ASSOCIATION INTERNATIONALE DE GÉODÉSIE

BUREAU GRAVIMETRIQUE INTERNATIONAL

BULLETIN D'INFORMATION

N° 61

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18, avenue Edouard-Belin
31055 TOULOUSE CEDEX
FRANCE

INFORMATIONS FOR CONTRIBUTORS

Contributors should follow as closely as possible the rules below : Manuscripts should be typed (double-spaced) in Prestige-Elite characters (IBM-type), on one side of plain paper 21 cm x 29,7 cm, with a 2 cm margin on the left and right hand sides as well as on the bottom, and with a 3 cm margin at the top (as indicated by the frame drawn on this page).

Title of Paper. Titles should be carefully worded to include only key words.

Abstract should be informative rather than descriptive. It is not a table of contents. It should be suitable for separate publication and should include all words useful for indexing. Its length should be limited to one typescript page.

Table of Contents. Essential for long papers (should follow the abstract.

Footnotes. Because are distracting, they should be avoided as much as possible.

Mathematics. For papers with complicated notation, a list of symbols and their definitions should be provided as an appendix. All characters that are available on standard typewriters should be typed in equations as well as test. Symbols that must be handwritten should be identified by notes in the margin. Ample space (1.9 cm above and below) should be allowed around equations so that type can be marked for the printer. Where an accent or underscore has been used to designate a special type face (e.g., boldface for vectors, script for transforms, sans serif for tensors), the type should be specified by a note in the margin. Bars cannot be set over superscripts or extended over more than one character. Therefore angle brackets are preferable to overbars to denote averages, and superscript symbols (such as *,', and #) are preferable to accents over characters. Care should be taken to distinguish between the letter O and zero, the letter l and the number one, kappa and k, mu and the letter u, nu and v, eta and n, also subscripts should be clearly noted and easily distinguished. Unusual symbols should be avoided.

Acknowledgements. Only significant contributions by professional colleagues, financial support, or institutional sponsorship should be included in acknowledgements.

References. A complete and accurate list of references is of major importance in review papers. All listed references should be cited in text. A complete reference to a periodical gives author (s), title of article, name of journal, volume number, initial and final page numbers (or statement "in press"), and year published. A reference to an article in a book, pages cited, publisher, publisher's location, and year published. When a paper presented at a meeting is referenced, the location, dates, and sponsor of the meeting should be given. References to foreign works should indicate wheter the original or a translation is cited. Unpublished communications can be referred to in text but should not be listed. Page numbers should be included in reference citations following direct quotations in text. If the same information has been published in more than one place, give the most accessible reference ; e.g. a textbook is preferable to a journal, a journal is preferable to a technical report.

Tables are numbered serially with Arabic numerals, in the order of their citation in text. Each table should have a title, and each column, including the first, should have a heading. Column headings should be arranged to that their relation to the data is clear.

Footnotes for the tables should appear below the final double rule and should be indicated by a, b, c, etc... Each table should be referred to in the text.

Illustrations. Original drawings of sharply focused glossy prints should be supplied, with two clear Xerox copies of each for the reviewers. Maximum size for figure copy is (25.4 x 40.6 cm). After reduction to printed page size, the smallest lettering or symbol on a figure should not be less than 0.1 cm high ; the largest should not exceed 0.3 cm. All figures should be cited in text and numbered in the order of citation. Figure legends should be submitted together on one or more sheets, not separately with the figures.

Mailing. Typescripts should be packaged in stout padded or stiff containers ; figure copy should be protected with stiff cardboard.

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PART I

INTERNAL MATTERS

A N N O U N C E M E N T

NEXT MEETING OF THE BGI DIRECTING BOARD WILL TAKE PLACE IN PARIS ON JUNE 21 AND 22, 1988 (TUESDAY AND WEDNESDAY). EXACT LOCATION WILL BE INDICATED IN A CIRCULAR TO BE MAILED TO D.B. MEMBERS AND W.G. CHAIRMEN END OF JANUARY 1988.

G E N E R A L   I N F O R M A T I O N S

1. HOW TO OBTAIN THE BULLETIN

2. HOW TO REQUEST DATA

3. USUAL SERVICES B.G.I. CAN PROVIDE

4. PROVIDING DATA TO B.G.I.

1. HOW TO OBTAIN THE BULLETIN

The Bulletin d'Information of the Bureau Gravimétrique International is issued twice a year, generally at the end of June and end of December.

The Bulletin contains general informations on the community, on the Bureau itself. It informs about the data available, about new data sets, ...

It also contains contributing papers in the field of gravimetry, which are of technical character. More scientifically oriented contributions should better be submitted to appropriate existing journals.

Communications presented at general meetings, workshops, symposia, dealing with gravimetry (e.g. IGC, S.S.G.'s,...) are published in the Bulletin when appropriate - at least by abstract.

Once every four years, a special issue contains (solely) the National Reports as presented at the International Gravity Commission meeting. Other special issues may also appear (once every two years) which contain the full catalogue of the holdings.

About three hundred individuals and institutions presently receive the Bulletin.

You may :

- *either request a given bulletin, by its number (60 have been issued as of June 1 1987, but numbers 2, 16, 18, 19 are out of print),*
- *or subscribe for regularly receiving the two bulletins per year plus the special issues.*

Requests should be sent to :

Mrs. Nicole ROMMENS
CNES/BGI
18, Avenue Edouard Belin
31055 TOULOUSE CEDEX - FRANCE

Bulletins are sent on an exchange basis (free of charge) for individuals, institutions which currently provide informations, data to the Bureau. For other cases, the price of each number is as follows :

- *60 French Francs without map,*
- *70 French Francs with map.*

2. HOW TO REQUEST DATA

2.1. Station Description Diagrams for Reference, Base Stations (including IGSN 71's)

Request them by number, area, country, city name or any combination of these.

When we have no diagram for a given request, but have the knowledge that it exists in another center, we shall in most cases forward the request to this center or/and tell the inquiring person to contact the center.

Do not wait until the last moment (e.g. when you depart for a cruise) for asking us the information you need : station diagrams can reach you by mail only !

2.2. G-Value at Base Stations

Treated as above.

2.3. Mean Anomalies, Mean Geoid Heights, Mean Values of Topography

The geographic area must be specified (polygon). According to the data set required, the request may be forwarded in some cases to the agency which computed the set.

2.4. Gravity Maps

Request them by number (from the catalogue), area, country, type (free-air, Bouguer...), scale, author, or any combination of these.

Whenever available in stock, copies will be sent without charges. If not, two procedures can be used :

- *we can make (poor quality) black and white (or ozalide-type) copies at low cost,*
- *color copies can be made (at high cost) if the user wishes so (after we obtain the authorization of the editor).*

The cost will depend on the map, type of work, size, etc... In both cases, the user will also be asked to send his request to the editor of the map before we proceed to copying.

2.5. Gravity Measurements

They can be requested :

(a) either from the CGDF (Compressed Gravity Data File). The list and format of the informations provided are the following :

CGDF RECORD DESCRIPTION
60 CHARACTERS

Col.	1	Classification code - 0 if not classified
	2- 8	B.G.I. source number
	9-15	Latitude (unit = 1/10 000 degree)
	16-23	Longitude (unit = 1/10 000 degree)
	24	Elevation type 1 = Land 2 = Subsurface 3 = Ocean surface 4 = Ocean submerged 5 = Ocean bottom 6 = Lake surface (above sea level) 7 = Lake bottom (above sea level) 8 = Lake bottom (below sea level) 9 = Lake surface (above sea level with lake bottom below sea level) A = Lake surface (below sea level) B = Lake bottom (surface below sea level) C = Ice cap (bottom below sea level) D = Ice cap (bottom above sea level) E = Transfer data given
	25-31	Elevation of the station (0.1 M) This field will contain depth of ocean (positive downward) if col. 24 contains 3, 4 or 5.
	32-36	Free air anomaly (0.1 mgal)
	37-38	Estimation standard deviation free air anomaly (mgal)
	39-43	Bouguer anomaly (0.1 mgal) Simple bouguer anomaly with a mean density of 2.67 - No terrain correction.
	44-45	Estimation standard deviation bouguer anomaly (mgal)
	46	System of numbering for the reference station 1 = IGSN 71 2 = BGI 3 = Country 4 = DMA
	47-53	Reference Station
	54-56	Country code
	57	1 : measurement at sea with no depth given 0 : otherwise

Col. 58 Information about terrain correction
0 = no information
1 = terrain correction exists in the archive file

59 Information about density
0 = no information or 2.67
1 = density ≠ 2.67 given in the archive file

60 Information about isostatic anomaly
0 = no information
1 = information exists but is not stored in the archive file
2 = information exists and is included in the archive file.

(b) or from the Archive file. The list and format of the informations provided are the following :

ARCHIVE FILES
RECORD DESCRIPTION
160 CHARACTERS

Col. 1- 7 B.G.I. Source number

8- 12 Block number
Col. 8-10 = 10 square degree
Col. 11-12 = 1 square degree

13- 19 Latitude (Unit : 1/10 000 degree)

20- 27 Longitude (unit : 1/10 000 degree) (-180 to +180 degree)

28 Accuracy of position
The site of the gravity measurement is defined in a circle of radius R
0 = No information on the accuracy
1 = R <= 20 M (approximately 0'01)
2 = 20 < R <= 100
3 = 100 < R <= 200 (approximately 0'1)
4 = 200 < R <= 500
5 = 500 < R <= 1000
6 = 1000 < R <= 2000 (approximately 1')
7 = 2000 < R <= 5000
8 = 5000 < R
9 ...

29 System of position
0 = unknown
1 = Decca
2 = visual observation
3 = radar
4 = loran A
5 = loran C
6 = omega or VLF
7 = satellite
9 = Solar/stellar (with sextant)

30- 31 Type of observation

A minus sign distinguishes the pendulum observations from the gravimeter ones.

0 = current observation of detail or other observation of a 3 rd or 4th order network
1 = observation of a 2nd order national network
2 = observation of a 1st order national network
3 = observation being part of a national calibration line
4 = individual observation at sea
5 = mean observation at sea obtained from a continuous recording
6 = coastal ordinary observation (Harbour, Bay, Sea-side...)
7 = harbour base station

32 Elevation type

1 = Land
2 = Subsurface
3 = Ocean surface
4 = Ocean submerged
5 = Ocean bottom
6 = Lake surface (above sea level)
7 = Lake bottom (above sea level)
8 = Lake bottom (below sea level)
9 = Lake surface (above sea level with lake bottom below sea level)
A = Lake surface (below sea level)
B = Lake bottom (surface below sea level)
C = Ice cap (bottom below sea level)
D = Ice cap (bottom above sea level)
E = Transfer data given

33- 39 Elevation of the station (0.1 M)

This field will contain depth of ocean (positive downward) if col. 32 contains 3, 4 or 5.

40 Accuracy of elevation (E)

0 = unknown
1 = E <= 0.1 M
2 = 1 < E <= 1
3 = 1 < E <= 2
4 = 2 < E <= 5
5 = 5 < E <= 10
6 = 10 < E <= 20
7 = 20 < E <= 50
8 = 50 < E <= 100
9 = E superior to 100 M

41- 42 Determination of the elevation

= no information
0 = geometrical levelling (bench mark)
1 = barometrical levelling
2 = trigonometrical levelling
3 = data obtained from topographical map
4 = data directly appreciated from the mean sea level
5 = data measured by the depression of the horizon

(marine)
Type of depth (if Col. 32 contains 3, 4 or 5)
1 = depth obtained with a cable (meters)
2 = manometer depth
4 = corrected acoustic depth (corrected from Mathew's tables, 1939)
5 = acoustic depth without correction obtained with sound speed 1500 M/sec. (or 820 Brasses/sec)
6 = acoustic depth obtained with sound speed 800 Brasses/sec (or 1463 M/sec)
9 = depth interpolated on a magnetic record
10 = depth interpolated on a chart

43- 44 Mathews'zone
When the depth is not corrected depth, this information is necessary.
For example : zone 50 for the eastern Mediterranean Sea

45- 51 Supplemental elevation
Depth of instrument, lake or ice, positive downward from surface

52- 59 Observed gravity (0.01 mgal)

60 Information about gravity
1 = gravity with only instrumental correction
2 = corrected gravity (instrumental and Eotvos correction)
3 = corrected gravity (instrumental, Eotvos and cross-coupling correction)
4 = corrected gravity and compensated by cross-over profiles.

61 Accuracy of gravity (e)
When all systematic corrections have been applied
0 = E <= 0.05
1 = .05 < E <= 0.1
2 = 0.1 < E <= 0.5
3 = 0.5 < E <= 1.
4 = 1. < E <= 3.
5 = 3. < E <= 5.
6 = 5. < E <= 10.
7 = 10. < E <= 15.
8 = 15. < E <= 20.
9 = 20. < E

62 System of numbering for the reference station
This parameter indicates the adopted system for the numbering of the reference station
1 = for numbering adopted by IGSN 71
2 = BGI
3 = Country
4 = DMA

63- 69 Reference station
This station is the base station to which the concerned station is referred

70- 76 *Calibration information (station or base)*
This zone will reveal the scale of the gravity network in which the station concerned was observed, and allow us to make the necessary corrections to get an homogeneous system.

77- 81 *Free air anomaly (0.1 mgal)*

82- 86 *Bouguer anomaly (0.1 mgal)*
Simple bouguer anomaly with a mean density of 2.67 - No terrain correction.

87- 88 *Estimation standard deviation free air anomaly (mgal)*

89- 90 *Estimation standard deviation bouguer anomaly (mgal)*

91- 92 *Information about terrain correction*
Horizontal plate without bullard's term

0 = no topographic correction			
1 = CT computed for a radius of		5 km	(zone H)
2 = CT		30 km	(zone L)
3 = CT		100 km	(zone N)
4 = CT		167 km	(zone 02)
11 = CT computed from	1 km to	167 km	
12 = CT	2.5	167	
13 = CT	5.2	167	

93- 96 *Density used for terrain correction*

97-100 *Terrain correction (0.1 mgal)*
Computed according to the previously mentioned radius (col. 91-92) & density (col. 93-96)

101-103 *Apparatus used for the measurements of G*
0.. pendulum apparatus constructed before 1932
1.. recent pendulum apparatus (1930-1960)
2.. latest pendulum apparatus (after 1960)
3.. gravimeters for ground measurements in which the variations of G are equilibrated or detected using the following methods :
30 = torsion balance (Thyssen...)
31 = elastic rod
32 = bifilar system
4.. Metal spring gravimeters for ground measurements
42 = Askania (GS-4-9-11-12), Graf
43 = Gulf, Hoyt (helical spring)
44 = North American
45 = Western
47 = LaCoste-Romberg
48 = LaCoste-Romberg, Model D (microgravimeter)
5.. Quartz spring gravimeter for ground measurements
51 = Norgaard
52 = GAE-3
53 = Worden ordinary
54 = Worden (additional thermostat)
55 = Worden world wide

56 = Cak
57 = Canadian gravity meter, sharpe
58 = GAG-2
6.. Gravimeters for underwater measurements (at the bottom of the sea or of a lake)
60 = Gulf
62 = Western
63 = North American
64 = LaCoste-Romberg
7.. Gravimeters for measurements on the sea surface or at small depth (submarines..)
70 = Graf-Askania
72 = LaCoste-Romberg
73 = LaCoste-Romberg (on a platform)
74 = Gal and Gal-F (used in submarines) Gal-M
75 = AMG (USSR)
76 = TSSG (Tokyo Surface Ship Gravity meter)
77 = GSI sea gravity meter

104 Conditions of apparatus used
1 = 1 gravimeter only (no precision)
2 = 2 gravimeters (no precision)
3 = 1 gravimeter only (without cross-coupling correction)
4 = 2 gravimeters (influenced by the cross-coupling effect) with the same orientation
5 = 2 gravimeters (influenced by the cross-coupling effect) in opposition
6 = 1 gravimeter (compensated for the cross-coupling effect)
7 = 1 gravimeter non subject to cross-coupling effect
8 = 3 gravimeters

105 Information about isostatic anomaly
0 = no information
1 = information exists but is not stored in the data bank
2 = information exists and is included in the data bank

106-107 Type of the isostatic anomaly
0.. Pratt-Hayford hypothese
01 = 50 km including indirect effect (Lejay's tables)
02 = 56.9 km
03 = 56.9 km including indirect effect
04 = 80 km including indirect effect
05 = 96 km
06 = 113.7 km
07 = 113.7 km including indirect effect
1.. Airy hypotheses (equality of masses or pressures)
10 = T = 20 km (Heiskanen's tables, 1931)
11 = T = 20 km including indirect effect (Heiskanen's tables 1938 or Lejay's)
12 = T = 30 km (Heiskanen's tables, 1931)
13 = T = 30 km including indirect effect
14 = T = 40 km
15 = T = 40 km including indirect effect
16 = T = 60 km

17 = T = 60 km including indirect effect

6.......

