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The contributions of the International Gravimetric Commission (IGC) to global surface-gravity determinations

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Abstract. The role of the IGC in the development of global terrestrial and marine gravity can be illustrated by two examples: the International Gravity Standardization Net 1971 (IGSN 71) and the Gravity Survey of the Mediterranean Sea. In both cases, the IGC organization and the international cooperation, with the open minded spirit of the participating scientists were at the basis of its success. Some results, with important theoretical and practical consequences, are briefly outlined.

1. Introduction

The International Association of Geodesy (I.A.G.) is the oldest international scientific organization (1862). It has many merits: one of which is the creation of IGC (1951(1)). The scientific activity summarized here was promoted, discussed and realized in international cooperation, with the ICC, mostly during the presidential terms of the writer (1967-1983).

In reality, the measurements of gravity started with pendulums a long time before, in the 19th Century: they were tedious, time consuming and uncertain in the reductions. Consequently they remained at the individual experimental stage till the introduction of the von Sterneck's pendulum (1887), which permitted a first homogeneous net of relative gravity measurements (accuracy ~ 10^{-5} m s^{-2}) in the Austro-Hungarian Empire and surrounding countries. With a few absolute measurements as reference, the Vienna Gravity System was adopted by IAG in 1900.

But already in 1894 the uncertainties in the absolute measurements (~ 10^{-4} m s^{-2}) gave Helment the idea for a new absolute determination of the greatest accuracy in the Geodetic Institute in Potsdam (1898-1904).

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(1) as it rappened, the Osservatorio Geofisico Sperimentale (OGS), was founded in Trieste in the same year for which most of the experimental mentioned work here is recognized with thanks.

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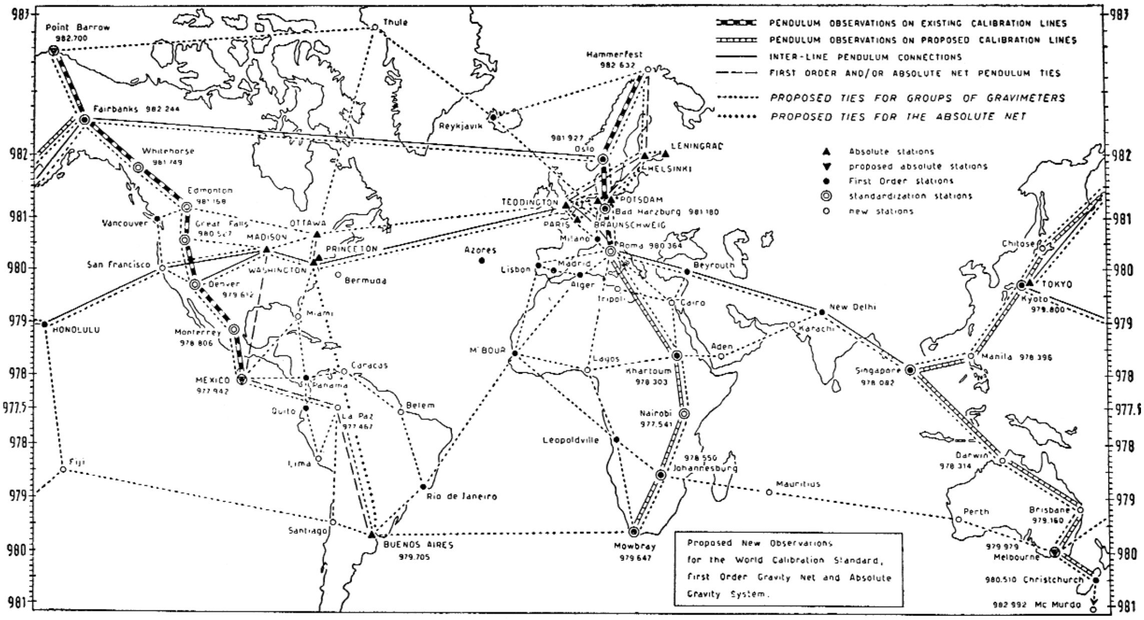

Fig. 1 - Calibration Lines in the project of the Global Net.

