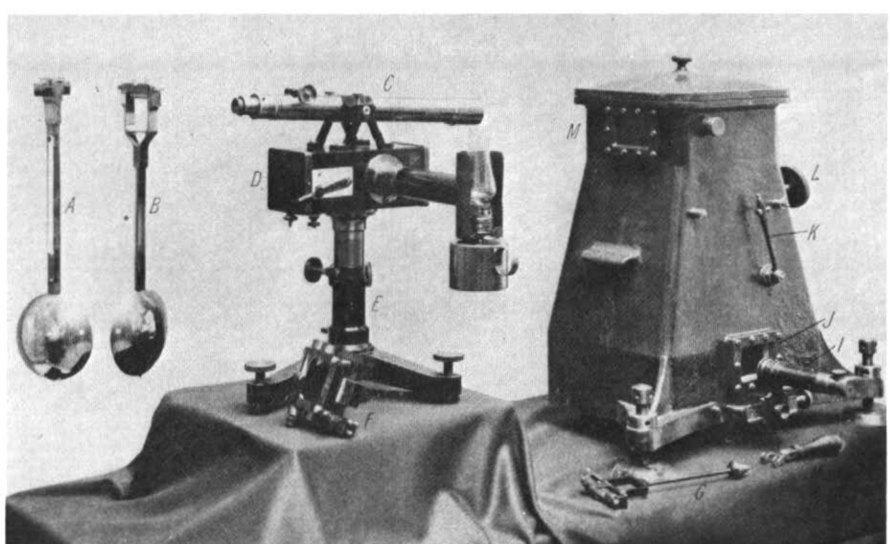


Figure 1
The Mendenhall invariable half-second pendulum apparatus.

Canadian landmass in this fashion, McDiarmid reiterated the "reasons for the prosecution of pendulum work" given by C. S. Peirce of the United States Coast and Geodetic Survey at a conference on gravity determinations held in Washington in 1882 (Peirce, 1883). His reasons were for geodetic studies, for application to metrology, for geological studies, for application to the use of gravity as a unit in the measurement of forces, for plumb line deflection studies, and for a need to measure gravity because it is a fundamental quantity. McDiarmid concluded that "what was true in 1882 applies with equal force in 1914, and especially in a country such as Canada where a geodetic survey is only in its infancy". Here, then, were sown the seeds of a national gravity mapping program. Unfortunately, the multidisciplinary structure of the Dominion Observatory did not always allow for a concentrated effort in pursuing the goals outlined by McDiarmid, and consequently this factor in conjunction with the slow and laborious procedure of obtaining pendulum measurements resulted in only about 150 observations being included in the 1939 Gravity Map of Canada, most of which had been made in the populated south (Miller, 1940). During the period 1929 to 1934, the Eötvös torsion balance, which measures the horizontal and curvature gradients of gravity, was used briefly as a prospecting tool. However, it was not until 1944, when the gravity meter supplanted the pendulum, that a new era in gravity mapping began in Canada. This innovation coupled with the use of float-equipped aircraft for landings on lakes, resulted in a rapid re-survey of parts of southern Canada previously covered by the pendulum observations, and in the coverage of large areas of northern Canada. Thus at the end of 1956, when the first Gravity Map of Canada based essentially on gravity meter measurements was in preparation, some 15,000 observations had been made (Innes, 1957). Station spacing during this period (1944 to 1956) was quite variable, generally ranging from 10 to 50 km and an average of 1100 new observations was made each year. Approximately half of these stations have since been discarded and replaced by new stations established with improved elevation control and modern gravity meters. A graph of a number of observations per year depicting progress in the gravity mapping program of the Earth Physics Branch for the period 1944 to 1975 is shown in Figure 2. Figure 3 is the cumulative total observations obtained by the Gravity Service from all sources for the same period.

In 1957 the mapping program was modified to measure gravity at intervals no greater than 15 km to obtain a more uniform distribution of stations. With the increased use of fixed-wing aircraft in 1958 and the introduction of helicopters in 1960, an average of 7000 new stations was observed annually in the period 1958 to 1967 and a third edition of the Gravity Map of Canada was published in 1967 (Innes and Gibb, 1970). This significant increase in station production fortunately coincided with the advent of electronic computers and the Division rapidly adopted computer methods for gravity data processing (Tanner and Buck, 1964). Most of the Canadian Shield had been covered by this time along with large areas of the Arctic islands and seas. Relatively little progress had been made in the Cordillera.