65 = Vening Meinesz hypothesis "modified Bouguer anomaly" (Vening Meinesz, 1948)

108-112 Isostatic anomaly a (0.1 mgal)

113-114 Type of the isostatic anomaly B

115-119 Isostatic anomaly B

120-122 Velocity of the ship (0.1 knot)

123-127 Eotvos correction (0.1 mgal)

128-131 Year of observation

132-133 Month

134-135 Day

136-137 Hour

138-139 Minute

140-145 Numbering of the station (original)

146-148 Country code (B.G.I.)

149 Flag (internal use)

150-154 Original source number (ex. D.M.A. Code)

155-160 Sequence number

Whenever given, the theoretical gravity (gO), free-air anomaly (FA), Bouguer anomaly (BO) are computed in the 1967 geodetic reference system.

The approximation of the closed form of the 1967 gravity formula is used for theoretical gravity at sea level :

$$gO = 978031.85 * [1 + 0.005278895 * \sin^2(\varphi) + 0.000023462 * \sin^4(\varphi)], \text{ mgals}$$

where φ is the geographic latitude.

The formulas used in computing FA and BO are summarized in the table below.

Formulas used in computing free-air and Bouguer anomalies

Elev Type	Situation	Formulas
1	Land Observation	FA = g + 0.3086*H - g0 BO = FA - 0.1119*H
2	Subsurface	FA = g + 0.2238*D2 + 0,3086*(H-D2) BO = FA - 0.1119*H
3	Ocean surface	FA = g - g0 BO = FA + 0.06886*H (H = depth of ocean positive downward from surface)
4	Ocean submerged	FA = g - g0 BO = FA + 0.06886*H (D2 =depth of instrument positive downward) (H = depth of ocean positive downward)
5	Ocean bottom	FA = g + 0.3086*H - g0 BO = FA + 0.06886*D1 (D1 = depth of ocean positive downward)
6	Lake surface (above sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.04191*D1 - 0.1119*(H-D1) (D1 = depth of lake positive downward)
7	Lake bottom (above sea level)	FA = g + 0.08382*D1 + 0.3086*(H-D1) - g0 BO = FA -0.04191*D1 - 0.1119*(H-D1)
8	Lake bottom (below sea level)	FA = g + 0.08382*D1 + 0.3086*H-D1) - g0 BO = FA - 0.04191*D1 - 0.06999*(H-D1)
9	Lake surface (above sea level with bottom below sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.04191*H - 0.06999*(H-D1)
A	Lake surface (below sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.1119*H + 0.06999*D1
B	Lake bottom (surface below sea level)	FA = g + 0.3086*H - 0.2248*D1 - g0 BO = FA - 0.1119*H + 0.06999*D1 (D1 = depth of lake positive downward)
C	Ice cap (bottom below sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.03843*H - 0.07347*(H-D1) (D1 = depth of ice positive downward)
D	Ice cap (bottom above sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.03843*D1 - 0.1119*(H-D1) (D1 = depth of ice)

2.6. Satellite Altimetry Data

BGI has access to the Geos 3 and Seasat data base which is managed by the Groupe de Recherches de Géodésie Spatiale (GRGS). These data are now in the public domain.

Since January 1, 1987, the following procedure has been applied :

(a) Requests for satellite altimetry derived geoid heights (N), that is : time (julian date), longitude, latitude, N, are processed by B.G.I.

(b) Requests for the full altimeter measurement records are forwarded to GRGS, or NASA in the case of massive request.

In all cases, the geographical area (polygon) and beginning and end of epoch (if necessary) should be given.

All requests for data must be sent to :

Mr. Daniel LAMY
Bureau Gravimétrique International
18, Av. E. Belin - 31055 Toulouse Cedex - France

In case of a request made by telephone, it should be followed by a confirmation letter, or telex.
Except in particular cases (massive data retrieval, holidays,...) requests are satisfied within one month following the reception of the written confirmation, or information are given concerning the problems encountered.

If not specified, the data will be written, formatted (EBCDIC) on unlabeled 9-track tape (s) with a fixed block size. The exact physical format will be indicated in each case.

3. USUAL SERVICES B.G.I. CAN PROVIDE

The list below is not restrictive and other services (massive retrieval, special evaluation and products...) may be provided upon request.

The costs of the services listed below are a revision of the charging policy established in 1981 (and revised in 1987) in view of the categories of users : (1) contributors of measurements and scientists, (2) other individuals and private companies.

The prices given below are in french francs. They are effective January 1, 1988 and will be revised periodically.

3.1. Charging Policy for Data Contributors and Scientists

For these users and until further notice, - and within the limitation of our in house budget, we shall only charge the incremental cost of the services provided. In all other cases, a different charging policy might be applied.

However, and at the discretion of the Director of B.G.I., some of the services listed below may be provided free of charge upon request, to major data contributors, individuals working in universities, especially students...

3.1.1. Digital Data Retrieval

- *on one of the following media*
  - *printout* — *2F/100 lines*
  - *magnetic tape* — *2F per 100 records +100F per tape - 1600 BPI (if the tape is not to be returned)*
- *minimum charge : 100 F.*
- *maximum number of points : 100 000 ; massive data retrieval (in one or several batches) will be processed and charged on a case by case basis.*

3.1.2. Data Coverage Plots : in Black and White, with Detailed Indices

- *20° x 20° blocks, as shown on the next pages (maps 1 and 2) : 400 F each set.*
- *For any specified area (rectangular configurations delimited by meridians and parallels) : 1. F per degree square ; 100 F minimum charge (at any scales, within a maximum plot size of : 90 cm x 180 cm).*
- *For area inside polygon : same prices as above, counting the area of the minimum rectangle comprising the polygon.*

3.1.3. Data Screening

(Selection of one point per specified unit area, in decimal degrees of latitude and longitude, i.e. selection of first data point encountered in each mesh area).

- *5 F/100 points to be screened*
- *100 F minimum charge.*

3.1.4. Gridding

(interpolation at regular intervals Δ in longitude and Δ' in latitude - in decimal degrees) :

. $\frac{10\ F}{\Delta\Delta'}$ per degree square

. minimum charge : 150 F

. maximum area : 40° x 40°.

3.1.5. Contour Maps of Bouguer or Free-Air Anomalies

at a specified contour interval Δ (1, 2, 5,... mgal), on a given projection :

$\frac{10.\ F}{\Delta}$ per degree square, plus the cost of gridding (see 3.4) after agreement on grid stepsizes. (at any scale, within a maximum map size of : 90 cm x 180 cm).

. 250 F minimum charge

. maximum area : 40° x 40°.

3.1.6. Computation of Mean Gravity Anomalies

(free-air, Bouguer, isostatic) over $\Delta \times \Delta'$ area : $\frac{10\ F}{\Delta\Delta'}$ per degree square

. minimum charge : 150 F

. maximum area : 40° x 40°.

3.2. Charging Policy for Other Individuals or Private Companies

3.2.1. Digital Data Retrieval

. 1 F per measurement
. minimum charge : 150 F

3.2.2. Data Coverage Plots, in Black and White, with Detailed Indices

. 2 F per degree square ; 100 F minimum charge. (maximum plot size = 90 cm x 180 cm)
. For area inside polygon : same price as above, counting the area of the smallest rectangle comprising the polygon.

3.2.3. Data Screening

. 1 F per screened point
. 250 F minimum charge

3.2.4. Gridding

Same as 3.1.4.

3.2.5. Contour Maps of Bouguer or Free-Air Anomalies

Same as 3.1.5.

3.2.6. Computation of Mean Gravity Anomalies

Same as 3.1.6.

3.3. Gravity Maps

The pricing policy is the same for all categories of users

3.3.1. Catalogue of all gravity maps :

printout : 200 F
tape : 100 F (+ tape price, if not to be returned)

3.3.2. Maps

- Gravity anomaly maps (excluding those listed below) : 100 F each

- Special maps :

Mean altitude maps

FRANCE	(1: 600 000)	1948	6 sheets	65 French Francs the set
WESTERN EUROPE	(1:2 000 000)	1948	1 sheet	55 French Francs
NORTH AFRICA	(1:2 000 000)	1950	2 sheets	60 French Francs the set
MADAGASCAR	(1:1 000 000)	1955	3 sheets	55 French Francs the set
MADAGASCAR	(1:2 000 000)	1956	1 sheet	60 French Francs

Maps of gravity anomalies

NORTHERN FRANCE, Isostatic anomalies (1:1 000 000)	1954	55 French Francs
SOUTHERN FRANCE, Isostatic anomalies Airy 50 (1:1 000 000)	1954	55 French Francs
EUROPE-NORTH AFRICA, Mean free air anomalies (1:1 000 000)	1973	90 French Francs

World maps of anomalies (with text)

PARIS-AMSTERDAM, Bouguer anomalies (1: 1 000 000)	1959-60	65 French Francs
BERLIN-VIENNA, Bouguer anomalies (1: 1 000 000)	1962-63	55 French Francs
BUDAPEST-OSLO, Bouguer anomalies (1: 1 000 000)	1964-65	65 French Francs
LAGHOUAT-RABAT, Bouguer anomalies (1: 1 000 000)	1970	65 French Francs

EUROPE-AFRICA, Bouguer anomalies (1:10 000 000)	*1975*	*180 French Francs with text (120 F. F. without text)*
EUROPE-AFRICA, Bouguer anomalies Airy 30 (1:10 000 000)	*1962*	*65 French Francs*

Charts of recent sea gravity tracks and surveys (1:36 000 000)

CRUISES prior to	*1970*	*65 French Francs*
CRUISES	*1970-1975*	*65 French Francs*
CRUISES	*1975-1977*	*65 French Francs*

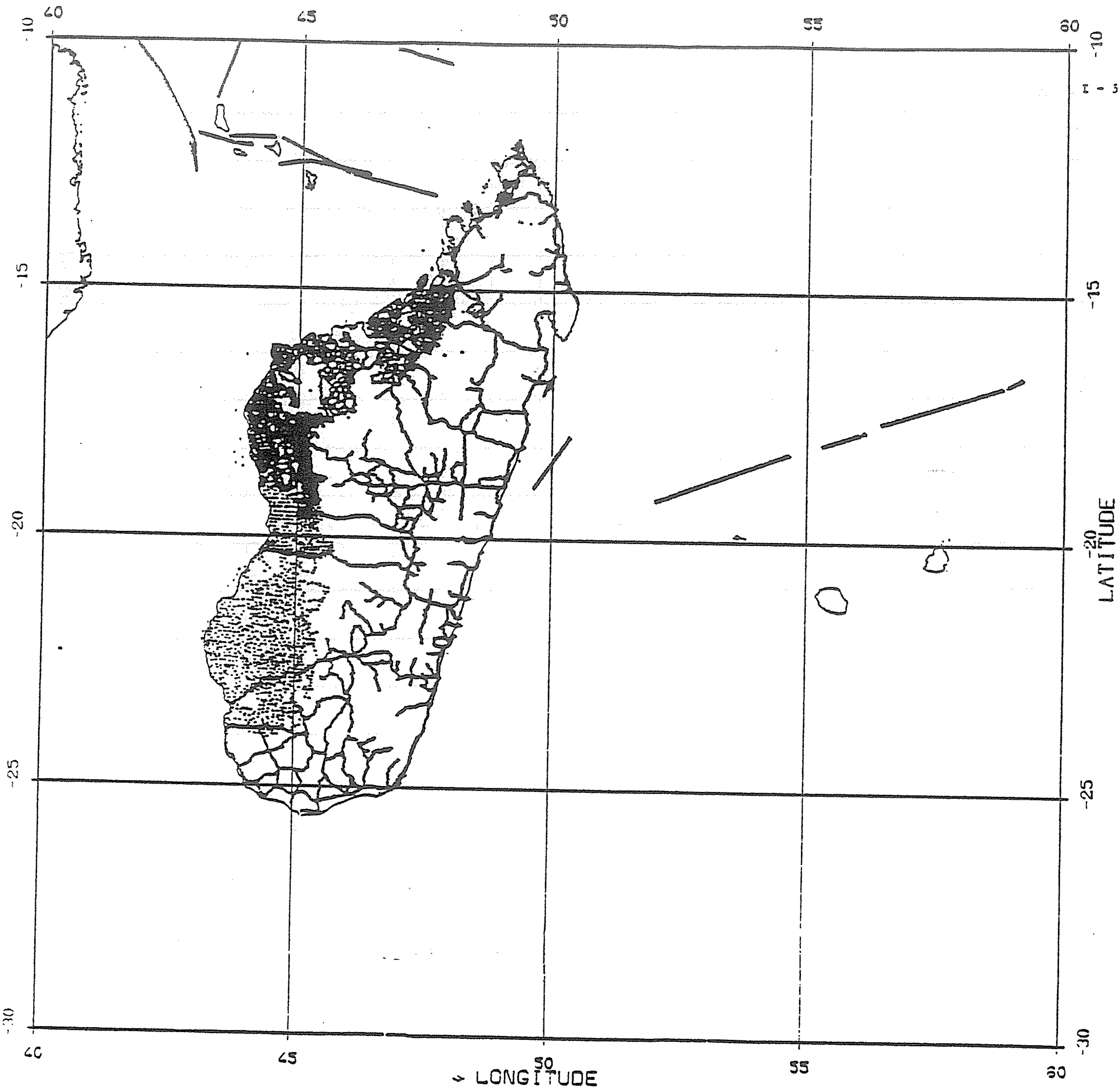
Miscellaneous

CATALOGUE OF ALL GRAVITY MAPS (listing)	*1985*	*200 French Francs*
THE UNIFICATION OF THE GRAVITY NETS OF AFRICA (Vol. 1 and 2)	*1979*	*150 French Francs*

- *Black and white copy of maps : 150 F per copy*
- *Colour copy : price according to specifications of request.*

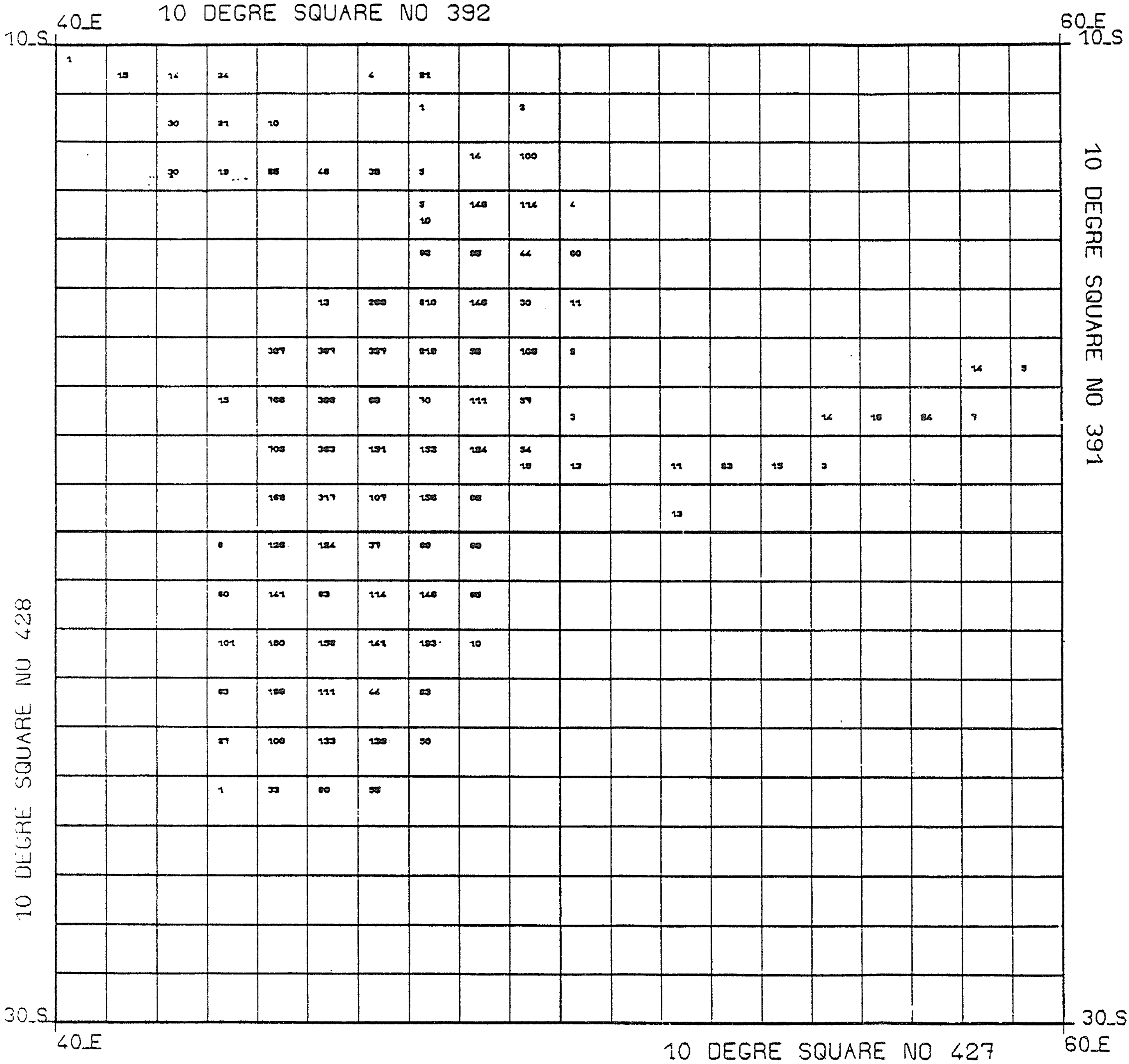
Mailing charges will be added for air-mail parcels
(when "Air-Mail" is requested)

Map 1. Example of data coverage plot



Map 2. Example of detailed index (Data coverage corresponding to Map 1)

REPRESENTATION OF EARTH AND SEA GRAVIMETRIC STATIONS



4. PROVIDING DATA TO B.G.I.

4.1. Essential Quantities and Information for Gravity Data Submission

1. *Position of the site :*

   - *latitude, longitude (to the best possible accuracy),*

   - *elevation or depth :*
     . *for land data : elevation of the site (on the physical surface of the Earth)**
     . *for water stations : water depth.*

2. *Measured (observed) gravity, corrected to eliminate the periodic gravitational effects of the Sun and Moon, and the instrumental drift**.*

3. *Reference (base) station (s) used. For each reference station (a site occupied in the survey where a previously determined gravity value is available and used to help establish datum and scale for the survey), give name, reference station number (if known), brief description of location of site, and the reference gravity value used for that station. Give the datum of the reference value ; example : IGSN 71.*

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* Give supplementary elevation data for measurements made on towers, on upper floor of buildings, inside of mines or tunnels, atop glacial ice. When applicable, specify whether gravity value applied to actual measurement site or it has been reduced to the Earth's physical surface (surface topography or water surface).
Also give depth of actual measurement site below the water surface for underwater measurements.