The result (981,274 ± 0.003 Gal = 10^{-2} m s^{-2}) and the inclusion, in the final adjustment, of all the other absolute and relative gravity measurements available (~2500) led to the Potsdam System, adopted by IAG in 1909. The correction to the Vienna System was -16 · 10^{-5} m s^{-2}. All the old and new gravity measurements were referred to Potsdam.

After World War I they increased rapidly, both in number and accuracy, especially after the 1930's. This period can be considered as the transition from an admitted mGal accuracy to a real one. Indeed:

1. the relative gravity measurements with pendulums increase to the μm s^{-2} accuracy (Askania, Gulf, Cambridge, Dominium Observatory Ottawa, GSI Tokyo, Italian Geodetic Commission, ...);
2. the relative spring gravimeters benefit from their strong request for prospecting with new instruments also with the μm s^{-2} accuracy (Holweck-Lejay, Western, Worden, Graf-Askania, ...). Millions of new relative gravity measurements covered practically all the land areas in the following decades;
3. two new absolute measurements are being completed:
   Washington, National Bureau of Standards, 1928/29 (g = 980080 μm s^{-2}; Heyl, 1930);
   Teddington, Nat. Phys. Lab., 1939 (g = 981,1815; Clark, 1939).

The existing relative connections with Potsdam, of these new absolute values, began to bring doubts about the Potsdam value. But only after World War II could the problem be tackled in the right way.

The first attempt was made (due to the need for calibration of the new gravity meters) utilizing the existing measurements (Morelli, 1946a). A net of 33 stations, mainly in Europe, was selected (7 of which with absolute values), connected by 66 ties detected by various observers

Table 1 - IGSN 71 instruments and data.

(1) = US Coast and Geodetic Survey; (2) = Geophysical Survey Institute, Tokyo.

Instrument	***Type instrument***	***N° instrument***		***Surveys***
Absolute	Cook	1		1 station
	Sakuma	1		1 station
	Faller - Hammond	1	3	**9** station
Pendulum	Gulf	2		**23** trips
	Cambridge	1		12 trips
	IGC	2		4 trips
	USCGS(1)	2		2 trips
	EPB	1		1 trips
	GSI(2)	1	9	8 trips
Gravimeter	LaCoste - Romberg	53		98 trips
	Worden	14		12 trips
	Askania	2		6 trips
	North American	2		5 trips
	Western	3	74	2 trips

with different pendulum instruments and methods, in different years. Two adjustments indicated a mean accuracy better than 10^{-5} m s^{-2}.

They therefore, gave, the confidence to create a first calibration line in Europe (Hammerfest-Catania, later on extended to Nairobi; Fig.1). Considering that the gravity meters need calibration and datum, and that the global gravity problems request that have an accuracy of 10^{-6}, the proposal was further advanced (Morelli, 1946b) and led to the establishmetn of a new "International reference system" based on all the best available absolute gravity values and the best relative ties (both pendulum and gravity -meter ones).

2. The International Gravity Standardization Net 1971 (IGSN 71)

World War II had deferred interest from the problem, but, just after the War, the publication (1950) of the results of the German pendulum measurements 1934-1943 offered an unique opportunity for the solution of the gravity reference problem. Indeed, the published data were pertinent to 171 pendulum ties divided in to 16 districts, all connected Potsdam many times to generally by different observers, with different instruments, in different years. The mean error for the different stations resulted from between ± 0.25 to $\pm 0.5 \cdot 10^{-5}$ m s^{-2}; for Bad Harzburg (22 ties): $\pm 0.13 \cdot 10^{-5}$ m s^{-2}. From the beginning, the gravity range included all of Europe (from Sicily to Denmark) and most of the absolute new sites (Washington, Ottawa, Sevres, Teddington, Potsdam, Copenhagen). The first Calibration Line was realized in Europe, from Hammerfest to Catania.