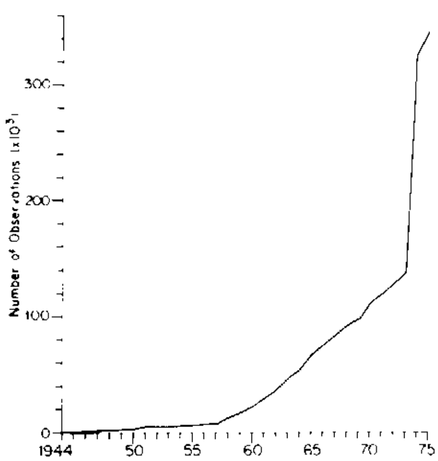


Figure 2
Graph of number of gravity observations per year measured by the Gravity Service, Earth Physics Branch for the period 1944 to 1975. Appropriate symbols indicate highlights as follows: 1944 to 1957 - surveys by car with limited use of fixed-wing aircraft; 1958 - greatly increased use of aircraft for systematic surveys; 1960 - introduction of helicopters, 1961 - first ice-surface and underwater surveys; 1972 - introduction of systematic sea-surface surveys by the Gravity Service

The fourth edition of the Gravity Map of Canada compiled from 350,000 stations was published in 1974 (Fig. 4). The methods used to prepare the map are described by Nagy (1976). The greatest change in the period 1967 to 1974 was the increase in sea-surface surveys. This trend is likely to continue for several years.

Canada has an area of almost 10 million km². The adjacent shelf seas cover an additional 3.8 million km². Within this vast region considerable variations in climate (semi-arid to Arctic), in terrain (ancient peneplains to Cordilleran peaks), in vegetation (dense bush to treeless barren lands), and in the means of communication (roads restricted to the southern populated regions), have necessitated a variety of approaches to the gathering of gravity data, both in regard to transportation and to instrumentation. Four main categories of gravity surveys are conducted: land surveys (Fig. 5); ice-surface surveys; underwater surveys (Fig. 6); and sea-surface surveys. The planned coverage by each type of survey is indicated in Figure 7. The progress to January, 1976 in covering these regions is also indicated (the 500 m bathymetric contour is a purely arbitrary limit in Figure 7 as many surveys have gone and will continue to go beyond this limit). Approximately 80 per cent of the entire region has been covered by 134,000 discrete (static gravimeter) observations and 211,000 shipborne (dynamic gravimeter) observations as shown schematically in Figure 8.

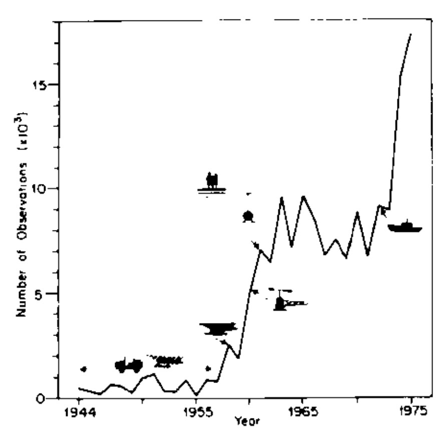


Figure 3
Cumulative total gravity observations contributed to the National Gravity Data Base from all sources for the period 1944 to 1975.