** For marine gravity stations, gravity value should be corrected to eliminate effects of ship motion, or this effect should be provided and clearly explained.

4.2. Optional Information

The information listed below would be useful, if available. However, none of this information is mandatory.

. *Instrumental accuracy :*

- *identify gravimeter (s) used in the survey. Give manufacturer, model, and serial number, calibration factor (s) used, and method of determinating the calibration factor (s).*

- *give estimate of the accuracy of measured (observed) gravity. Explain how accuracy value was determined.*

. *Positioning accuracy :*

- *identify method used to determine the position of each gravity measurement site.*

- *estimate accuracy of gravity station positions. Explain how estimate was obtained.*

- *identify the method used to determine the elevation of each gravity measurement site.*

- *estimate accuracy of elevation. Explain how estimate was obtained. Provide supplementary information, for elevation with respect to the Earth's surface or for water depth, when appropriate.*

. *Miscellaneous information :*

- *general description of the survey.*

- *date of survey ; organization and/or party conducting survey.*

- *if appropriate : name of ship, identification of cruise.*

- *if possible, Eötvös correction for marine data.*

. *Terrain correction :*

Please provide brief description of method used, specify : radius of area included in computation, rock density factor used and whether or not Bullard's term (curvature correction) has been applied.

. *Isostatic gravity :*

Please specify type of isostatic anomaly computed.
Example : Airy-Heiskanen, T = 30 km.

. *Description of geological setting of each site.*

4.3. Formats

Actually, any format is acceptable as soon as the essential quantities listed in 4.1. are present, and provided that the contributor gives satisfactory explanations in order to interpret his data properly.

The contributor may use, if he wishes so, the BGI Official Data Exchange Format established by BRGM in 1976 : "Progress Report for the Creation of a Worldwide Gravimetric Data Bank", published in BGI Bull. Info. n° 39, and recalled in Bulletin n° 50 (pages 112-113).

If magnetic tapes are used, contributors are kindly asked to use 1600 b.p.i. unlabeled tapes (if possible), with no password, and formated records of possibly fixed length and a fixed blocksize, too. Tapes are returned whenever specified, as soon as they are copied.

PART II

XIXTH IUGG GENERAL ASSEMBLY

Minutes

Meeting of Directing Board
of the
Bureau Gravimetrique International
held in Vancouver, Canada
August 8, 1987

Present:

Dr. J. Tanner, Chairman
Dr. G. Balmino
Prof. C. Morelli
Prof. W. Torge
Mr. R.K. McConnell

1. Report of the Director

Georges Balmino tabled a report of the activities of B.G.I. for the period 1983-87 and briefly reviewed and discussed as follows:

- Considerable new data has been acquired, particularly in Africa (160,000) stations) and over the oceans.

- The gravity anomaly database is now fully operational again. Steps have been taken to improve software documentation and to have more than one person familiar with the database software to avoid a recurrence of previous problems. The backlog of requests no longer exists and the one month turnaround objective set at the last Directing Board Meeting has been consistently met. Letters will be sent if requests are delayed more than one month. Dr. Balmino presented a new four-colour brochure recently printed to publicize the products and services of B.G.I. About 1,000 have been mailed out to date. As a result, a significant increase in the volume of requests to the B.G.I. is expected.

- The bibliographic database has been converted from an in-house to a commercial database package providing much improved operation. B.G.I. will soon offer selective retrievals on diskette from this database using a keyword thesaurus previously published in the B.G.I. Bulletin. Dr. Balmino noted that the maintenance of this database now requires about six person months of effort per year. The Directing Board asked him to continue maintenance of this database, to ensure adequate advertising of its existence and to re-evaluate the need for it after a year or so of service to the user community.

- The Directing Board agreed that no restrictions would be placed on release of data from the B.G.I. Other than those imposed by data contributors with respect to their data sets. Dr. Balmino was asked to review the schedule of charges for data with a view to increasing the charges to non-contributors of data to B.G.I.

- The policy concerning the working relationship between B.G.I. and other agencies such as DMA was raised by the Director. The Board agreed that, in future, B.G.I. should not enter into arrangements for on-going collaboration with other agencies in order to ensure that it is seen as an independent international agency.

- As requested at the September, 1986 meeting, B.G.I. has suspended work on the GEBCO project. Institute Geographique National has agreed to provide support to restart this project in September, 1987. The Directing Board asked Dr. Balmino to formally thank M. Louis of IGN for his assistance in securing this support.

- With respect to BGI priorities, the Board asked that Dr. Balmino continue under the priorities assigned at the September, 1986 meeting.

2. Working Group Reports

WGI - Data Processing

- McConnell reported that Mr. Serrailh of B.G.I. had spent a few weeks at the Geological Survey of Canada to familiarize himself with marine gravity adjustment software developed there and had tested the software on some B.G.I. marine data. He also reported that the preparation of the 1:20,000,000 world gravity map in collaboration between GSC and the Bureau had been suspended due to a lack of drafting support (presumed to be temporary) at the G.S.C. Attempts will be made to revive the project in the coming year.

WG3 - Data Presentation (see Table 1)

- Prof. Boulanger tabled a list of gravity maps prepared by the Working Group and stated that the work of the group would be completed in the coming year. The Directing Board thanked Prof. Boulanger for his efforts in the production of world-wide gravity maps and agreed to shut down Working Group 3.

WG2 - World Gravity Standards

Boedecker was not present to give a report but the Board suggested that new tasks for WG2 could be:

a) implementation of IAGBN proposed by S.S.G.3.87

b) development of a set of standard corrections for absolute gravity measurements

c) ensure that IAGBN is well connected to local absolute or relative nets.

3. Memberships and Mailing Lists

B.G.I. will compile updated mailings lists for the Commission, sub-commissions and Working Groups. The use of International Telecommunications networks (BITNET, NASANET, OMNET/TELENET, SPAN, etc.,) was discussed for the purpose of communications between B.G.I. and the Board members. No standard could be chosen but it is expected that some network, accessible by all concerned, should be available in a year or two. In the meantime, B.G.I. will try to establish two-way communication between OMNET and BITNET.

4. ICL Coordinating Committee

Balmino reported that the survey of gravity and magnetic databases around the world had gone ahead. McConnell noted that some room for improved communication between the project coordinators was evident since both Hinze and Gvishiani seem to have requested the same information independently from organizations around the world. Balmino will attend a meeting in USSR in November where the ICL project will be discussed.

5. Gravity Map of North America

McConnell reported that the compilation of the data and notes had been completed and that only the final cartographic work remained. The maps will consist of 5 sheets at a scale of 1:5,000,000 and will be published in January 1988. The Directing Board recognized a need to have a similar map for Europe.

R.K. McConnell
Recorder

Table 1

List of Gravimetric Maps

Included in Geological Geophysical Atlas of the Atlantic Ocean

Established by W.G. 3

1. Map of Anomalies in Free-Air Reduction (Faye)
   Scale 1:10.000.000, 4 pages

2. Map of Geoid Heights
   Scale : 1:10.000.000, 4 pages

3. Map of Average Gravity Anomalies in Free-Air Reduction (Faye) $1^\circ \times 1^\circ$
   Scale : 1:30.000.000, 1 page

4. Map of Gleni Anomalies
   Scale : 1.30.000.000, 1 page

5. Map of Anomalies in Isostatic Reduction
   Scale : 1:30.000.000, 1 page

6. Map of Long Wave Component of Anomalies in Isostatic Reduction
   Scale : 1:30.000.000, 1 page

7. Map of Anomalies in Free-Air Reduction (Faye) of the Bay of Biscay
   Scale : 1:2.500.000, 1 page

8. Map of Geoid Heights of the Bay of Biscay
   Scale : 1:2.500.000

9. Map of Anomalies in Free-Air Reduction (Faye) of the Caribbean Sea
   Scale : 1:2.500.000, 1 page

G.S. 3

SECTION 3 MEETING

Tuesday, August 8, 1987 (2 - 5.30 p.m.)

(Buchanan 100)

AGENDA

2.00 p.m.	Report of Section 3 President
2.20	Report of I.G.C. President
2.35	Report of Director of B.G.I.
2.50	Report of President of S.S.G. 3.85
3.05	Report of President of S.S.G. 3.86
3.20	Report of President of S.S.G. 3.87
3.35	Coffee Break
4.00	Report of President of S.S.G. 3.88
4.15	Report of President of S.S.G. 3.89
4.30	Report of President of S.S.G. 3.90
4.45	General Discussion : - Future Research - Future Structure of Section 3 - Special Study Group - Recommendations - Resolutions
5.30	Adjourn

IAG Section III

Determination of the Gravity Field

Report of Activities 1983 – 1987
to the IAG General Assembly, Vancouver, August 1987
by *Wolfgang Torge*, President Section III

This report presents in summary form the activities of Section III since the IAG General Assembly in Hamburg 1983. At that General Assembly, Section III has been reorganized, covering now the field of gravimetry including the determination of non-tidal gravity variations (responsible Section III Secretary *I.Nakagawa*, as well as the estimation of the gravity field from all kind of gravity field related data, including reduction and interpolation procedures (responsible Section III Secretary *C.C. Tscherning*). The report is based on the reports of Section III bodies, on papers presented at scientific meetings and literature relevant to gravity field determination, and on national reports, and it continues the annual Section III reports published in Bulletin Géodésique. Bibliography is given in the reports of Section III bodies and in the national reports; a current updating of gravimetric literature can be found in the Bulletin d'Information of the Bureau Gravimetrique International, which issued nos. 52 – 60, between 1983 and 1987. Consequently, only some summarizing references and articles representing samples of certain research fields are mentioned here.

IAG bodies working under the aegis of Section III have been

- the International Gravity Commission (IGC), President *J.G. Tanner*,
- the Bureau Gravimetrique International (BGI), Director *G. Balmino*,
- Six Special Study Groups (SSG):

  SSG 3.85 "Comparison of high-precision relative gravimetry techniques", President *E. Groten*,

  SSG 3.86 "Evaluation of absolute gravity measurements", President *Yu. D. Boulanger*,

  SSG 3.87 "Development of a new world absolute gravity network", President *G. Boedecker*,

  SSG 3.88 "Determination of the geoid in Europe", President *G. Birardi*,

  SSG 3.89 "Observation and adjustment procedures in dynamic gravimetry", President *J. Makris*,

  SSG 3.90 "Evaluation of local gravity field determination methods", President *C.C. Tscherning*.

These bodies and Section III organized a number of scientific and organisational *meetings* between 1983 and 1987:

- IAG Symposium "The role of gravimetry in geodynamics" (*E. Groten*), IAG General Assembly, Hamburg, August 1983,
- 2 Section III meetings (*J.G. Tanner*), IAG General Assembly, Hamburg, August 1983,
- 11. IGC meeting (*C. Morelli*), Hamburg, August 1983,
- IGC/CGA (Comm. for Geodesy in Africa) joint meeting, "African Gravity Standardization Network", Paris, May 1985,
- 12. IGC meeting, Toulouse, September 1986,
- SSG 3.85, 3.86, 3.87 joint workshop at the "Absolute Gravimeter Campaign", Paris, June 1985,
- International Symposium on the "Definition of the Geoid", organized by SSG 3.88, in cooperation with SSG 3.90, 4.91, 4.92, 5.97, Florence, May 1986,
- SSG 3.85 meetings at the "Recent Crustal Movements in Africa" Symposium, Cairo, December 1984 and at the International Symposium on "Neotectonics in South Asia", Dehra Dun, February 1986,
- SSG 3.88 meetings at Paris, June 1984 (representatives), and at the Hotine-Marussi-Symposium, Rome, June 1985.

At the IAG General Assembly, Vancouver, August 1987, the following meetings are scheduled:

- IAG Intersection Symposium "Advances in gravity field modeling" (*C.C. Tscherning*), together with Section II and IV,
- scientific meeting "Advances in gravimetric techniques" (*I. Nakagawa*),
- scientific meeting "The challenge of the cm-geoid—strategies and state of the art" (*H.-G. Wenzel*),
- Section III business meeting (*W. Torge*),
- IGC meeting (*J.G. Tanner*).

We now concentrate on the main results obtained in the field of gravity field determination within the last four years, through these bodies and through individual scientists and institutions. Emphasis is laid on not only describing the progress, but also pointing to open problems and tendencies. A division has been made according to the *subjects*

- terrestrial gravimetric techniques and gravity networks,
- regional gravity surveys and dynamic gravimetry,
- non-tidal gravity variations with time,
- global gravity field modeling, and
- local gravity field modeling.

General *trends* to be observed are

- strengthening of cooperation with other geodetic groups, in order to exploit all gravity field related data for the determination of geometric (geoid heights and vertical deflections) and geokinematic (vertical crustal movements) parameters, as well as for the combined use of geometric and gravity data at dynamic surveys,
- increased interdisciplinary cooperation with other natural sciences, in order to better model and interpret gravity variations in space and time,
- strengthening of international cooperation, with an increasing number of regional and local coprojects, in the fields of high precision gravity networks especially for investigation of gravity variations with time, and high resolution geoid determinations.

Terrestrial gravimetric techniques and gravity networks

In *absolute gravimetry*, progress continued, opening a new era in the 300 years history of gravimetry (*Torge* 1987). More than 10 transportable instruments, based on the free-fall or the symmetrical rise and fall method are available now, and more than 100 stations have been observed all over the world, during the last 10 years (*Marson* and *Faller* 1986, *Faller* and *Sakuma* 1987). A major step forward to wide application came through the development and production of a series of six free-fall gravimeters, by *J.E. Faller* and his coworkers at the Joint Institute of Laboratory Astrophysics (JILA), Boulder, Col., and delivery of five of them to different institutions active in gravimetry, within the framework of cooperation programs. Generally, development in absolute gravimetry is directed to employ the multiposition method, to improve isolation against microseismics, to more automation including on-line evaluation, and to reduction of size and weight. At present, with most advanced instruments one station can be observed in one day with a precision (standard deviation) of a few μgal (1 μgal = 10 nms^{-2}), e.g. *Torge* et al. (1987). The problem of accuracy, of systematic errors, and of local gravity field non-linearities affecting the comparison and connection of different gravity measurements, has been investigated by SSG 3.86 . Following IUGG resolution no. 18, Hamburg 1983, a second international campaign for comparing absolute gravity meters has been organized and performed at BIPM, Sèvres, in June/July 1985 (*Boulanger* et al. 1986). Six different instruments have been compared, with mean value standard deviations of 5 to 10 μgal. In order to determine the vertical gravity gradients and to connect the different absolute sites, a relative gravimeter campaign was organized through SSG 3.85, resulting in a few μgal accuracy for these local connections. From this comparision, as well as from other recent determinations, discrepancies up to some 10 μgal have been found between the results of different absolute gravity meters. This is a very alarming result, which strongly requires further research. Reasons for these discrepancies may include instrumental effects, different reduction and evaluation procedures, errors at local gravity transfer, and local mass shifts if observations have not been performed at the same time.