This gave origin to a 20-year work of calibration of gravity meters, of ties between selected

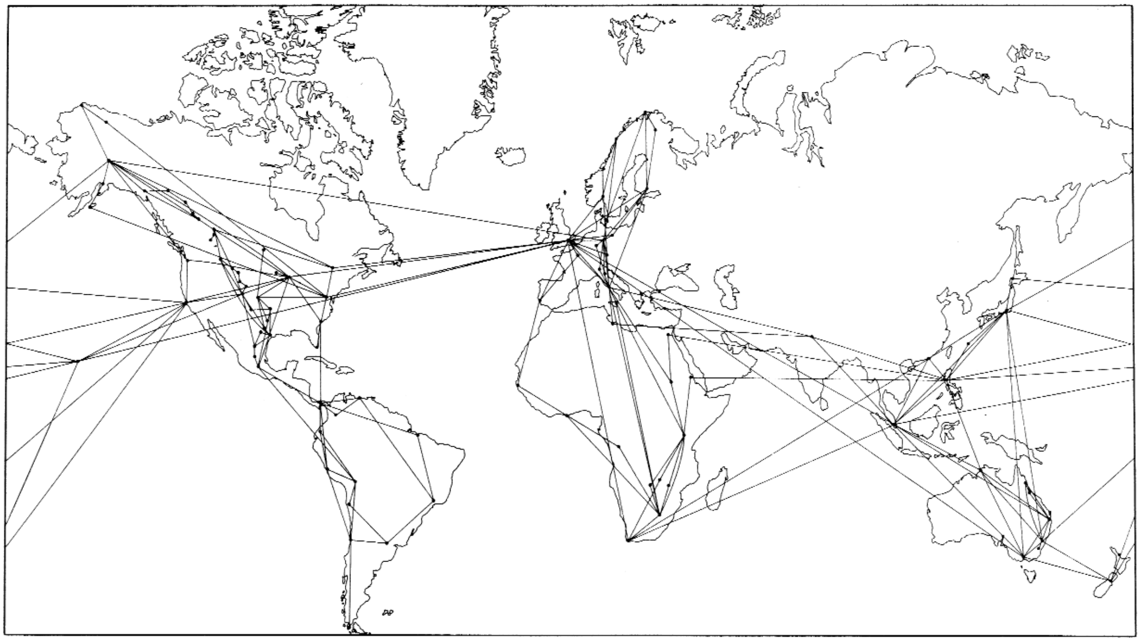

Fig. 2 - The PENDNET Diagram, in IGSN 71.

absolute or reference sites, that guided by a Special Study Group (SSG) of the IGC and enlarged to a world wide international cooperation finally led one single Reference Gravity System. The SSG met every one and a half, years from 1954 to 1970. Initially the members were:

C. Morelli, C. Gantar, Osservatorio Geofisico Sperimentale, Trieste, Italy;

T. Honkasalo, Geodeetinen Laitos, Helsinki, Finland;

R. K. McConnell, J. G. Tanner, Earth Physics Branch, Gravity Div., Dept. of Energy, Mines and Resources, Ottawa, Canada (E.P.B.);

B. Szabo, Air Force Cambridge Research Laboratories, Bedford, Mass., U.S.A.;

U. Uotila, Dept. of Geodetic Science, Ohio State Univ., Columbus, Ohio, U.S.A.;

C. T. Whalen, Ist. Geodetic Survey Squadron, Cheyenne, Wyo., U.S.A.

The acquisition of the data (Figs. 2 and 3) required cooperation among many countries. Data from 184 surveys using 86 different instruments were collected at OGS, who acted as the data coordinating agency for the project. Approximately 25 000 observations interconnecting 473 primary and 139 816 excenter bases were used. The instruments employed are indicated in Table 1.

For the adjustment of the System, the absolute data provided the datum and contributed to scale, the pendulum data contributed to scale and the gravimeter data gave the basic structure of the net. The absolute stations were Bogotà, Washington, Denver, Boston, Paris, Teddington, Fairbanks.