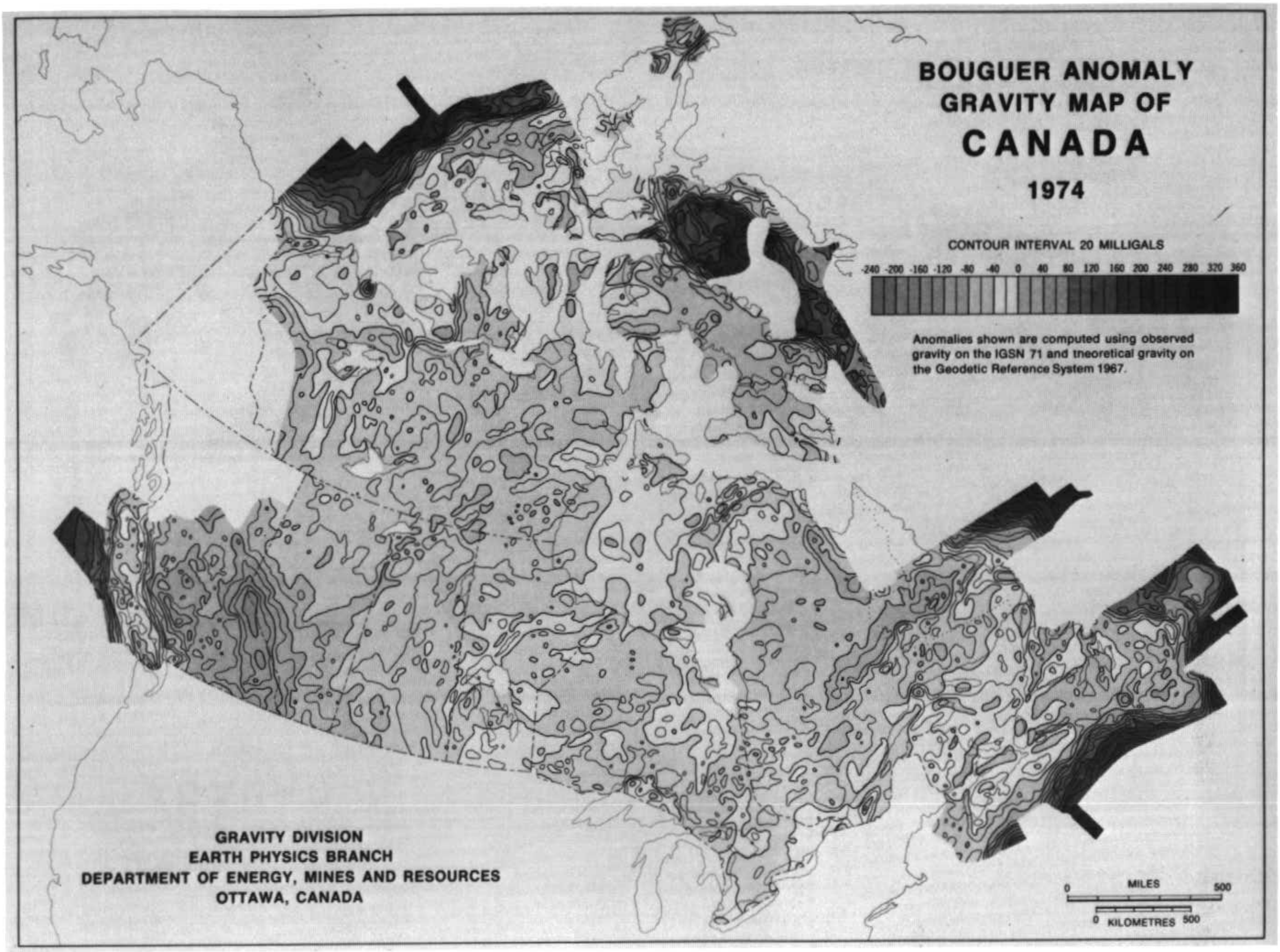


Figure 4
Gravity Map of Canada.

Figure 5
Today, La Coste and Romberg model G gravity meters are used for all land surveys made by the Earth Physics Branch.

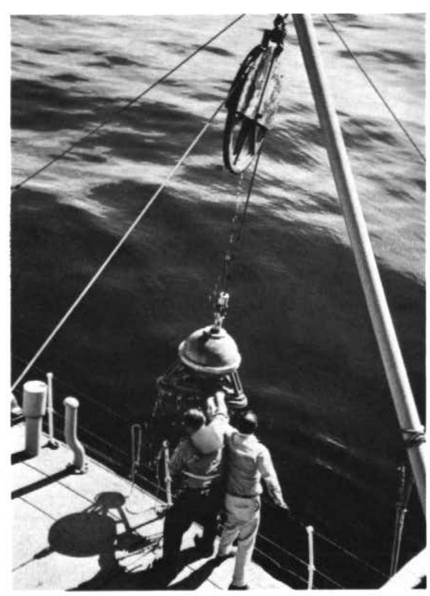


Figure 6
A La Coste and Romberg underwater gravity meter is hauled aboard after an observation on the sea-floor.