In *relative gravimetry* many problems have been attacked mainly within SSG 3.85. The calibration problem for not too large gravity differences has been largely solved through the establishment of calibration systems based on absolute and relative measurements, and designed to detect all possible wavelengths of calibration functions (*Kanngieser* et al. 1983, *Nakagawa* et al. 1986). More economic for the detection of short period calibration terms is the use of electronic feedback systems, which have been developped at different institutes and implemented into LaCoste-Romberg gravity meters (e.g. *Röder* et al. 1985, *Valliant* 1986). Even more important is the application of feedback-equipped gravimeters for the observation of small (some mgal) gravity differences, thus completely eliminating the effect of short-period calibration errors. Long-wave calibration terms can be derived from IGSN 71, if sufficiently large gravity differences are used (*Nakagawa* et al. 1983). No significant progress has been made in reducing residual temperature and vibration or shock effects during field surveys as additional isolation devices obviously hinder operational surveys too much. The only way of reducing these errors still seems to be "randomization" by performing multiple measurements with different instruments and under different environmental conditions. Accuracy achievable is now a few μgal for small networks, and better than 10 μgal for large nets, if the gravimeters have been calibrated carefully in the corresponding gravity range (*Becker* et al. 1987).

There is a strong tendency to establish global, regional and local *gravity networks* of high precision (1 to 10 μgal) through combination of absolute and relative techniques. Reasonable distances of absolute control stations in regional networks may be at about 100 to 200 km, and for densification relative gravimeters with feedback-system should be employed if possible. A major step forward is the plan for establishing an International Absolute Gravity Basestation Network (IAGBN), developped by SSG 3.87, following IAG resolution no. 11, Hamburg 1983 (*Boedecker* and *Fritzer* 1986).

Altogether 36 globally distributed absolute sites have been proposed, the locations being selected according to different criteria, with main emphasis on geodynamical considerations. It is a strong challenge to realize this plan within the next 5 to 10 years, and a realistic approach seems to be the realization within limited campaigns, possibly in connection with the establishment of regional absolute control. A connection to geometric control stations (satellite techniques) is highly advisable, and a careful site supervision (national agency) and documentation of the results (BGI) is absolutely necessary. The same demands are valid for the base stations of national networks, which are increasingly established with absolute gravimeters (e.g. *Song Xingli* et al. 1986). There is a strong need to establish fundamental networks of high quality especially in regions where IGSN 71 and densification is weak, and the plan of an African Gravity Standardization Network as discussed within IGC and CGA. and prepared by *Ajakaiye* (1986), is one example of a regional effort within IAG to attack this problem. High precision local gravity networks are mainly established for monitoring gravity variations with time. Many new networks have been established all over the world, partly through initiative of SSG 3.85 (e.g. *Becker* et al. 1986). Absolute gravity measurements now start to stabilize these networks with respect to datum and calibration, and sophisticated software developped for microcomputers enables to control high precision surveys in the field and optimize the results (*Röder* and *Torge* 1987).

Regional gravity surveys and dynamic gravimetry

Regional gravity surveys are generally conducted through the responsible national agencies. *Data coverage* is quite different at different regions of the world, reaching from average station distances of 1 to 2 km (few regions) to 5 to 15 km and more, with many regions not surveyed at all. Although BGI further collected a large amount of new data, especially from African and European countries, the problem of having neither point nor mean gravity anomalies available for large parts of the world could not be solved. This is due to data restrictions, and to the time-consuming terrestrial observation technique, on land as well as on the oceans, which includes also positioning and height determination. For ocean areas, the data coverage situation is better as satellite altimetry results have been converted to gravity anomalies of high resolution, taking long-wave sea surface topography into account (e.g. *Rapp* 1986a, *Balmino* et al. 1987); an improvement is to be expected from new satellite altimetry missions. But in order to derive sea surface topography from altimetry, direct gravity determinations of high resolution are needed.

Marine gravimetry has reached a high standard. Different sea gravimeters are available now, operating in integrated systems with gyro-stabilized platforms and navigation. Efficiency of these systems has been investigated partly within SSG 3.89, and a precision of better than 0.5 to 1 mgal has been found even under severe conditions (e.g. *Valliant* 1983, *Segawa* et al.1984, *Bell* and *Watts* 1986). Navigation problems hinder until now the full exploitation of this precision, as the Eötvös-correction cannot be calculated with sufficient accuracy. With continuing development of the GPS-system, this problem will be solved through GPS or integrated (with inertial systems) navigation (e.g. *Wong* et al. 1985).

Airborne gravimetry and *gravity gradiometry* has made a step forward after long years of experimental stage. This is due to improvements in stabiliziation, navigation, and data evaluation. Further development of gravimetry from low flying fixed-wing airplanes is expected to yield a 2 to 3 mgal accuracy at about 20 km resolution (*Brozena* 1984), while helicopter gravimetry has proved its operational capability with 0.5 mgal accuracy and about 1 km resolution (*Hammer* 1983). Gravity gradiometry entered a very promising phase now (*Eckhardt* 1986), after careful model studies (*Jekeli* 1985). In connection with GPS positioning, the Bell Gravity Gradiometer Survey System is scheduled to operate either in a van or in a low flying airplane with an expected 1 mgal (gravity disturbance) respectively 0."2 (vertical deflection) accuracy (*Jordan* 1986). In connection with positioning, *inertial gravimetry* at traverses of some 10 to 100 km length now reaches a 1 to 5 mgal respectivly 1" accuracy (*Boedecker* 1986, *Forsberg* et al. 1986), and it might be able to improve these results through post-mission adjustment, with new possibilities also coming from combination with GPS. So we may expect, that dynamic gravimetry will be able to fill more rapidly existing gaps in gravity field coverage of many parts of the world, at short and medium wavelengths. For obtaining a better global coverage at medium wavelengths, expectations are directed to satellite gradiometry or satellite-to-satellite-tracking missions, planned in heights of about 200 km for the 1990s. Using either conventional (*Balmino* et al. 1984) or superconducting (*Paik* 1981) techniques, accuracies of 2 to 5 mgal and resolutions of 50 to 100 km are expected (*Wells* 1984).

The large amount of gravity field related data available and expected in the future, forces to establish *gravity data banks* of high flexibility and efficiency with data management systems capable of data screening, transformation, reduction, gridding, and contouring, and the possibility of rapid updating. Besides of the BGI data bank, regional centers have been established at different parts of the world (e.g. *O'Hara* and *Lyons* 1985), but more efforts have to be directed to a smoother interchange between different data bases, in order to fully exploit available gravity field information for scientific purposes.

Non-tidal gravity variations with time

With the 1 to 10 μgal accuracy level achieved now at local respectively regional gravity networks, the interest in using gravity as one information source for geokinematics and geodynamics has further increased (*Torge* 1986). The close interrelation between gravity and height variations has led to synoptic studies (*Biro* 1983, *Heck* and *Mälzer* 1986), and to combination of gravity and height measurements at numerous control networks. While *high-precision relative gravimetry* has proved its efficiency for monitoring gravity variations with time, absolute gravimetry is just entering into this field of research. Significant part of activities has been performed by members of SSG 3.85, following IAG resolutions no.10, Hamburg 1983, which recommended high prioritity to research related to application of relative gravimetry for investigating recent crustal movements, underlying dynamic processes, and as an element in earthquake prediction research.

Until now, no gravity variations of global character have been found, but this problem will be attacked through absolute measurements, which now start at many places. Regionally and locally, a number of results of *tectonic* interest is available now , partly from networks or profiles which have been observed since 15 years or more (*Boulanger* 1984). Long-time control systems generally include also other geodetic and geophysical methods, and operate at all kind of tectonic plate boundaries, as well as inside the plates. Long and short-wave variations have been found at diverging (e.g. *Torge* and *Kanngieser* 1985), colliding (e.g. *Satomura* et al. 1986), and strike-slip boundaries, with special effort directed to contribute to earthquake prediction research (e.g. *Jachens* and *Roberts* 1985, *Wei Menghua* et al. 1985). Intraplate investigations have been successful at postglacial rebound areas (*Ekman* et al. 1987), but revealed also geological block behaviour (*Elstner* et al. 1986). Interpretation of the results is generally hindered from short-periodic and seasonal variations of *groundwater* level and soil moisture (e.g. *Drewes* et al. 1983), and more research is needed in order to be able to model these disturbances (e.g. *Mäkinen* 1985).

There is also a growing tendency to employ high-precision gravimetry for monitoring the effects of *man-made mass shifts*, especially if they happen to occur in tectonically active areas. Promising results have been achieved at investigating exploitation-induced changes in hydrocarbon (e.g. *Drewes* et al. 1983) and geothermal (e.g. *Allis* and *Hunt* 1986) areas, and at reservoir studies (e.g. *Lambert* et al. 1986).

The problem of detecting gravity variations with time generally covering a large spectral range, will in the next future be attacked through combined gravimetric techniques, employing transportable gravity meters with registrating instruments (e.g. *Kuo* et al. 1983), taking advantage also from the high stability and resolution of superconducting gravimeters (*Goodkind* 1986, *Richter* 1987).

Global gravity field modeling

Gravity field modeling is performed on global and regional scales, using corresponding data sets of different kind of gravity field quantities. The data are generally restricted in space (outer space data, data on land or sea) and in spectrum. Global *gravity field information* has improved through

— availability of new satellite tracking data and new sets of spherical harmonic coefficients complete to degree and order 20, derived from satellite orbit analysis (*Lerch* et al. 1982)

— ocean-wide satellite altimetry from GEOS-3 and SEASAT-1 (*Marsh* et al. 1986) missions, adjusted, combined and transformed to 30′ × 30′ and 1° × 1° mean free air anomalies, and

— extension of the terrestrial gravity anomaly data set through inclusion of new data, leading to an improvement of the 1° × 1° mean anomalies (appr. 70% of the earth's surface) and calculation of 30′ × 30′ mean anomalies for well surveyed regions (*Rapp* and *Cruz* 1986).

From combination of these data, new high-degree *potential coefficient models* have been calculated (*Rapp* 1986b), generally now taking into account also sea surface topography models for reducing altimetric data. Adjustment of satellite observations and 1° × 1° mean values gave improved earth models, with a set of station coordinates and potentional models to degree and order 36 (*Reigber* et al. 1985), while the combination of satellite derived models, altimetric and gravimetric data resulted in models up to degree and order 200 (GPM-2, *Wenzel* 1985), respectively 360 (OSU E/F, *Rapp* and *Cruz* 1986). Error analysis and comparison of different models gives accuracy estimates of 1 m and better for the geoid (quasigeoid), the main part of this figure stemming from the short wave field omission errors. Developments beyond degree 180 to 200 do not significantly improve the overall accuracy, but give more information in well surveyed areas. There is still the problem, that differences of more than 10 m respectively 100 mgal occur between different solutions, depending on the data sets used, and on different ways of interpolating non-surveyed regions.

Progress has been made also at global modeling *field structures of geophysical interest*. From comparisons of SEASAT-altimetry and gravity field models, long-wave global ocean circulation patterns have been derived (*Engelis* and *Rapp* 1984), but further progress in this direction will probably need global high-resolution gravity field data, to be expected in the 1990s from new satellite missions. Candidates for these missions are satellite-to-satellite-tracking, with successful tests already available (*Marsh* et al. 1984), and satellite gradiometry, with numerous instrumental and theoretical studies performed, but still rather open problems at physical modeling (*Rummel* 1986). The development of a topographic-isostatic earth model to degree and order 180, using regional compensation of Vening-Meinesz type, does not only help geodesy at gravity field smoothing on regional and local scale, but is also an important step towards a closer unity of geodesy and geophysics, by introducing a more realistic model of the outer shell of the earth, with further refinements still possible (*Sünkel* 1986b).

Local gravity field modeling

Local gravity field modeling has received increasing importance, with high demands for resolution and accuracy coming from the successful operation of advanced positioning techniques, as GPS and inertial surveying. Present requirements may be summarized by accuracy demands of a few cm for geoid or quasigeoid differences over some 10 to 100 km, a few seconds of arc for vertical deflections, and about one mgal for gravity anomalies. These figures are a challenge for theory, as well as for data collection and evaluation methods. Available methods have been carefully studied by SSG 3.90 (e.g. *Tscherning* 1986) and SSG 3.88 has made remarkable contributions to geoid and quasigeoid determination and analysis within the European test area, with many highlights documented in the Proceedings of the International Symposium on the Definition of the Geoid, held in Florence, Italy, in 1986 (*Birardi* 1986).

Local gravity field data include

- point gravity anomalies and mean anomalies for small block sizes (e.g. $5' \times 5'$ or $10' \times 10'$) as collected in some regions of the world (e.g. *Ganeko* 1983, *Torge* et al. 1984a). Being observable on land and at sea, this data set is in principle the most valuable information source, although handicapped by different restrictions mentioned above,
- satellite altimetry forms another important data set, with regional geoid accuracy often exceeding that derived from gravity data (e.g. *Brennecke* et al. 1982),
- astronomic vertical deflections have been further collected in some regions of the world, especially by employing transportable zenith cameras (e.g. *Seeber* and *Torge* 1985). These data can complement and eventually substitute gravity anomalies on land, especially for geoid calculations in areas where gravity data are restricted.

General adopted strategy for local *gravity field determination* is to separate from the local data the long-wave part through a high-degree potential model, and to smooth the field through reduction of the short-wave part calculated from a digital terrain model, applying computational methods of high efficiency (e.g. *Forsberg* 1985). For interpolation and error estimation, regional statistical characteristics of the gravity field have to be derived, and are available now for many areas (e.g. *Goad* et al. 1984). Although knowledge of error behaviour is essential for a realistic accuracy estimation of the results by error propagation procedures, only few investigations could be performed in this direction (e.g. *Weber* and *Wenzel* 1983). Among the evaluation methods investigated are refined integral methods (*Sjöberg* 1986), least-squares collocation (*Tscherning* 1985a, 1985b), and Fourier techniques (e.g. *Sideris* and *Schwarz* 1986), and attempts have been made to include the gravity field determination into the concept of "integrated geodesy" (*Hein* 1986). Although the methods have different advantages and disadvantages, they obviously all give approximately the same results (e.g. *Kearsley* et al. 1985).

Geoid determinations with real data have been performed in many areas, using different kind of data and evaluation methods, from astronomical levelling in flat regions (e.g. *Seeber* and *Torge* 1985) to combination solutions including topography and density models in mountain regions (e.g. *Sünkel* 1987). It appears that at well surveyed areas, a decimeter accuracy for geoid height differences over 100 km has been reached. For larger areas, error propagation and heterogeneous data coverage pose severe problemes, but with a good gravity anomaly knowledge, e.g. by $6' \times 10'$ mean anomalies as in Europe, average accuracy of 1 m/1000 km and 2 seconds of arc can be achieved (*Torge* et al. 1984b). As a next step in regional solutions, a 0.05 m/100 km and 0.2 m/1000 km accuracy for geoid/quasigeoid differences should be attacked, but as improvements in data coverage will not be simultaneous for different areas of a larger region, strategies of merging high resolution and accurate solutions with less accurate ones have to be developped (e.g. *Tscherning* et al. 1986). A realistic approach seems to be the use of topography reduced point gravity anomalies with average station distance of 2 to 10 km, processed after trend reduction (global geopotential model) by least squares collocation techniques over limited areas (*Denker* et al. 1986). High accuracy of GPS translocation techniques has provided another tool of controling and strengthening local geoid/quasigeoid solutions, by combining the results with levelled heights (e.g. *Engelis* et al. 1984). While the power of this method is already sufficiently reliable for limited distances (e.g. *Seeber* 1986), long-range investigations are still necessary, as started with the North-South-European GPS traverse, now observed along selected European leveling network lines, with 50 km station distance (*Torge* and *Doliff* 1987).

More investigations are still necessary in order to fulfil the strong requirements of a "cm"-geoid, put to physical geodesy from surveying agencies, and have to contain among others the development of optimum strategies for attacking this problem in well and insufficient surveyed regions, the significance of including topographic, geological and geophysical information, and more realistic error estimation.

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REPORT OF THE INTERNATIONAL GRAVITY COMMISSION TO THE GENERAL ASSEMBLY OF THE INTERNATIONAL ASSOCIATION OF GEODESY

VANCOUVER, 1987

SUMMARY

In addition to its regular quadrennial meeting the IGC held two special meetings to discuss, jointly with representatives of the African Geodetic Commission, technical details and strategies for effecting the African Gravity Standardization Net. In addition it had representation at several workshops organized by Special Study Groups and the quadrennial meeting of the African Geodetic Commission. Its quadrennial meeting was a week long affair that saw three business sessions interspersed with nine lively and stimulating technical sessions.

The age of the absolute instrument as a field device has truly arrived with the delivery of six Faller-type instruments to agencies throughout the world. Preliminary reports on its use by operational personnel in these agencies are positive about the instrument and at least one agency has begun a process of modifications designed to improve the accuracy of the measurements and to make it more easily adaptable to field conditions. This coupled with the successes of the Italian apparatus over the past several years leave us in a strong position with respect to gravity standards.

Data base activities continue to be a priority of the IGC and its operational agency, the International Gravity Bureau, has made steady progress in its quest for a truly world wide data base. The recent increase in regional map compilations by working groups around the world underlines the importance of data base related activities and are a strong indicator of how far we have come since the early days of gravity mapping. The IGC hopes its regional sub-commissions will take up the challenge of its North American colleagues and undertake a regional compilation of their own.

The IGC will continue to stress world gravity standards and data base activities in the future. In particular it will take vigourous action to promote the reality of a World Absolute Gravity Base Station Network.