A Working Sub-Group, established the guidelines for the final adjustment. The gravity values and their standard errors are published in the final report (Morelli et al., 1974). The IGSN.71 gravity value for Potsdam A is 9 812 601.9±0.2 with a correction of $-14.0 \cdot 10^{-5}$ m s^{-2} to the

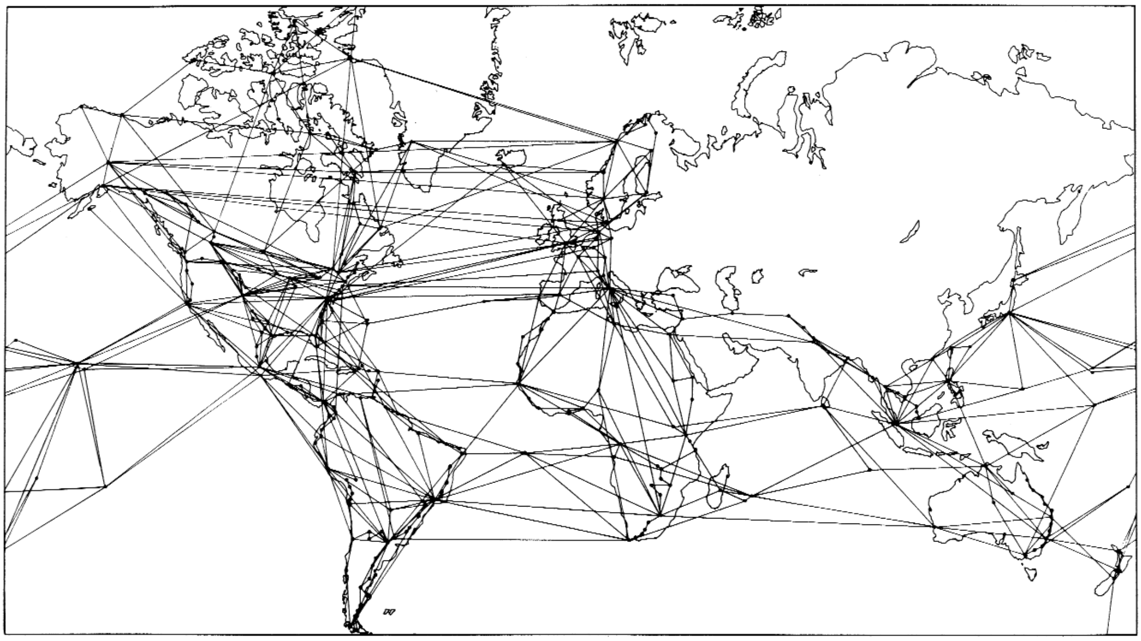

Fig. 3 - The Main Gravimeter connections in IGSN 71.

Potsdam reference value.

The System has been adopted by the International Association of Geodesy and by the International Union of Geodesy and Geophysics in their General Assemblies in Moscow (1971).

The station descriptions and the pertinent gravity values can be obtained from the International Gravity Bureau.

2.1 Present status and validity of IGSN 71

IGSN 71 provides global gravity values with standard errors of less than 10^{-6} m s^{-2} over the gravity range of the earth. This statement has been, and is continuously controlled by the new precise gravity national reference nets and gravity surveys for geodetic purposes that have been performed in the latest years (e.g. in France, Germany, Italy, USA, etc.): they confirm within ±0.1 mGal the gravity values of the IGSN 71 stations.

The same resulted from comparison measurements, specially performed in different areas or different ranges, e.g. in Japan, Potsdam, the Western Pacific Calibration Zone, etc.

With almost no exception, the IGSN 71 values are in good agreement with the new observed values or with the values of the new adjustments; much better than 100 μGal (1μm s^{-2}), which was the accuracy claimed by the IGSN 71 values.

The above-mentioned new absolute and relative gravity measurements and their careful adjustment and analyses in different countries have given hope for improved reference systems in the relevant countries, and for a worldwide coverage with new regional and local absolute nets

Table 2 - Absolute gravimeters, status 1995**.**
FF = Free Fall; SFF = Symmetrical Free Fall.