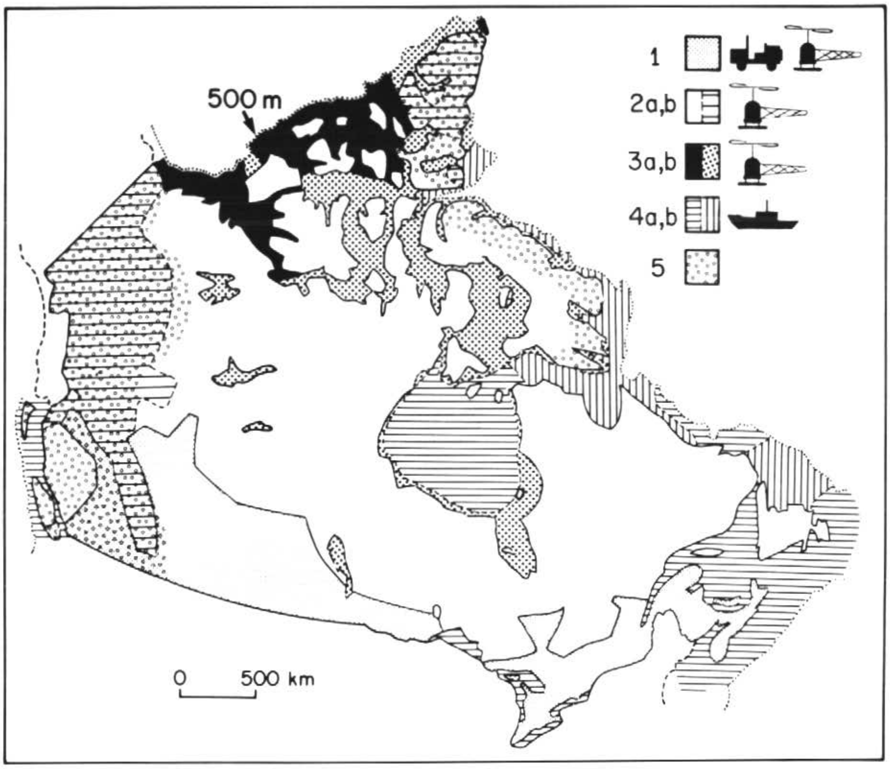
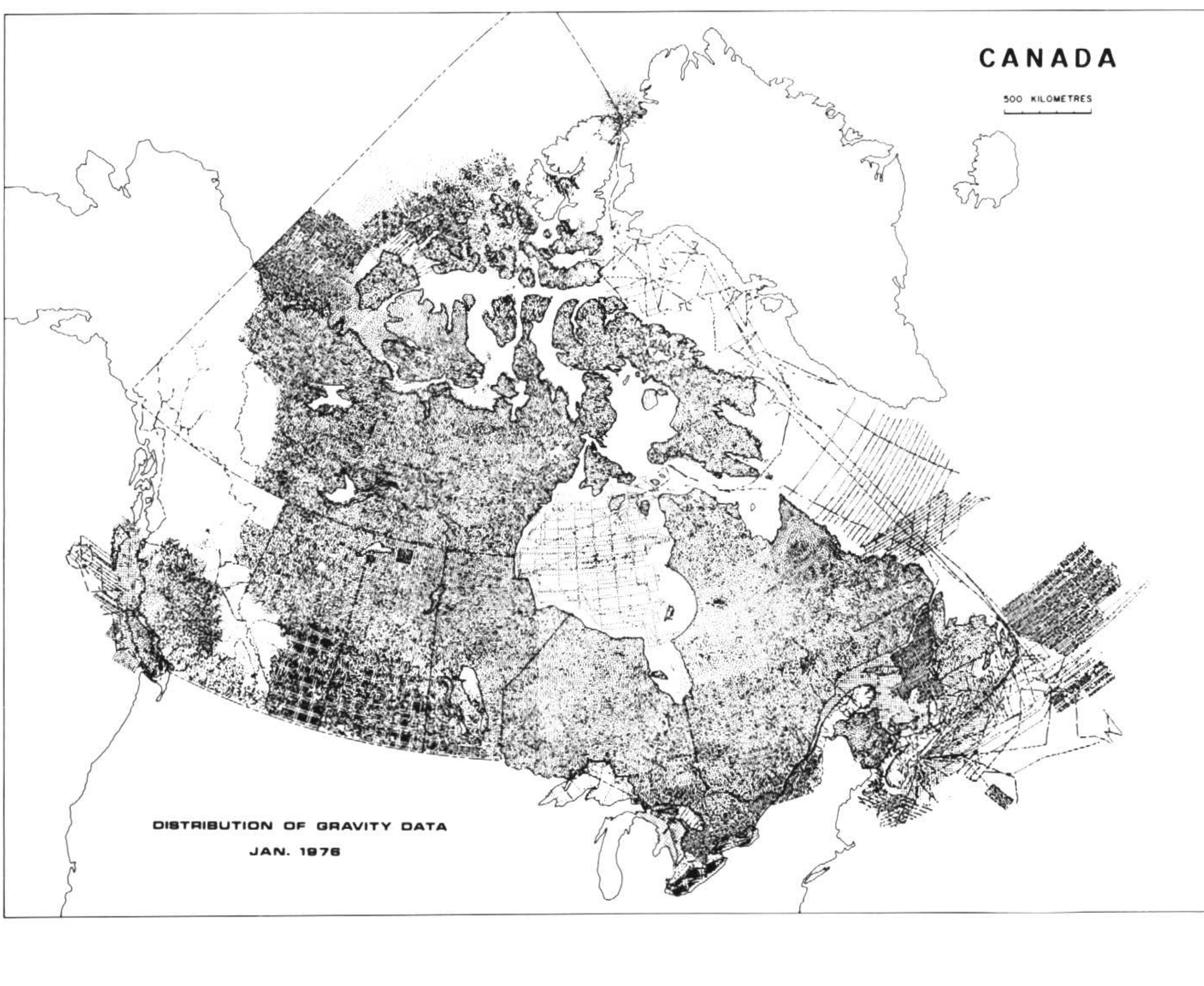