INTRODUCTION

The International Gravity Commission and its operating agency, the International Gravity Bureau, realized a number of achievements and suffered some disappointment during the course of the four-year period since the last General Assembly at Hamburg. Perhaps the biggest disappointment was our inability to complete a a computer-based listing of publications in the field of gravity. This enormous undertaking was originally scheduled for completion by this General Assembly, but staff departures from the International Gravity Bureau (IGB) forced priorities to be placed elsewhere. As we counted on this listing as the source of any bibliography for this report, no bibliography can be presented here. However, most countries submit national reports to both the IGC and the IAG complete with bibliographies, the reader can obtain such information from these sources. In addition, fairly extensive reviews and/or listings of important publications in the field are given in the Bulletin d'Information published in June and December of each year by the IGB.

The IGC actively involved itself in a number of projects during the period since the last General Assembly. The project involving the most effort was the African Gravity Standardization Net. Working Group 2 helped out with the design and specifications for the network and the IGC itself held two special meetings in an effort to raise as much support as possible for the project. The first of these took place in Cairo in December, 1983 where the execuive of the IGC met with the executive of the African Geodetic Commission to discuss possible strategies for our approach to the project. The result was a decision to hold a joint meeting of the two commissions in May, 1985 to discuss the technical details of the proposal and to discuss ways and means of generating support for the project. The technical portion of the meeting was an undoubted success as was that part related to generating the interest and commitment of specialists from around the world to help our African colleagues with such technical aspects as training, etc.. Although the possibilities of financial support initially looked promising, in the end we were not successful, for a number of reasons, in gaining any commitments for financial support.

Representatives of the IGC also participated in the joint workshop of S.S.G. 3.85, 3.86 and 3.87 held in conjunction with the Absolute Gravity Campaign in July, 1985. This highly succesful workshop covered a number of subjects relating to absolute gravity, including the African Gravity Standardization Net. Similarly, the IGC was represented at the quadrennial meeting of the African Geodetic Commission in Yamoussoukro, in April, 1986.

The main meeting of the IGC took place in Toulouse in September, 1986. The meeting consisted of 9 technical sessions covering the entire spectrum of gravity measurements and three business sessions. A wrap-up session that was part business and part technical was held on Friday morning. The technical sessions worked out particularly well with the chairmen of the sessions holding speakers to their allotted times, thus allowing ample time for good discussion periods. Resolutions passed at the meeting generally related to support for the technical activities in which the IGC is either involved or interested.

Finally it is always a sad occasion to note the passing of our colleagues. These have been reported in the Bulletin d'Information and the Bulletin Géodésique regularly throughout the period between General Assemblies. One particularly tragic passing was that of Dr. Ogier of France at a young age. His energy and enthusiasm will be missed by all his colleagues.

STRUCTURE OF THE INTERNATIONAL GRAVITY COMMISSION

The IGC is divided into regional sub-commissions (8) to facilitate regional input to the commission. The sub-commissions are:

1. North Pacific Region	I. NAKAGAWA - Japan
2. Southwest Pacific Region	I. Reilly - New Zealand
3. North America	C. Goad - USA
4. Central and South America	C. Gemael - Brasil
5. Africa	R.O. Coker - Nigeria
6. Western Europe	I. MARSON - Italy
7. Eastern Europe and USSR	Y.D. Boulanger - USSR
8. India and Arab Countries	C.S. JOSHI - India

This structure is supplemented by a Directing Board and Working Group structure set up to govern the operation of the International Gravity Bureau. The Directing Board of the IGB establishes the priorities of the Bureau and is the medium through which the Bureau can seek added technical support from the community at large. It consists of four ex-officio members and four elected members, the latter chosen by the membership of the IGC. The Directing Board, chaired by the president of the International Gravity Commission, is supported by three working groups established to provide technical support to the IGB in the fields of data base management, world gravity standards and data presentation.

The Directing Board met twice between General Assemblies and will meet again before the General Assembly in Vancouver. At the last meeting it became apparent that the IGB had lost the confidence of segments of the community because of failure to respond to queries from outside for information on the holdings of the IGB and requests for information. This unfortunate situation had developed to the point that agencies no longer wished to contribute their data to the Bureau. Lengthy discussions of this issue took place within the Directing Board and within the main meeting of the Commission in an effort to arrive at a solution that would put the situation right. It would appear that the problems at the IGB stemmed from two causes. The first was the unexpected and untimely departure from the Bureau of the principal programmer responsible for the development of the data base management software. The second was a valiant but misguided effort to maintain the same level of service in the face of an undoubted crisis within the Bureau. This resulted in a hard-pressed director being unable to provide the supervision needed to keep outside requests for data and/or information on track with the result that responses to them were delayed by months or even lost.

Projects within the IGB were given strict priorities by the Directing Board with top priority going to the collection of data and the fulfilment of requests for data or information. No other activity was to be given any priority in the face of outstanding requests - no matter what the requirement. The Directing Board also decided that it must give more assistance and guidance to the IGB by meeting at least once every year.

WORLD DATA BASE

One of the principal concerns of the IGC is the collection of a world-wide data base on an absolute standard. Such data are required principally for the production of geoid maps and the publication of gravity maps in conjunction with various international projects. Remarkable strides have been made in the past few years and the prospects even greater for expansion of the data base toward the goal of world-wide coverage. A first published version of the gravity map for North America should be available before the end of 1987 with possibly a proof of the map on display for the IUGG. Colleagues in South and Central America are taking their first steps toward organizing a project to compile a gravity map for their entire region. Our colleagues in Africa are making steady progress with their efforts to put together a continent-wide absolute reference network which should serve as a means for unifying the regional anomaly data currently available within Africa.

There still remains, unfortunately, a fairly widespread practice within member countries of classifying gravity data on military grounds. Consequently there are vast regions of the world where no gravity data are publicly available and are not likely to be so in the near future. This circumstance is extremely unfortunate for the scientific community as it deprives them of sorely needed data to compute a world-wide geoid, to produce a set of world-wide geophysical maps and to carry out geophysical and geological research applications. Eventually we will be able to fill these gaps to a certain extent with satellite data, although results from the new high accuracy satellites are probably a few years away. In the meantime we will continue to urge our colleagues in the countries in question to make strong representations to their governments that the release of regional gravity data will not compromise the military and their ability to carry out their national defence responsibilities.

WORLD GRAVITY STANDARDS

IGSN 71 continues to be an important and appropriate world gravity standard, although the ravages of time brought on by reconstruction and new development have probably led to over 50% of the sites being destroyed. No effort has been or will be mounted to replace these sites because the increasingly widespread availability of absolute instruments and the great strides made in understanding, and improving, the performance of the spring gravimeter has brought the establishment of absolute networks within the realm of the possible for any country wishing to develop is own absolute standard. Indeed, many countries or regions are proceeding in this direction.

One good example of this is the proposed African Gravity Standardization Net. Designed with the help of the IGC, colleagues in Africa are making good progress with plans to provide the training necessary to provide the pool of expertize throughout Africa to carry out this important work. At the time of writing a training course for African specialists in gravity surveying is being held. Those being trained will return to their national agencies to train others in this highly specialized activity. There is no doubt that, as financial conditions improve within Africa, great strides will be made in the development of AGSN and ultimately toward the goal of regional gravity coverage throughout the continent.

INSTRUMENTATION

Undoubtedly one of the most satisfying developments since the last General Assembly is the completion of the design and construction of six Faller-type instruments ordered by agencies in Europe and North America. This culminates a period of research and development spanning decades. While by no means can we claim there is no need for further R&D, the transportability and precision of the instruments have reached the point where the equipment can be turned over to the observers with confidence that, given the requisite care and maintenace, absolute measurements can be made in a comparatively short time. In fact, the new Faller instruments can be set up, operated and dismantled in a day or less under reasonable circumstances. The precision of the instruments is better than ten (10) microgals with the accuracy in the range of tens of microgals.

We have already seen the benefits of turning the instruments over to field observers in the evaluation and subsequent modification of one of the Faller instruments by colleagues in Germany. This impressive piece of work has not only increased our understanding of the performance of the instrument, but also led to improvements that have significantly bettered its performance (to an accuracy of ten microgals under good conditions).

While absolute instruments give a precision of a few microgals in most cases, their accuracy can only be regarded as being at the level of tens of microgals. There are still differences between absolute instruments that significantly exceed their respective precisions and between absolute and relative instruments that are as large as several tens of microgals. While our German colleagues have furthered our understanding of their performance we by no means have a complete grasp of the sources of systematic error in absolute measurements. Therefore, we must continue to carry out comparisons of absolute instruments such as have taken place at Sèvres periodically in recent years. On the positive side, however, there can be no doubt that the performance will be improved steadily during the next decade to the point where procedures with absolute instruments will be well defined, the results more predictable at the microgal level (or at least a few microgals) and the transportation and observation of these instruments a much more straightforward process. In making this statement I realize that it took us many decades of research and development on the relative instruments to reach present levels of performance and that we can expect a lengthy learning curve with the absolute instruments.

At the quadrennial meeting of the IGC it was reported that the Defence Mapping Agency in the USA was about to test its prototype airborne gravity gradiometer, culminating many long years of research and development. Laboratory tests suggest that a design accuracy of 1 EU was achievable in field situations. Unfortunately these tests do not appear to have taken place because of budget cuts and the information available suggests that the delay in carrying out these important tests might be years. Undoubtedly this is a major disappointment to the developers and proponents of the system in the USA as it is to all of us. Airborne gradiometers would appear to be a major improvement over the operation of gravimeters in a similar mode.

No major new developments have taken place in the field of relative gravimetry, although continued improvements in their operation have been made, particularly with the use of digital read-out devices. Gravity differences over a relatively small range of gravity can be made with an accuracy of a few microgals with the use of several instruments. Differences over larger ranges of gravity involving car or aircraft transport can be observed at an accuracy of a few tens of microgals. The principal reasons for the decreased accuracy are such factors as vibrations caused by the transportation medium, bumps, etc..

Marine gravity measurements are a relatively straightforward process with new recording and control packages allowing this equipment to be readily moved on board ships and set up for operation in short order . The new so-called linear dynamic gravimeters are an undoubted improvement over the beam-type instrument. Their performance holds comparatively steady with increasingly rough sea conditions (the performance of the beam-type instruments on the other hand deteriorates as the sea state worsens or as the size of the ship decreases). Given an experienced observer, good observing procedures should produce results accurate to a milligal in regions where good navigation exists.

GRAVITY MAPS

The steady increase in the amount of data accumulated over many years of surveying, improved gravity standards world-wide, the availability of data base management systems and the ease of access to powerful computers at reasonable cost have combined to generate enormous interest in the use of data bases to produce specialized thematic maps for large regions and to apply the results to geophysical and geological problems as well as geodetic research. Consequently we are experiencing an increasing number of international projects aimed at compiling gravity and other maps for publication as part of an atlas and to make the data base available to the world community for further research. There are a number of examples of this kind of activity. For example, the Mediterranean project that involved the participation of a large number of institutions throughout Europe in the compilation of gravity geological, hydrographic, magnetic and other maps for this region was completed recently. The International Gravity Bureau took part in this project and has most of the data available in its data base.

Another such project is the the Decade of North American Geology (DNAG), an enormously large undertaking sponsored by the Geological Society of America to mark its centennial in 1988. Among others a gravity map extending from equator to pole and from the mid-Atlantic to the mid-Pacific Ocean will be published in late 1987 for distribution through the offices of the GSA. The sources of data for this map include national agencies in a dozen or more countries stretching from Denmark (Greenland) to Columbia and Venezuela in South America, satellite altimetry data and marine data collected by scientists from a large number of institutions. The International Gravity Commission is one of the sponsors of this important work and the gridded data set used to compile the map will be made available through the International Gravity Bureau where agreement has been obtained from the originating agency or country to release the digital data. It appears that many of the countries will release their data only on the grounds that they not be given out to countries which have not released their national data sets to the IGB for use in international projects. This situation, while not the healthiest for science generally at least represents a step in the right direction, a step that we hope will eventually lead to a truly world data set.

Other regions and continents are in the early stages of their own regional compilations, although we can expect them to take up to ten years or more to bring them to completion. Everyone benefits from these projects in one form or another and the International

Gravity Commission is anxious to assist these undertakings in any way possible. As we can not provide financial support we can only operate as a kind of co-operative by arranging for the help of the IGB itself and by putting the participating countries in touch with the highly talented individuals who can help by contributing their enthusiasm and personal expertize to the project.

FUTURE DIRECTIONS

1. The IGC will continue to encourage the development of national and regional gravity standards by supporting with all its means projects set up to observe and adjust regional or national gravity base station networks. The IGB will house the data and where necessary advise in the establishment of national or regional data bases for use by local scientists. In this connection we should emphasize that ~~the IGB~~ exists to provide a world data base and is not intended to replace national or institutional data bases. If no capability or desire exists to set up a regional or national data base the IGB will help out by making special arrangements within the limits of its capability.

2. The IGC will continue to encourage and assist regional compilations of gravity data. In fact this is one area where our regional sub-commissions could emulate our North American colleagues and undertake the compilation and publication of gravity maps for their region.

3. Despite the excellent work by our German colleagues there is still a need for intercomparison of different types of absolute apparatuses to evaluate their performance and to track down the sources of systematic error. In this connection we should consider the possibility of locations other than Sèvres as there has been some suggestion that this may not be the best site at which to set up several apparatuses simultaneously.

4. The IGC will continue to seek out new areas of research involving co-operation at the international level. One such area of current interest is the gravitational constant, "G", and whether it varies in time or space. If the latter is true the variations are small - we hope that a number of experiments underway will help improve our understanding of this fascinating topic.

5. The IGC will push strenuously to have the proposed World Absolute Gravity Base Station Network become a reality. The new chairman of Working Group II (Gravity Standards), Dr. Boedecker, has done an excellent job as the president of the Special Study Group set up to define the network and I am sure will wish to exercise some leadership in developing the project, either through the working group or another Special Study Group. The IGC has no preferences as to which course of action is chosen, but will push vigourously for a start to the project.

6. The IGC will keep under review the effectiveness of the regional sub-commissions as a vehicle for providing regional co-ordination. These sub-commissions have been of help in one or two cases, but on the whole they have not proved to be really effective as yet. We hope that the idea of regional compilations of gravity maps will provide a suitable vehicle to revitalize these sub-commissions.

7. The IGC will continue to review the practicality of publishing a world gravity map. Its first effort in this respect came to failure because some countries refused to release gravity data for the map. Perhaps the DNAG gravity map can serve as a useful example in this respect. For this map agreement was obtained to use a gridded data set compiled from the original observations. All but one country eventually agreed to make this gridded data set available for their national areas with the restrictions indicated earlier. Although by no means an ideal solution, this approach seems to ease the minds of the security conscious individuals in that original data are not being released.

8. Assistance to developing countries remains a continuing priority to the IGC.

9. One issue that requires resolution is the proposal to create a separate commission for the determination of the geoid. Renewed interest in the geoid has been brought about by the need for increasingly detailed, high accuracy geoid determinations to meet the technical requirements of modern survey instruments and the legal trappings that surround surveying within present day societies. This activity was formerly carried out through a Special Study Group headed by Prof. Birardi who unfortunately will retire after this General Assembly. The vacuum created by his departure will be hard to fill. Discussion of the possible courses of action took place at the quadrennial meeting of the IGC in Toulouse in Sept. 1986 with two clear schools of thought on the matter emerging from the discussion. The basic options would appear to be a separate commission or a sub-commission of the IGC. There are pros and cons for both courses of action emphasizing the need for considerable thought before a final decision can be made. One major consideration is the International Gravity Bureau. It can not serve two masters and the International Gravity Commission can not operate as successfully as it has in the past without the means of directing its activities.

SUMMARY OF BGI ACTIVITIES IN THE PERIOD

Aug. 1983 - Aug. 1987

The Bureau Gravimétrique International, one of the FAGS services, has its offices located inside the Observatoire du Pic du Midi et de Toulouse (OPMT), within the Rangueil Scientific Complex. The main staff is composed of seven persons working in these offices. In addition, students or scientific visitors or temporary technical aids and engineers stay at BGI during time periods from a few days to a year or so to perform various investigations with the Bureau data base, software and equipment. Also, two persons are working part time for BGI in the Bureau de Recherches Géologiques et Minières in Orléans ; BRGM has been the GRGS (Groupe de Recherches de Géodésie Spatiale) partner from the begining when the office was reorganized and transferred. BGI staff, logistics and activities are supported by many french organizations : Centre National d'Etudes Spatiales, Centre National de la Recherche Scientifique, Université Paul Sabatier, BRGM, to quote only the main ones. BGI receives also some funds from FAGS.

The reader will find below a summarized list of the points of activities and some additional informations.