Country	*Numbers and method of absolute gravimeter*
Austria	1 FF (type JILA-G)
Belgium	1 FF
Canada	1 FF (type JILA-G), 1 FF (type AXIS FG5)
China	2 FF
Finland	1 FF (type JILA-G)
France	1 SFF, 1 FF (type AXIS FG5)
Germany	1 FF (type JILA-G), 1 FF (type AXIS FG5)
Italy	1 SFF, 1 SFF in development
Japan	2 SFF, 2 FF (type AXIS FG5)
Poland	1 SFF
Russia	2 FF, 1 SFF
Ukraine	1 FF
United Kingdom	2 FF (type AXIS FG5)
USA	3 FF (type JILA-G), 2 FF (type AXIS FG5)

(also independent). But a few things be done, before a reference system, much above the IGSN 71 one, can be obtained. The 70-100 μGal differences between some of the absolute measurements at the same sites must be resolved. New portable apparatuses, developed by Faller and his associates, and Marson in Trieste, must be used to measure absolute gravity once more at several absolute sites included in the new networks. Hopefully, these new measurements will give us some ideas about the above-mentioned differences.

Causes for these differences could be instrumental in nature, but they could also be partly produced by environmental factors, e.g. changing water level, moving air masses, ocean loading, etc. which are all very difficult to estimate. Comparison of absolute-gravity apparatuses should be continued, as well as studies on the effect of changes in environments on gravity. Meanwhile, better calibration for gravity meters should be accomplished by establishing necessary calibration lines and improving laboratory calibration procedures. In order to strengthen the base networks, additional relative gravity measurements are needed. These new gravity meter measurements should be scheduled, so that most of the instrumental behaviour can be modelled mathematically as well as possible.

In the meantime, the decision of the I.A.G. to extend, in time, the validity of IGSN 71 is still valid, and the role of IGSN 71 for gravity users, is consolidated. It was also extended to the Eastern Countries, China, etc.

In synthesis, homogeneity throughout the globe is secured by IGSN 71. All the new, high precision, absolute and relative gravity measurements, new regional adjustments and special comparisons in the 1970’s to the 90’s confirm the accuracy of the IGSN 71 values.

I would like to conclude the presentation of this first IGC cooperative effort with the wordss in the Geodesist Handbook 1996, of the past IAG President Prof. Torge:

“The mean accuracy of ±100 μGal (and better) of IGSN 71 suffices for most users in physics, geodesy, geophysics, and navigation. The IGSN 71 has also quickly ensured that gravimetric

Fig. 4 - The Sakuma-Colonnetti transportable absolute apparatus (Cerutti et al., 1974).

surveys can be correspondingly transformed, and new networks either connected, or based upon new absolute measurements, with an improvement of from a half to one order of magnitude (and can thus be declared to be compatible with IGSN 71)."

2.2 The advancement of accuracy in gravity determination

Notwithstanding the refinement and expansion of the satellite methods, terrestrial methods remain superior for the determination of point gravity values.