Figure 7
Gravity coverage in Canada according to type of survey (to January, 1976). Surveyed and unsurveyed areas beyond the 500 m bathymetric contour are not shown. The distribution of data in oceanic areas is shown in Figure 5. 1 - road covered area, 100% surveyed; 2a - hinterland area, 84% surveyed; 2b - unsurveyed area 1,315,000 km^2; 3a - ice-covered area, 35% surveyed; 3b - unsurveyed area 942,000 km^2; 4a - water-covered area, 75% surveyed; 4b - unsurveyed area 526,000 km^2; 5 - mountainous terrain. Total unsurveyed area 2,783,000 km^2.

Figure 8
Distribution of gravity data in Canada to January, 1976.



The remaining unsurveyed areas of Canada have a common requirement for non-routine survey techniques due to difficulties of terrain or other hostile environments. On land the main unsurveyed areas are the western Cordillera of British Columbia and the Yukon, and the mountainous northern Arctic Islands. There progress will depend largely on the availability of monumented stations with known elevations and sufficiently detailed topographic maps. At sea the remaining areas include parts of the Atlantic and Pacific continental shelves, and parts of Hudson Bay, Hudson Strait, Davis Strait and Baffin Bay. Ice covered regions include the Canadian sector of the Arctic Ocean, the inter-island channels of the Arctic Islands, Foxe Basin, and some of the large inland lakes. The sea and ice surveys are usually undertaken as cooperative efforts with other mapping agencies such as the Canadian Hydrographic Service, the Polar Continental Shelf Project, and the Geological Survey of Canada. The rate of progress will therefore depend not only on availability of ships and navigation aids but also on the concerns, priorities, and continued cooperation of these agencies. At the present rate of coverage the reconnaissance gravity mapping program is likely to continue for 15 to 20 years. In addition to the environmental constraints, the increased cost of navigation and transportation in the remaining areas compared to the remainder of Canada will mean that the area mapped each year will decrease if operations remain at about the present level.

Gravity Standards

The reference standard for relative gravity observations in Canada has recently been converted to the new world system of absolute gravity values adopted by the International Union of Geodesy and Geophysics (McConnell and Tanner, 1974). This system known as the International Gravity Standardization Network 1971 (IGSN71) consists of 1854 stations around the world (Morelli *et al.*, 1974). The datum for IGSN71 is provided by absolute measurements, the scale is controlled by both absolute and pendulum measurements, and the internal structure is provided by some 24,000 gravimeter observations.