A. GRAVITY DATA AND RELATED ACTIVITIES

1. Data Collection

New data acquired during this time period cover the following countries (or part of them), or areas :

- Terrestrial : Australia, Finland, Canada, Italy, Japan, United Kingdom, France, Morocco, Mali, Algeria, Brazil, S.W. Africa, Greenland, Cameroon, Congo Rep., Ivory Coast, Burkina Fasso, Gabon, Norway, South Africa, Zimbabwe, Zambia, Ethiopia, Swaziland, Mozambique, Tanzania, Botswana, Malawi, French Guyana (measured by BGI), Egypt. Total amount of data is ≈ 160 000.
  A complexly new data set over many french speaking african territories was provided by ORSTOM, after re-evaluation and corrections.
  BGI also cooperates with Leeds University (UK) on the African Gravity Project.

- Marine : Cruises made by USSR, Japan, U.K., France.
  New set of marine measurements from Lamont Doherty Lab.
  New data base in the Atlantic from french organization IFREMER (previously CNEXO).

A large set of new gravity measurements was received from DMAAC in 1985 ; it concerns a large number of countries/areas around the world (500 000 new values). Not all of them have yet been merged (see below).

2. The Data Base

BGI went through a very hard period of time ; for eighteen months (Jan. 1985-June 1986) the data base system was more or less frozen due to the unexpected leave of the person responsible for it and the lack of documentation behind.

The problems were discussed during the 12th meeting of the I.G.C., especially those related to data distribution, an activity which obviously badly suffered from this situation.

The revival and revision of the whole software (which main character is to be in house and extremely dedicated to gravity data, for sake of optimum disk storage and speed of access) took the whole year, though most data retrieval operations had been again possible since august 1986.

Non all data newly acquired and quoted above have been merged as of today. The DMAAC major set, plus a few others were incorporated, though without any evaluation, (after revival - and revision, of the software). The number of measured gravity stations amount now to about 3.6 millions.

The bibliography data base system also stopped in early 1985 for the same reason. Two attempts at restarting its functions (we had one student and other temporary personal working on it) more or less failed. BGI then decided to buy a commercial system (ORACLE) which works on a P.C. As of today the system operates well, and the bank is again gradually fed.

3. The Data Exchange and the Services

BGI not only receives and stores gravity data, but sends out many sets of measurements on request, as well as various pieces of informations.

Material provided to the users are :

- gravity observations (a large set was transferred to DMAAC early 1985).
- satellite altimetry observations.
- gridded gravity values : point values, means.
- gridded geoid values.
- topographic height : raw and gridded values.
- gravity maps (Bouguer anomalies mostly).
- reference station descriptions (put on microfiches in 1982-1983).
- algorithms, pieces of software.
- reports, references, copies of scientific papers...

Summaries of our service activity per year were presented at the meeting.

4. The Data Processing and Evaluations

Preprocessing and fast editing are performed on each received data set before merging. No systematic data evaluation (scientific processing) could be done so far due to lack of manpower to concentrate on this, except in a few cases when it was necessary to fulfil a peculiar request. Pieces of software (in batch mode, as well as interactive ones) exist though, such as ones which can grid and contour data and isolate (zoom) some of them.

In the fall of 1986 after highest priority had been given to this task by our D.B. a detailed system was analyzed to perform various operations of evaluation. Putting together the existing pieces of software and writing additional ones took six months. Test phases will be carried out with the help of the GCS in Ottawa and the IFE in Hannovre.

5. Mean Values

As it was done in the past, BGI is currently updating a set of 1° x 1° mean values and specialized (and regional) sets at higher resolution. Appropriate software was developped for this purpose. It includes a gridding package by polynomial smoothing and quadrature, or collocation, or Bjerhammar interpolation, or by splines.

Mean values over oceanic areas have in many cases replaced by values derived from a 15' x 15' set computed from Seasat (at BGI) because of their homogeneity and reliability (8 mgal r.m.s.).

6. Maps

- 10° x 10° maps displaying marine gravity data, cruises location and gravity values themselves were made at BGI for the following areas :
  . North Atlantic Ocean (in 1984).
  . Whole Pacific Ocean (in 1985).
  This important work was done at the request of the Soviet Geophysical Committee to complete their Geological-Geophysical Atlas.

- Gravity Maps over the Mediterranean Area :
  At the request of the UNESCO/IBCM project, BGI compiled a first series of 10 maps of Bouguer Gravity anomalies (scale 1:1 000 000) from existing measurements plus additional values which were gridded from maps, and a second series which is mostly based on the maps by Morelli. A 3' x 5' grid was produced as an intermediate product.

B. USE OF SATELLITE ALTIMETRY

Satellite altimetry derived geoid heights have been used in various research activities in cooperation with GRGS and with other groups.

The Seasat mean sea surface was especially used to produce a quasi-global oceanic set of 15' x 15' free air gravity values (by the inverse Stokes operator method). This was sent to various centers (including OSU, EPB, GSFC) for further evaluation.

Further work is anticipated, on a regional basis, which will also make use of Geos 3 data which quality is not as good as Seasat's but which are generally much denser. First attempts at combining both satellites data have been done over the North-Algerian Marge, the Aegeen trench, and around the Reunion Island, in collaboration with the Centre Géologique et Géophysique in Montpellier. Deviation of the vertical has also been computed on request from these data.

C. GEOID COMPUTATIONS

1. Madagascar

For the first time, the geoid over and around Madagascar has been computed from a combination of gravity and Seasat altimetry data, and from a 180 x 180 spherical harmonics reference field. The work was performed by J. Rakotoary, from Prof. Andriamihadja's group, and will be evaluated in the near future by this group.

Results were presented at 12th IGC meeting.

2. France

A 3' x 5' gravimetric geoid over France is in preparation. It will involve about 400 000 gravity observations over France and neighbouring countries, as well as some altimetric Geos 3 and Seasat data at sea. This is a work done in collaboration with IGN and BRGM. Satellite Doppler derived positions and GPS positioning results will be used in combination of survey data to evaluate this geoid.

D. DIGITIZATION OF THE WORLDWIDE BATHYMETRY

BGI engaged itself in the digitization of the GEBCO 5th Edition Bathymetric Charts in 1982-83, with the help of the GEBCO Sub-Committee on Digital Bathymetry, the Canadian Hydrographic Service and the Institut Géographique National.

The main steps involved in such a work are :

(a) automatic numerization of the contours (by a scanner) - performed at IGN, France.
(b) interactive correction of the digitized level curves.
(c) constitution of a data base for future updating of the GEBCO maps.
(d) computation of analytical terrain models and production of grid values.

Step (b) is by far the most difficult, and demanding in manpower and software. It was completely reanalyzed in 1985 after it was discovered that the previously developped package was very incomplete and inadequate.

A lot of progress were then made and 5 maps have been completed in 1986. However, and following a new definition of BGI priorities during the 12th IGC meeting, namely the development of sophisticated data validation tools (see A4, above), it was decided to freeze this activity for about a year. The task will be resumed in September 1987 thanks to additional aid in personal from the french Institut Geographique National.

E. OTHER ACTIVITIES

1. Participation to the definition of the requirements for a standardized gravity network over Africa (AGSN). Organization of a Workshop (May 1985, Paris).

2. Coordination of some of the BIPM intercomparisons activities, and organisation of the SSG 3.86 and 3.87. Workshops in Paris (July, 1985).

3. Participation to the 3rd Symposium on Geodesy in Africa (Yamoussoukro, April 1986). Proposition to African countries to help them in the computation of the geoid over Africa.

4. Participation in the definition of the requirements, in the instrument characteristics and design, and in the GRADIO mission concept, for mapping the Earth Gravity Field by satellite gravity gradiometry.

5. Participation in the development of the GRIM 3-L1 spherical harmonics geopotential model (with GRGS, in collaboration with DGFI-F.R.G.).

6. Organization of, and participation to the September 22, 1987 Directing Board meeting.

7. Organization of the 12th meeting of the International Gravity Commission, held in Toulouse (Sept. 23-26, 1986) ; presentation of four papers by BGI staff.

8. Software developments : various.

9. Publication of Bulletin d'Information : twice a year.

10. Collection and publication of National Reports in gravimetry (sent with the June 1987 Bulletin d'Information, n° 60).

11. Preparation and realization of a folder publicizing the role, activities and services of BGI (distributed at this IUGG General Assembly).

12. Preparation of an announcement (advertising) in EOS. Appeared in EOS, Vol. 68, N° 30, July 28, 1987.

G. BALMINO
Director, BGI

SUMMARY REPORT OF THE

INTERNATIONAL GRAVITY COMMISSION MEETING

(Aug. 20, 1987, 14.00-17.00 ; Convenor : C. Morelli, on behalf of J. Tanner)

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1. International Gravity Standardization Net 1971 (IGSN 71)

Morelli recalled the present situation.

Notwithstanding the refinement and expansion of the satellite methods, terrestrial methods remain superior as to the determination of point gravity values. Since 1971, homogeneity throughout the whole globe is secured by IGSN, performed in 20 years of cooperative work and internationally accepted. All the new high precision absolute and relative gravity measurements, new regional adjustments and special comparisons in the years 70's and 80's confirm the accuracy of the IGSN 71 values.

E.g. :

- in France 1980-83, the new French Gravity Net RGF 83 (Ogier 1983) with 6 absolute stations (accuracy few μgal), 52 first order (17 μgal) and 280 second order stations (34 μgal),
- in Germany F.R. 1975-80, the new "DFR Gravity Base Net 1976" consisting of 21 stations with 4 absolute ones, r.ms. = ± 10 μgal (Sigl et al., 1981),
- in USA, 14 new absolute measurements, with different apparatuses (claimed accuracy 10 μgal, but estimated 20-25 μgal since at some sites they differed by as much as 100 μgals) and over 4500 new gravity meter measurements (accuracy 15-30 μgal), adjusted with many different assumptions and models (Uotila, 1982).

One important result is that they confirm within ± 0.1 mgal the gravity values of the IGSN 71 stations !

The same results came out from comparison measurements specially performed on different areas or different ranges ; e.g. :

- with 25 IGSN 71 stations in USA (Strange, 1975),
- with 21 IGSN 71 stations in Japan (Suzuki, 1975),
- with the absolute value in Potsdam (Elstner and Harnisch, 1978),
- with 10 IGSN 71 stations between 60°N and 43°S (Boulanger et al., 1983),
- with 26 IGSN 71 stations along the Western Pacific Calibration Line, the North American Calibration Line and the South American Calibration Line (Nakagawa et al., 1983).

With almost no exception, the IGSN 71 values are with the new observed values or with the values of the new adjustments in a good agreement, much better than 100 μgal, which was the accuracy claimed to the IGSN 71 values.

Quite recently (Bull. Inf. BGI n° 60) were published the results of the Establishment of the Iranian Gravity Datum (IGD) by H. Zomorrodian.

The datum was obtained from the results of the tie Ledovo-Teheran-Shiraz in 1972 with five pendulum instruments of the General Research Institute of Geodesy. Aerial Surveying and Cartography of USSR, each equipped with two quartz pendulums mounted in thermostated and vaccumized cases.

Major conclusions are :

"a) The suggested IGD is in good agreement with the gravity values of the stations of IGSN 71 (greatest variations amount to 0.08 mgal).

b) In spite of not existing direct connection between IGSN 71 and the USSR gravity network, the data of both networks are in good agreement within the limits of their standard errors."

The decision of the I.A.G. to extend the validity of IGSN 71 for the next decade is therefore still valid, and the role of IGSN 71 for the gravity users consolidated.

2. IAGBN

Boedecker summarized the work of Study Group 3.87, presented in his report "International Absolute Gravity Basestation Network, Status Report March 1986" (Veröff. Bayer. Komm. f. Int. Erdm., n° 47, München 1986).

The report was carefully discussed and adopted (in the Sept. 1986, IGC Toulouse Meeting the same report was presented, but not formally adopted).

3. Structural Problem

3.1. Sub-Commissions

The S.C. are the regional operating bodies of IGC. They have been formed for tackling particular practical and organizatory problems : e.g., the up-dating and recovery of the IGSN 71 stations. Some of them have worked properly, others not. Their status and membership must be therefore revised (decision taken in Toulouse, 1986), but the absence of most of the Chairmen imposed to shift the problem also at the present meeting.

It was proposed that the IGC Chairman will handle the problem in written form.

3.2. Working Groups

Morelli recalled the status and terms of reference for the existing W.G.s. They were formed for helping the IGB in special tasks. Their present situation is :

WG 1 (Maintenance, Chairman : Ken McConnell) : O.K.

WG 2 (Standardization, Chairman : Boedecker, at the place of Uotila, who resigned) : to be revised.

WG 4 activities were stopped in 1985 and it was decided on August 8, 1987 (IGB Directing Board meeting) to shut down WG 3.

The following new W.G.'s have been proposed and accepted :

WG 5 (Super-conducting gravimeters and absolute gravity meters), chairman : Ch. Poitevin.

WG 6 (Absolute measurements comparison) : Chairman : Yu. D. Boulanger.

4. Absolute Measurements in Japan

Nakagawa informed on the present situation and programs of the two transportable absolute gravity meters in Japan (Mizusawa and Sakuma type). A recent comparison at the absolute site in Misuzawa gave a 40 µgal difference. Further studies are performed for discovering eventual systematic errors.

5. Recent Crustal Movements Monitoring Network in Western Europe

Pr. Torge presented a proposal which was brought up by the Western European Sub-Commission for Recent Crustal Movements, on behalf of the chairman Dr. W. Augath, Hannover. It is recommended to establish a three dimensional control network through space techniques, including the existing observatories and new sites to be occupied by transportable devices, and to observe absolute gravity at the same stations, in order to control height variations and eventual internal mass shifts. The Institutes operating transportable absolute gravity meters were asked to participate in this project.

6. Map of Gravimetric Anomalies in the South-Eastern Zone of South America

Dr. Blitzkow summarized as follows the project :

Objectives :

a) To complete the inter connection of fundamental gravity nets of Brazil, Argentina and Uruguay.

b) To draw gravimetric maps (free air and Bouguer anomalies) in the region, after data homogeneization.

c) To define a complementary program of gravimetric surveys.

d) To draw the final maps.

Region :

Brazil : Sao Paulo, Parana, Santa Caterina and Rio Grande do Sul States

Argentina : Buenos Aires, Entre Rios, Corrientes and Misiones provinces

Uruguay : The whole country.

Background :

The region is already covered with numerous gravity measurements. There are also some gravimetric ties between Buenos Aires, Montevideo and Rio de Janeiro. In addition, gravimetric determinations in the ocean were already done. The map to be drawn will serve for the future definition of the geoid in the region.

Institutions :

Instituto de Geodesia Fiuba, Buenos Aires
Instituto Astronomico USP, Sao Paulo
Instituto Geografico Militar, Montevideo.

SECTION III

DETERMINATION OF THE GRAVITY FIELD

Structure for the Next Four Years

President	: I.	Nakagawa	(Japan)
Secretaries	: D.	Ajakaiye	(Nigeria)
	H.G.	Wenzel	(F.R.G.)

INTERNATIONAL GRAVITY COMMISSION

President	: J.G.	Tanner	(Canada)
Secretaries	: C.	Morelli	(Italy)
	D.	Ajakaiye	(Nigeria)
Vice-Presidents	: S.	Krynski	(Poland)
	H.T.	Hsu	(China)

DIRECTING BOARD OF B.G.I.

Ex-Officio Members	: J.G.	Tanner	(Canada)	Chairman, President IGC
	I.	Nakagawa	(Japan)	President Section III
	H.G.	Wenzell	(F.R.G.)	Secretary Section III
	G.	Balmino	(France)	Director BGI
	R.H.	Rapp	(U.S.A.)	President, International Geoid Commission. Proposed (Subject to D.B. agreement)
Nominated Members	: J.	Woodside	(Canada)	
	C.	Morelli	(Italy)	
	J.	Faller	(U.S.A.)	
	J.	Krynski	(Poland)	

WORKING GROUPS

. WG 1 : Collection of Gravity Data

Chairman	: R.K.	McConnell	(Canada)
Members	: C.C.	Tscherning	(Denmark)
	H.G.	Wenzel	(F.R.G.)
	G.	Balmino	(France)
	M.	Sarrailh	(France)

. **WG 2 : World Gravity Standards**

Chairman :	G.	Boedecker	(F.R.G.)
Members :	R.K.	McConnell	(Canada)
	B.	Szabo	(U.S.A.)
	W.	Torge	(F.R.G.)
	U.	Uotila	(U.S.A.)

. **WG 5 : Super-Conducting Gravimeters and Absolute Gravity Meters**

Chairman : Ch. Poitevin (Belgium)

. **WG 6 : Absolute Measurements Comparison**

Chairman : Y.D. Boulanger (U.S.S.R.)

I.G.C. SUB-COMMISSIONS

. North Pacific Region	I.	Nakagawa	(Japan)
. South-West Pacific Region	I.	Reilly	(New-Zealand)
. North America	C.	Goad	(U.S.A.)
. Central and South America	C.	Gemael	(Brazil)
. Africa	R.O.	Coker	(Nigeria)
. Western Europe	I.	Marson	(Italy)
. Eastern Europe and USSR	Y.D.	Boulanger	(U.S.S.R.)
. India and Arab Countries	C.S.	Joshi	(India)

TEXT OF RESOLUTIONS
PASSED DURING THE IUGG GENERAL ASSEMBLY,
WHICH ARE RELEVANT TO IGC ACTIVITIES

RESOLUTION N° 2

The International Association of Geodesy

recognizing the continuing need to investigate systematic errors in transportable absolute gravity instruments, and

considering the achievements to date of previous comparison campaigns at BIPM, Sèvres,

recommends that such comparisons continue at Sèvres and other major observatories, as well as in conjunction with the observations of the International Absolute Gravity Base Station Network, and

invites the institutions concerned to cooperate as requested by the International Gravity Commission.