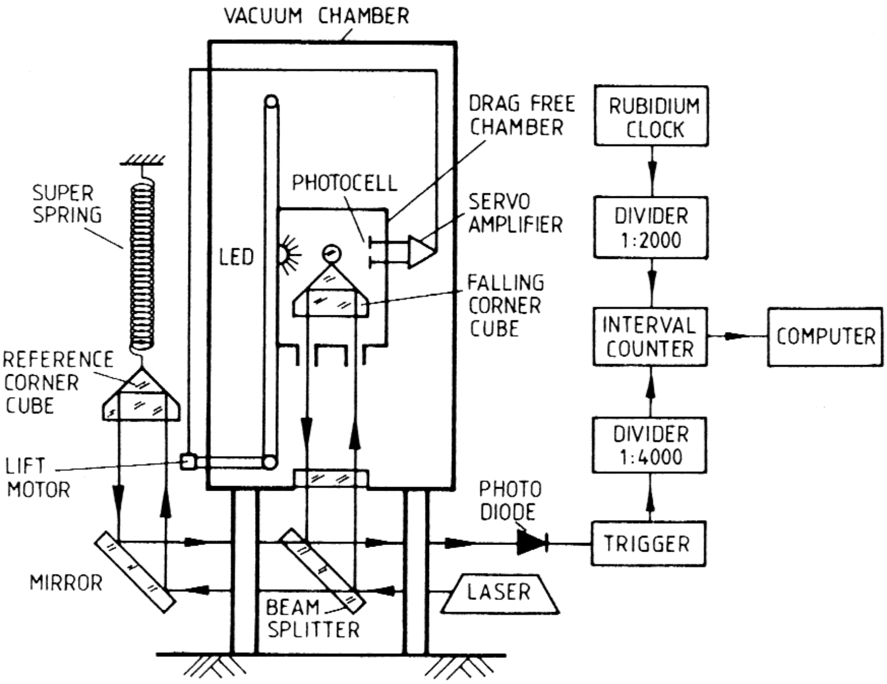

Fig. 5 - JILA free-fall gravimeter principle, Joint Institute for Laboratory Astrophysics, Boulder, Colorado, after Faller (1963) and Niebauer et al. (1995).

Since 1971, the need of a higher accuracy (10^{-6}–10^{-9} g) is increased for different purposes with regional and local implications and extension: e.g., for studying geodynamical and tectonic processes, as crustal deformations which manifest themselves as time dependent variations of g. Phenomena such as land uplift, dilatancy such as occurs in seismic areas, geothermal activity, and water table depth variation, all result in changes of g which, require gravity measurements of the highest accuracy (few parts in 10^{-9}) before being detected.

The transportable absolute gravity meters decreased in size and weight from the Sakuma-Colonnetti ones (Fig. 4), with developments by Marson, to the Faller JILA apparatuses and connected developments (Figs. 5 and 6).

Transportable absolute gravimeters, which now permit an accuracy in the range of 3 to $10 \cdot 10^{-2}$ μm s^{-2}, were 28 in number in 1995, and make the use of gravimetry for the study of global geodynamic processes possible. They are summarized in Table 2 (from Marson and Richter, 1998). The IAG has taken this issue up with the proposal for the establishment and regular measurement of the global International Absolute Gravity Basestation Network (IAGBN). Of 36 stations, mainly chosen from geodynamic considerations, more than ~80% have been set up and measured at least once.

Our USSR colleagues, under the leadership of Prof. Boulanger, participated in the workshops in Sevrés for the comparison of the absolute gravimeters.

Of course, perturbing noise, mainly microseismicity, can decrease the above-stated quality to an accuracy level of $60\text{-}70 \cdot 10^{-2}$ μm s^{-2}. A possible improvement of the absolute gravity

Fig. 6 - The AXIS Instruments Company (now Micro-g Solutions) FG-5 Absolute Gravimeter.

measuring techniques can be provided by the use of a vertical in-line interferometer which prevents the tilt of the interferometer. Along this line the AXIS Instrument Company (now Micro-G Solutions, Erie, Co., USA), Boulder, Co. USA, has begun producting new gravity meters (FG5, free-fall type).

Another instrument based on the symmetrical free-fall method and on the vertical in-line interferometer, is at an advanced stage of development, in Italy, by Marson. Besides the above-mentioned features, this instrument adopts a vertical in-line interferometer with a multiple reflections path. Thus, the resolution of the distance measurements is increased by