In Canada all gravity measurements in the National Gravity Data Base are tied to the National Gravity Network (Fig. 9), which comprises approximately 3,400 control stations having an absolute accuracy of ±0.1 mgal, and a relative accucacy of ±0.05 mgal (McConnell and Tanner, 1974). Most of the control stations have been established with LaCoste and Romberg gravimeters, although a limited number of older connections were made with Worden and North American gravimeters. The network is solidly tied to the 20 stations of IGSN71 that are located in Canada. These are spread throughout Canada and provide datum and scale for the adjustment of the Canadian net to the new absolute standard. The Geodetic Reference System 1967 has also been adopted in Canada to replace the International Ellipsoid of 1930 as the reference surface for the computation of theoretical gravity.

Gravity Data and Maps

The gravity and related data are stored in the National Gravity Data Base maintained by the Gravity Service in Ottawa. The evolution and design of this data base, which now contains approximately 345,000 observations, have been described by Buck and Tanner (1972). Information may be retrieved from the data base in several formats - listings, punched cards, magnetic tapes, and plots depending on the customer's preference. Plots are available at any specified scale and a variety of map projections. Customers who use these services include petroleum and mineral exploration companies, provincial and federal government agencies responsible for mapping and resource inventories, geophysicists, geodesists, and geologists of the Canadian and international scientific communities.

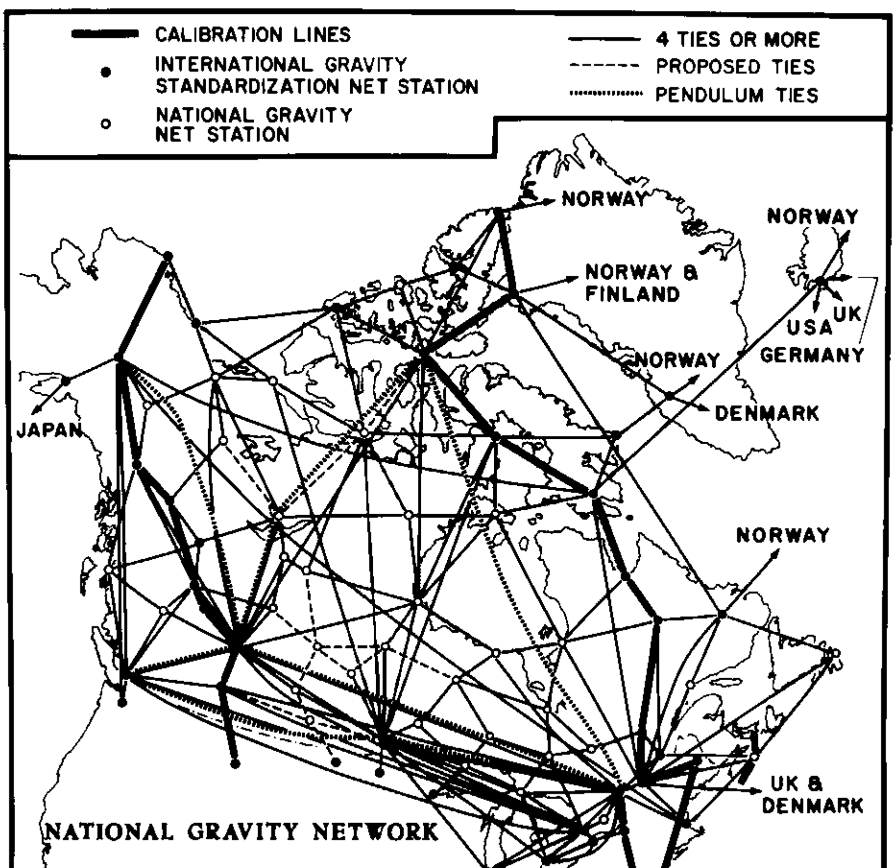


Figure 9
The principal control stations of the national gravity network.

The Gravity Service publishes the results of its surveys in a series of maps, generally at a scale of 1:500,000, known as the Gravity Map Series. These are usually accompanied by a report describing the gravity surveys, the gravity anomalies, and their correlation with geology. The Atlantic Geoscience Centre publishes its data in the form of maps of the Natural Resources Map Series at a scale of 1:250,000. This series is produced by the Canadian Hydrographic Service. Reports are published jointly by the Departments of Energy, Mines and Resources and Environment in a series of Marine Science Papers. Data are also released through the open file systems of the Earth Physics Branch and the Geological Survey of Canada respectively.

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