RESOLUTION N° 3

The International Association of Geodesy

recognizing the increased need to collect gravity data, on a local and regional scale, for scientific and practical requirements such as high resolution geoid determination, and

considering that various institutions in Argentina, Brazil and Uruguay have planned a detailed gravity mapping programme in the South-Eastern part of South America

approves these endeavours, and

invites the relevant agencies to support the work.

RESOLUTION N° 4

The International Association of Geodesy

recognizing the need to study non-tidal gravity changes on a global scale, and

considering the ability of both superconducting and absolute gravimeters to monitor variations of the gravity field at the microgal level.

endorses :

1) Resolution n° 2 of the Permanent Commission on Earth Tides (Madrid 1985), and

2) Resolution n° 2 of the International Gravity Commission (Toulouse

1986), and

recommends that the superconducting gravimeters be included in a network monitored by absolute gravity measurements, to fulfil this requirement, and

invites the institutions using absolute or superconducting gravimeters to participate in establishing this network.

RESOLUTION N° 5

The International Association of Geodesy

recognizing the urgent need for a global absolute gravity reference network of high accuracy, particularly for monitoring variations with time and maintaining world gravity standards, and

considering the proposal of **IAG SSG 3.87** for an International Absolute Gravity Base station Network (IAGBN) an appropriate basis,

recommends this should be put in hand now, coordinated by the International Gravity Commission,

requests :

1) relevant agencies to give active support to station installation and gravity connections to existing base networks such as **IGSN 71**,

2) institutes using absolute gravity meters to make the necessary observations, to cover the complete IAGBN in a reasonably short time interval, and

invites further groups to participate with other observations, e.g. positions as required.

RESOLUTION N° 6

The International Association of Geodesy

recognizing the highly efficient support of advanced space techniques and absolute gravimetry for terrestrial height systems when monitoring recent vertical crustal movements, and

considering that a number of scientific groups in Europe are operating sophisticated instruments of different types,

recommends that a fundamental network of space and absolute gravity stations should be established for investigating height variations, and

invites agencies and institutes using these advanced systems, as well as national survey agencies, to support these investigations.

PART III

CONTRIBUTING PAPERS

LES RESEAUX GRAVIMETRIQUES FRANCAIS

par

R. MILLON, F. RAVATIN

RESUME

La nécessité d'un réseau gravimétrique s'est fait sentir au début des années 1960 lorsqu'il a fallu intégrer, dans le levé gravimétrique français, toutes les prospections faites par divers organismes avec des gravimètres différemment étalonnés et sur des origines différentes.

1. Réseau C.G.F.

R. BOLLO et M. DIDOSKI, en 1965, ont alors établi un réseau de bases gravimétriques du premier ordre qui a formé l'ossature de la Carte Gravimétrique de la France : ce réseau (C.G.F.) était calé sur les deux bases fondamentales :

Paris E	(Observatoire)	980 942,65 mGals	établis dans le
Toulouse	(Observatoire, labo photo)	980 442,8 mGals	système de Potsdam

Les réseaux de second et troisième ordres ont été réalisés par le B.R.G.M., alors que celui du quatrième ordre comprenait les bases secondaires des levés effectués par divers organismes.

2. Réseau R.G.F.

L'International Gravity Standardization Network (IGSN 71) a permis, au début des années 1970, de s'apercevoir que les bases du système de Potsdam étaient trop fortes d'environ 14 mGals, grâce aux mesures plus précises des nouveaux gravimètres absolus.

Un nouveau réseau a alors été mis en place par M. OGIER (R.G.F. 1983) qui comprenait :

- 6 bases absolues (Paris-Sèvres, Orléans, Nancy, Dijon, Toulouse, Marseille) ;
- 47 stations de premier ordre (mesurées simultanément avec 4 gravimètres Lacoste & Romberg et calées sur les bases absolues)
- 275 stations de second ordre (réparties sur 78 segments)
- 9 bases d'étalonnage.

S'y sont ajoutées une vingtaine de stations internationales (aéroports, frontières).

Le réseau de troisième ordre a été recalé en bloc dans le nouveau système.

Bien qu'il soit souhaitable que toutes les nouvelles mesures gravimétriques soient raccordées au nouveau réseau R.G.F. 83, un souci de cohérence oblige à conserver le réseau C.G.F. pour toutes les opérations de cartographie intégrables dans la Carte Gravimétrique de France.

ABSTRACT

The need of a French Gravity Network appeared in the beginning of the sixties, when all the previous gravity surveys had to be integrated in the French Gravity Map. These surveys had been carried out by several agencies or companies with different gravitymeters from various non-connected base-stations.

1. C.G.F. Network

In 1965, R. BOLLO and M. DIDOSKI established a 1st order gravity net which formed the frame of the French Gravity Map ; this network was based upon 2 fundamental stations :

Paris E (Observatory)	980,942.65 mGal	in the Potsdam
Toulouse (Observatory, Photo-lab.)	980,442.8 mGal	gravity system

The 2nd and 3rd order gravity net were carried out by B.R.G.M. while the 4th one included base stations from surveys done by other agencies.

2. R.G.F. Network

The International Gravity Standardization Network (IGSN 71) showed up, in the beginning of the seventies, the inadequacy of the Potsdam gravity system (14 mGal in excess), thanks to the accuracy performance of the new absolute gravitymeters.

Thus, M. OGIER proposed a new gravity network (R.G.F. 1983) which included :

- 6 absolute base stations (Paris-Sèvres, Orléans, Nancy, Dijon, Toulouse, Marseille),
- 47 1st order base stations, measured with 4 Lacoste & Romberg gravitymeters;
- 275 2nd order base stations, along 78 segments connecting 1st order stations,
- 9 calibration bases,
- a score of international base stations (airports, borders).

The 3rd order net was adjusted in the new system.

Though it should be desirable that any gravity measurement be connected to the new RGF 83 Network, the CGF one must be kept for any gravity survey to be integrated in the French Gravity Map.

1. INTRODUCTION

La nécessité d'un réseau gravimétrique français s'est fait sentir au début des années 1960 lorsqu'il fut question d'intégrer, dans le levé gravimétrique français, toutes les prospections effectuées jusque-là par divers organismes sur des bases diverses et avec des gravimètres différemment étalonnés.

Tout réseau doit s'appuyer sur une ou plusieurs bases fondamentales et le choix de la valeur de g pour ces bases fondamentales n'était pas un problème simple, comme le montre le rapide historique qui suit :

- Avant 1954 :

Entre 1900 et 1935 plusieurs liaisons Paris-Potsdam ont été effectuées et fournissent à Paris-E (ancienne salle de pesanteur de l'Observatoire de Paris), des valeurs comprises entre 980 942,0 et 980 943,9 mGals (tableau 1).

Année	Auteur	Valeur de g	Méthode utilisée
1900	Putnam	980 942,0	Liaison pendulaire avec Potsdam
1909	Borrass	942,7	Compensation
1926	Vening Meinesz	942,8	Liaison pendulaire avec Potsdam
1932	Lejay	943,0	Compensation
1933	Nörlund	943,9	Liaison au pendule Holweck-Lejay avec Potsdam
1935	Lejay	943,1	Idem
1948	Woollard	943,0	Liaison au Worden 10b
1948	Hirvonen	943,5	Compensation
1950	Coron	942,5	Compensation
1951	Morelli	942,9	Mesure à l'aide des Worden 50 et 52
1953	Coron	942,8	Compensation

Tableau 1. Valeur de g à l'Observatoire de Paris point E (pilier E de l'ancienne salle de pesanteur).
(Bull. BNM n° 41, 7/1980)

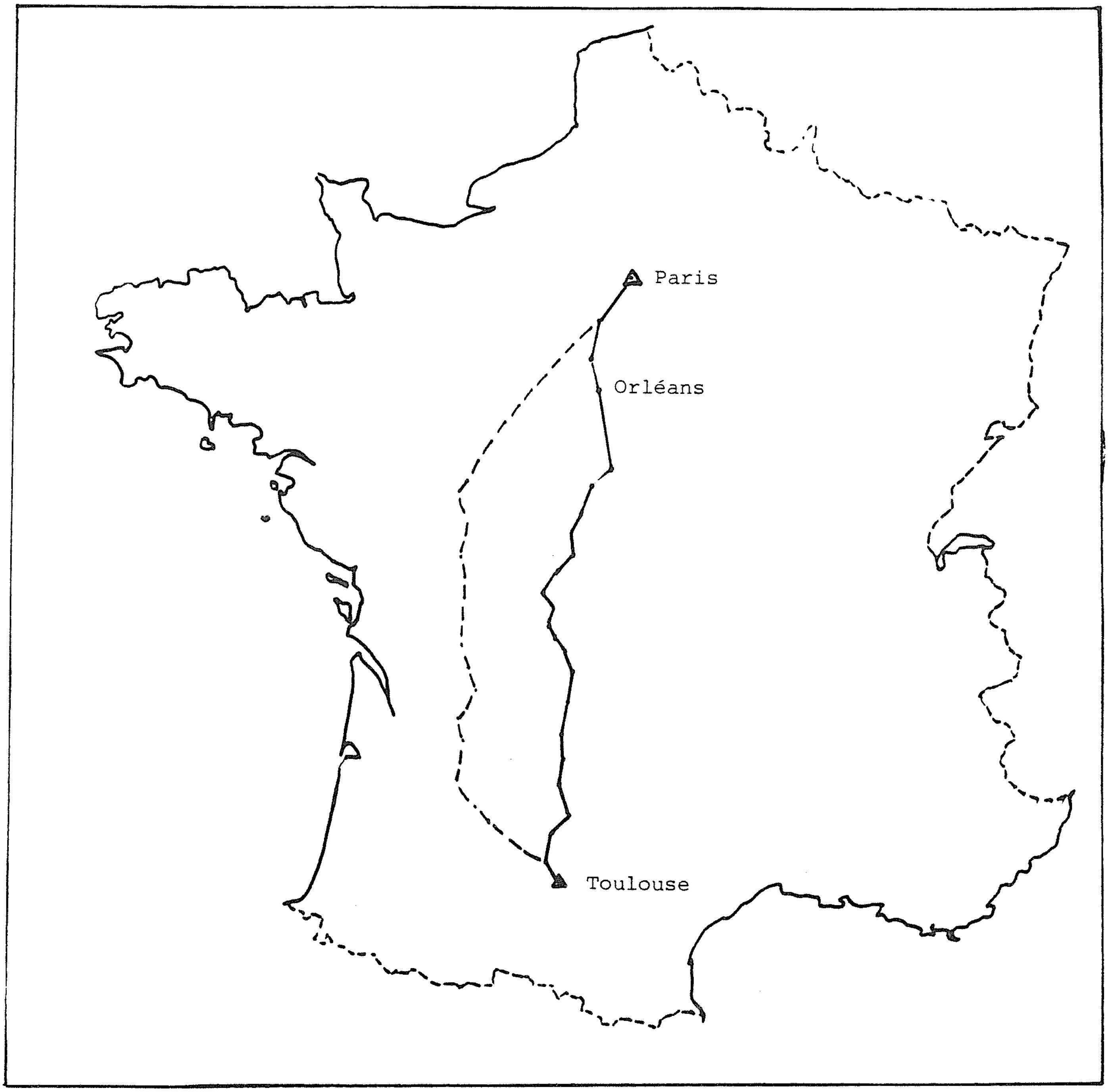


Fig. 1 - Liaisons gravimétriques PARIS-TOULOUSE

— — — ligne de base MARTIN

——— ligne de base B.R.G.M.

En 1947, J. MARTIN des Expéditions Polaires Françaises entreprend, à l'aide de gravimètres étalonnés sur des stations pendulaires européennes, l'établissement d'une ligne de base Paris-Toulouse-Pic du Midi de Bigorre.

En 1948, R. BOLLO (B.R.G.G.) se joint à cette série de campagnes. On a alors un seul réseau de référence : le réseau Martin qui utilise une ligne de base qui est : Chartres-Château-Renault-Châtellerault-Poitiers-Angoulême-Agen-Montauban (fig. 1).

En 1950, S. CORON effectue une synthèse des mesures effectuées à Paris-E et donne g = 980 943,0 $\pm$ 1 mGal pour ce point.

En 1951, cette valeur est adoptée par le Comité National Français de Géodésie.

- En 1954 :

J. MARTIN adopte donc la valeur de :

980 943,00 mGal pour Paris-E

980 943,35 mGal pour Paris-A (point extérieur à la salle de pesanteur)

Δg = 0,35 mGal

R. BOLLO, quant à lui, adopte les valeurs de :

980 942,65 mGal pour Paris-E

980 943,00 mGal pour Paris-A

Δg = 0,35 mGal

Les mesures de J. MARTIN donnent pour Toulouse :

980 443,10 labo-photo

980 443,07 pilier première salle

Δg = 0,03 mGal

Le B.R.G.G. avec un étalonnage différent obtient :

980 442,18 labo-photo

980 442,15 pilier

Δg = 0,03 mGal

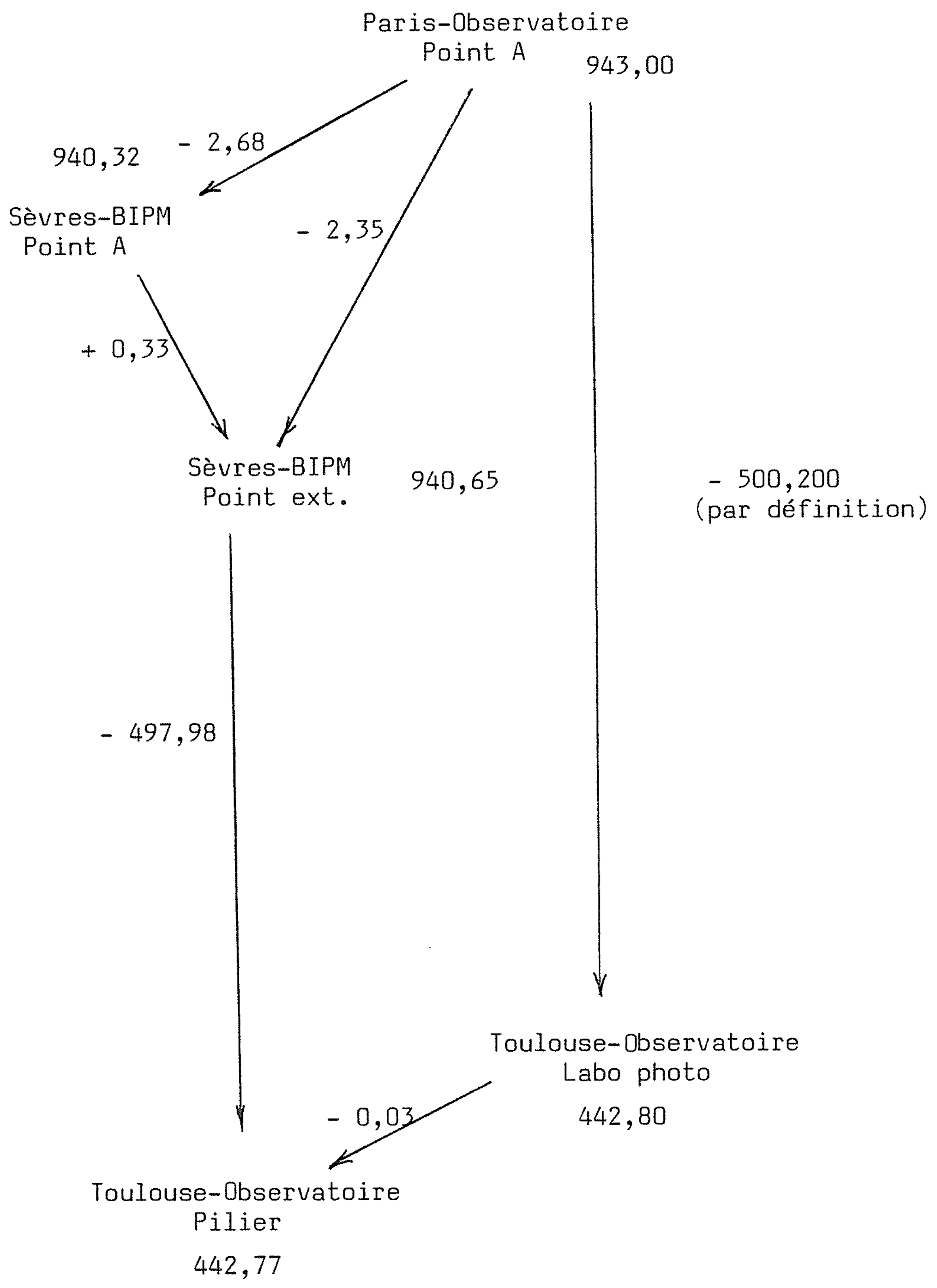


Figure 2 : Définition de la base d'étalonnage française (C.G.F.).