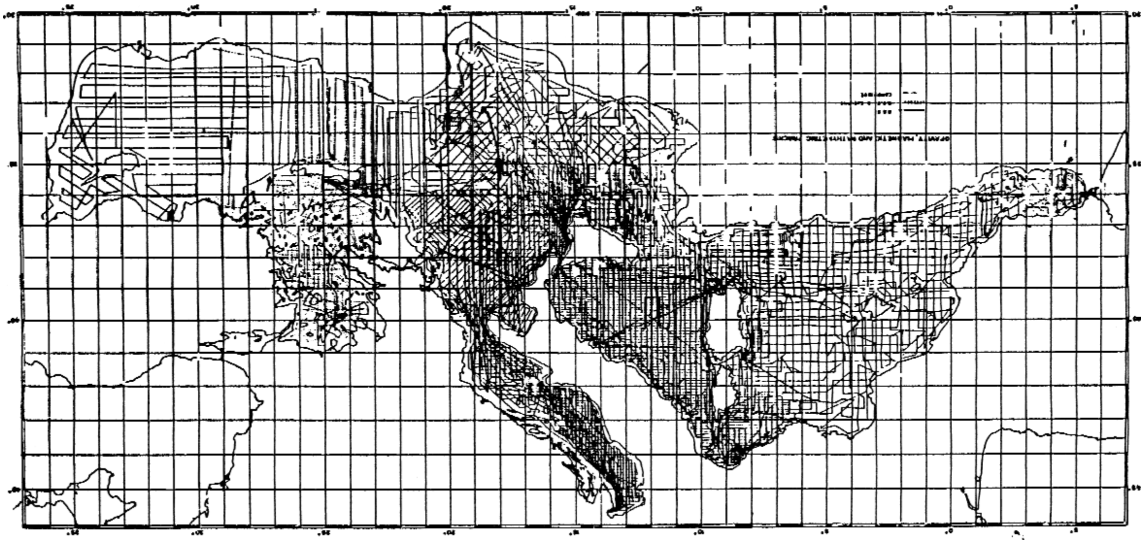

Fig.7 - Location map of the OGS Continuous Bathymetric, Gravimetric and Magnetic Profiles 1965-1972. The figure includes also tracks by OGS-SACLANT 1961-65 and Dept. of Geodesy and Geophysics Cambridge 1972-74, in the areas not covered by the OGS exploration.

a factor of three.

It is worth recalling that in the time-span of this history the accuracy both in absolute and relative gravity measurements increased by at least 3 to 4 orders of magnitude: something that does not happen very often in Science.

3. The Sea gravity measurements

The fundamental contribution for measurements of gravity at sea (is thanks to Vening-Meinesz), who introduced his tripendular apparatus in 1923. The first survey in a submarine was in the Sunda Sea, and the results led to the theory of the convection currents, in the Earth's mantle, responsible for the subduction of the crust, the formation of the volcanic arcs and the oceanic deeps.

Gino Cassinis realized two cruises with Italian submarines; the first consisted of 83 stations in the Central Mediterranean in 1931 with the Vening-Meinesz apparatus; the second in 1935 with a new apparatus of 38 stations right down to the Aegean Sea. These cruises gave the first indications on the existence of very strong positive gravity anomalies in the deeper parts of the Ligurian, Tyrrhenian and Ionian Seas.

In 1971 the basal problem of the gravity measurements on land was solved; that of the gravity measurements on the oceans (2/3 of the Earth's surface) remained. Continuing under IGC's auspices, this international cooperation also solved the problem of sea-surface gravity measurements (in this case, with the active participation of the USSR).

In Italy, OGS performed the survey of most of the Mediterranean Sea with a Graf-Askania gravity meter installed on a gyro-stabilized platform.

The surveys were carried out with:

1. the Italian Navy hydrographic ship "Staffetta" in 1958 (tests and calibration);
2. the Saclant Center ships "Aragonese" and "Maria Paolina", from 1961 to 1965, for a total of 115 000 km of profiles;
3. the CNR ship "Bannock" from 1965 to 1972.

For points 2 and 3, positioning was made with Loran C. The area from Gibraltar to 22° East was covered by the ship "Bannock" with a total of 329 500 km of profiles (Fig. 7).

For East to 22°E the measurements were performed in 1971-74 with the RRS "Shackleton" and "Discovery" by the Dept. of Geodesy and Geophysics, Cambridge, UK, with a Graf-Askania gravity-meter as well, but with satellite positioning.

The Bouguer gravity anomalies were computed from the observed gravity values. The accuracy of the observed gravity values, as determined from the track crossing is ±2 mGal. The accuracy of the anomaly values is also influenced by positioning errors, errors in interpolation, and errors in reduction.

The interpolation errors depend upon the track spacing, which varies from 3 km in the Central Mediterranean to 25 km or more in the Eastern Mediterranean.

Considering also the reduction errors, the overall accuracy in the Bouguer gravity anomalies on the surveyed profiles, ranges from ±3 mGal in the Central Mediterranean to ±7 mGal in the peripheral areas. It has to be considered that the measurements were performed between 1965-72, with a surface ship gravity-meter of the 2nd generation.

The 1961-65 measurements were published in 1971 (Boll. Geofis. Teor. Appl. n. 50) at 1:750 000 scale for Bathymetry, Free Air and Simple Bouguer anomalies and Total Magnetic Field intensity.

The 1966-72 measurements were published in 1975 (Boll. Geofis. Teor. Appl. n. 65-67) at 1:750 000 scale for Bathymetry, Free Air and Bouguer anomalies.

The data for the Bouguer Map at 1:1 000 000 scale, 10 sheets published in 1989 by the Intergovernmental Oceanic Commission (IOC) of UNESCO (Makris et al., 1988, Fig. 3) were derived from these maps.

It is important to mention, that - in addition to their importance for geologic and tectonic studies on the interior of the Earth - the gravity anomalies are essential for studies of Physical Geodesy. Inter alia, they have been used for the preparation of the Mediterranean Geoid by the International Geoid Service of Milano, Italy.

But other important products came out from the geophysical cruises indicated in Fig.7. Only those under the framework of IOC are mentioned here:

1. the international Bathymetric Chart of the Mediterranean (IBCM) not only from the soundings of the above-mentioned cruises, but also from a compilation from detailed soundings kindly offered by Oil and other Companies.

Due to the primary importance of this fundamental document (published in 1981) for any study or application on the sea-bottom, it was completed by following maps published by IOC at the same scale:

2. the Seismicity Map of the Mediterranean and surrounding countries (IBCM-S), prepared by

the Euro-Mediterranean Seismological Center in Strasbourg (1991);

3. the Plio-Quaternary thickness map (1994), on reflection seismic measurements by OGS, IFREMER and voluntary contributions by Oil Companies (IBCM-P/Q);
4. the Magnetic Anomalies map of the Mediterranean (IBCM-M) observed also on the same cruises indicated in Fig. 7;
5. the Recent Sediments map (IBCM-Sed., 1998).

All the Maps are illustrated in a brochure (IBCM-S also in a catalogue; for the gravity map and the maps 2, 3, 4 the brochures are published in the 1998 issues of B.G.T.A.(2)).

A further follow-up is worth mentioning. The advancement of surveying technology in bathymetry has introduced novel, superior means (multibeam,...) which offer new possibilities and greater accuracy. The quantity and quality of the new bathymetric data collected since the 1980's is so great, that a 2nd edition of IBCM (IBCM-II) is being prepared in digital form, with the active participation of the Hydrographic Institutes concerned, and with all the available new data (mainly multibeam).

The philosophy has also changed. The terms of Reference define IBCM-II "as a scientific initiative to build a seamless digital terrain model (DTM) on a 0.1' (~180 m) grid of all the area (land and sea) of the ten sheets of the IBCM. This DTM will be based upon all the data available to the compilers. This data will be from all sources and time periods. It is certain that most of the areal coverage for the sea will not be of hydrographic standard, but will be the best available at this time, and will be continuously evaluated during compilation as to its geological reality."

The bulk of the new available data is from scientific swath surveys and transit tracks.

A colour proof of IBCM-II sheet 10 (Levantine Sea) was presented and discussed in the last meeting of the IBCM-Editorial Board during the CIESM 35th General Assembly in Dubrovnik (June 1998).

The importance of this new project is evident. Among the practical benefits, thus projet will allow all users to make their own product areas of interest with the desired projection, formats and scales.

Acknowledgments. Gratitude is herewith expressed to the hundreds of IGC Members and local Authorities that from 1951 on, kindly supported the activity of IGSN 71. Particular thanks go to three Members of OGS, who, from the beginning (1951), cooperated actively in all the works that are summarized here: Claudio Gantar, Mario Pisani and Adriano Scotti.

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(1) The map can be obtained (when available, also in digital form) from: Ocean Mapping, IOC-UNESCO. 75732 Paris; Fax: +33.1.4568.5812. Information can also be found on OGS web site: http://www.ogs.trieste.it/bgta/, with the pertinent data bases and Earthquake Catalogue (for IBCM-S). Reprints can be obtained with the order.

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