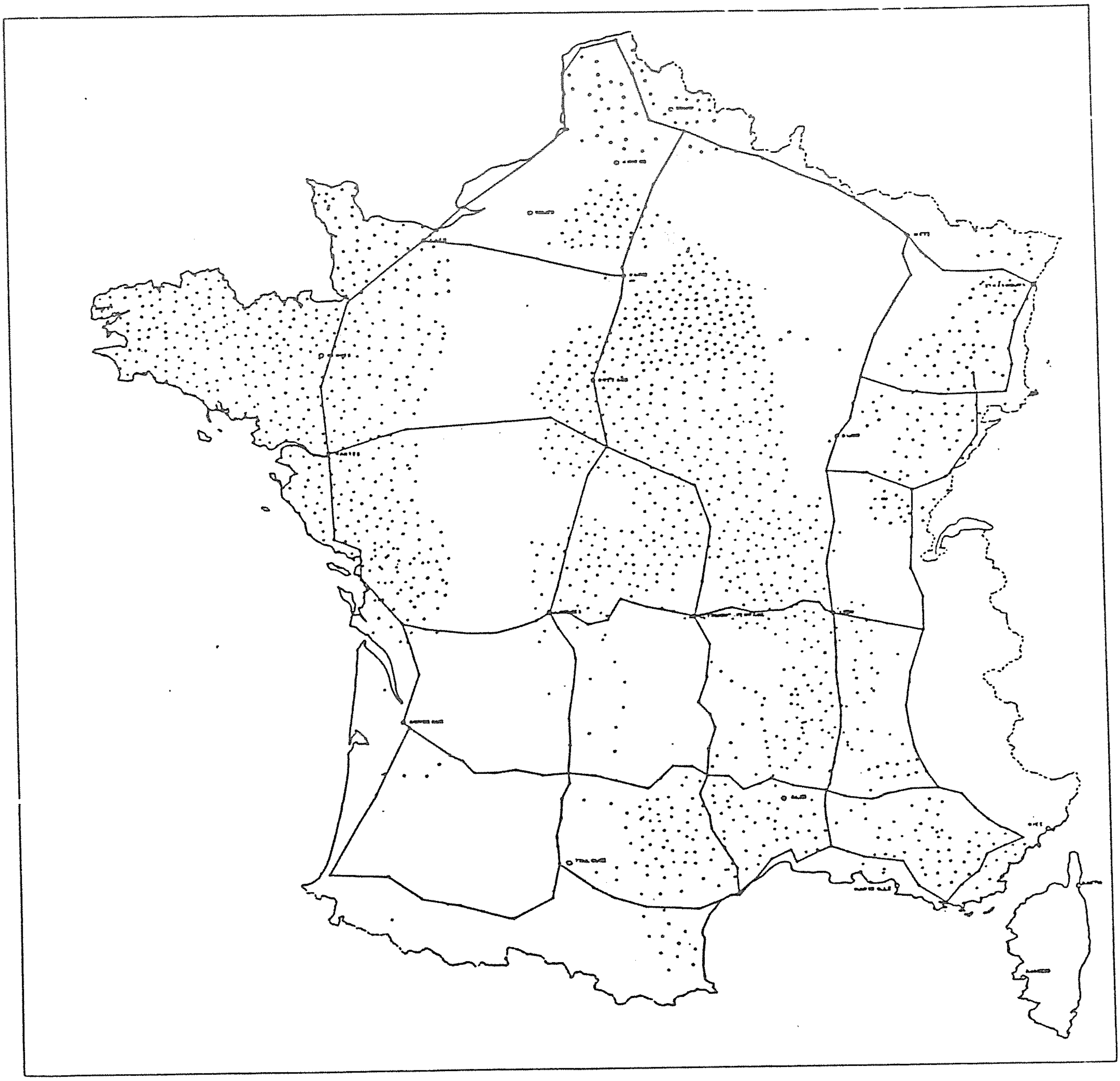


Fig. 3 - Réseau gravimétrique C.G.F. (1965)

1er ordre : noeuds
2e ordre : segments
3e ordre : points

Après 1955, le B.R.G.M. met en place le réseau dit de premier ordre et abandonne la ligne de base Martin au profit d'une ligne différente :

Orléans-Vierzon-Limoges-Brive-Cahors-Montauban (fig. 1).

En 1963, la ligne de base Paris-Toulouse est mesurée de nombreuses fois : le B.R.G.M. adopte la valeur de :

980 442,80 mGal pour Toulouse labo-photo.

2. LE SYSTEME C.G.F.

Le système C.G.F. (Carte Gravimétrique de la France) est donc défini à partir des bases fondamentales Paris A (980 943,0 mGal) et Toulouse labo-photo (980 442,8 mGal).

Dès 1965, on disposait dans ce système (R. BOLLO et M. DIDOSKI) (fig. 3) :

- d'un réseau de premier ordre (intersection des mailles),
- d'un réseau de second ordre (segments) (179 stations),
- d'un réseau de troisième ordre (1900 bases)

Ce réseau a été obtenu à partir des campagnes de prospection B.R.G.M., un réseau de quatrième ordre a été constitué par les levés effectués principalement par C.G.G. et les Mines domaniales de Potasse d'Alsace.

Ces réseaux ont formé l'ossature de la Carte Gravimétrique de France (carte de l'anomalie de Bouguer), que le B.R.G.M. a publié progressivement : en 1966, les 3/5 du territoire métropolitain étaient couverts à l'échelle du 1/80 000 ; le rythme des levés et des publications s'est, par la suite, fortement ralenti.

3. L'I.G.S.N. 71 : UNE PERIODE TRANSITOIRE

L'avènement des premiers gravimètres absolus (méthode de chute de corps) allait modifier considérablement les valeurs de g attribuées aux bases fondamentales.

En 1967, le premier appareil du professeur A. SAKUMA était installé à Sèvres, au B.I.P.M. ; cette station A allait devenir une des références du système IGSN 71 (International Gravity Standardization Network) :

valeur de g à Sèvres A :	IGSN 71	= 980 925,97 mGal
	CGF	= 980 940,32 mGal
soit une différence de		14,35 mGal

La base de Toulouse fut intégrée ultérieurement dans le système IGSN et la valeur de g publiée en 1974 par C. MORELLI (cf. tableau 2) est :

valeur de g à Toulouse pilier :	IGSN 71	= 980 427,47 mGal
	CGF	= 980 442,77 mGal
soit une différence de		15,30 mGal

On voit ainsi que le système IGSN 71 ne différait pas simplement du système CGF par une simple constante : il y avait en plus une variation notable (1 mGal) entre Paris et Toulouse.

La liaison Paris-Toulouse-Pic du Midi de Bigorre fut contrôlée à nouveau en 1977 par M. OGIER avec un gravimètre Lacoste & Romberg (D 125) et, à la suite de cette campagne, le réseau CGF de premier ordre fut recompensé par J.J. LEVALLOIS.

En 1978, M. OGIER reprit certaines des stations du tableau 2 avec un Lacoste & Romberg (D 225) du C.R.G.G. de Montpellier et effectua de nouvelles liaisons Paris-Toulouse, ce qui le conduisit à proposer la valeur de 980 427,48 mGal pour Toulouse-pilier.

TABLEAU 2

Référence IGSN 71	Stations	Valeurs L.R. G 225	Valeurs IGSN 71 en mGal*	Ecart en mGal
STATIONS EUROPEENNES (1978)				
180 82A	SEVRES A	Valeur de référence	980 925,97	-
216 04A	BRUXELLES A	980 117,186	981 117,32	- 0,134
180 98C	KARLSRUHE	980 492,116	980 942,00	+ 0,116
180 89J	STUTTGART	980 832,820	980 832,87	- 0,050
180 78Q	ZURICH (GEBENSDORF)	980 704,739	980 704,71	+ 0,029
180 66J	GENEVE	980 574,675 ?	980 574,44	0,235 ?
			Ecart moyen =	0,113
STATIONS FRANCAISES (1977-1979)				
180 41J	MONTAUBAN	980 491,527	980 491,54	- 0,013
180 40J	AGEN	980 519,360	980 519,41	- 0,050
180 40P	BERGERAC	980 568,511	980 568,55	- 0,039
180 70J	CHATEAU-RENAULT	980 818,599	980 818,59	+ 0,009
180 60P	CHATELLERAULT	980 767,132	980 767,13	+ 0,002
180 81J	CHARTRES	980 871,575	980 871,60	- 0,025
180 60K	POITIERS K	980 726,880	980 726,83	+ 0,050
180 30P	ST GAUDENS	980 328,82 (G 125)	980 328,82	0,000
180 82B	PARIS A (1968)	980 928,650	980 928,65	0,000
	(1978)	980 928,567		
180 31A	TOULOUSE	980 427,47	980 427,47	0,000
180 31X	CAPENS	980 388,01	980 388,03	- 0,020
180 82K	LE BOURGET	980 935,326 (G 125)	980 935,33	- 0,004
			Ecart moyen =	0,017

* Les valeurs IGSN 71 sont celles publiées par C. MORELLI et al. (1974).

Sur la demande du B.G.I., il effectua des mesures de liaison entre plusieurs stations européennes car l'on disposait à présent de la pesanteur absolue à Sèvres, Bruxelles, Weisbaden et Turin (tableau 2). La méthode était la suivante :

1) calcul d'un coefficient général pour tout le parcours effectué (fig. 8) : K = somme pondérée par le temps de parcours (Δg absolus/Δg mesurés Lacoste & Romberg) ;

2) à partir de Sèvres-A tous les Δg locaux sont multipliés par ce coefficient ; on obtient ainsi un g "Lacoste & Romberg" corrigé de façon générale, soit par exemple sur les stations absolues (tableau 3) :

	g-absolu	g-IGSN 71	g-L.R. corrigé
Bruxelles-A	981 117,272	981 117,32	981 117,29
Weisbaden	981 036,847		981 036,88
Turin	980 534,237		980 534,26

M. OGIER retrouva en particulier la valeur de 980 424,47 pour Toulouse-pilier à partir de la liaison Turin-Toulouse.

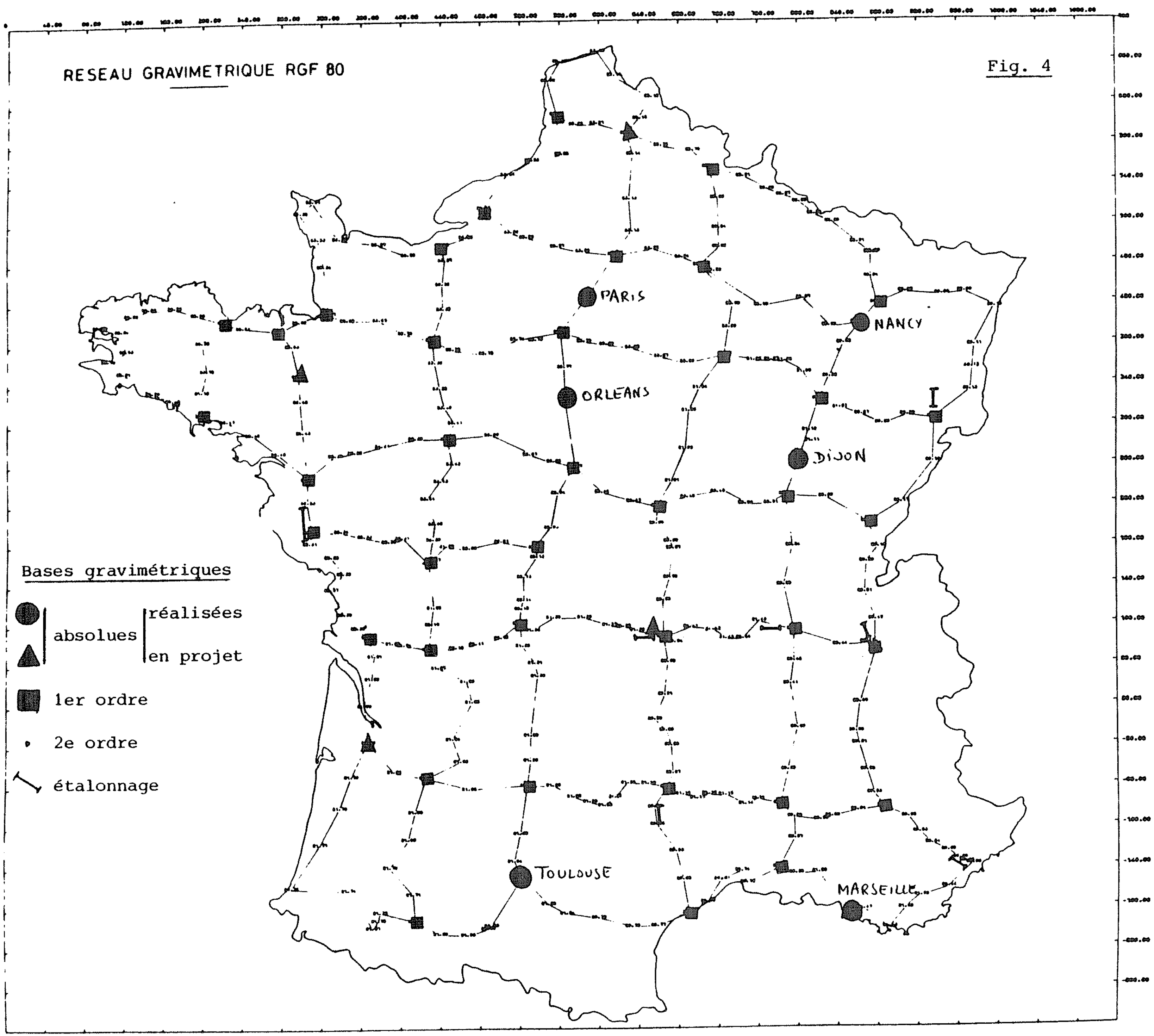
Enfin, M. OGIER établit une formule de conversion C.G.F.-IGSN 71 grâce à une formule de R. BOLLO et aux données de g-CGF et g-IGNS 71 :

$G_f = (\text{ALPHA} + 1) \cdot G_i + \text{BFOND}$ avec pour des stations k de 1 à n où l'on connaît G dans les systèmes $f_{(CGF)}$ et $i_{(IGSN)}$:

$$\text{ALPHA} = \frac{-n \sum_k G_i.(G_f - G_i) + \sum_k G_i . \sum_k (G_f - G_i)}{(\sum_k G_i)^2 - n \sum_k G_i^2}$$

$$\text{BFOND} = \frac{\sum_k G_i.(G_f - G_i) . \sum_k G_i - \sum_k G_i^2 . \sum_k (G_f - G_i)}{(\sum_k G_i)^2 - n \sum_k G_i^2}$$

$\rightarrow G_{IGSN} = G_{CGF} + 0{,}001205688 \cdot G_{CGF} - 1197{,}15$


RESEAU GRAVIMETRIQUE RGF 80
Fig. 4
PARIS
NANCY
ORLEANS
DIJON
TOULOUSE
MARSEILLE
Bases gravimétriques
absolues
réalisées
en projet
1er ordre
2e ordre
étalonnage

4. LE RESEAU GRAVIMETRIQUE FRANCAIS RGF

En 1980, à la suite d'une proposition du B.G.I. et du B.N.M. d'améliorer le réseau gravimétrique français, M. OGIER lança un projet de réseau français calé sur des mesures absolues : RGF-80.

Ce projet comportait notamment :

- la réalisation de mesures absolues sur Lille, Nantes, Dijon, Clermont-Ferrand, Bordeaux, Marseille, Orléans, Reims, Nancy et Toulouse, soit au total 11 stations absolues (fig. 4) en comptant Sèvres ;
- la matérialisation des stations avec des normes précises ;
- l'informatisation systématique du nouveau réseau avec :
  - . fichiers d'observation,
  - . fichiers de liaisons,
  - . fichiers de stations (GO Lucerne 1967, G-CGF65, G-IGSN71, G-RGF80),
  - . classeurs de schémas des stations.

En 1983, les mesures absolues furent faites, dans le cadre de cette convention, avec 6 stations seulement : Orléans, Dijon, Marseille, Nancy et Toulouse (+ Sèvres pour mémoire), par A. SAKUMA assisté de J.P. LESCOP et avec le gravimètre absolu JAEGER GA 60. A Orléans, l'écart-type sur une série de 134 mesures était de l'ordre de 5 µGals.

A la fin de 1982, le réseau de premier ordre avait été établi sous la direction de M. OGIER à partir des futures bases absolues : il consistait en 52 stations (avec 112 stations satellites) matérialisées par une plaque en fonte (fig. 4). Les mesures avaient été faites par F. DUPONT et C. MENNECHET simultanément avec 4 gravimètres Lacoste & Romberg G, la précision sur ces bases de premier ordre était estimée à 17 µGals.

Cette campagne avait été précédée par la mesure du réseau de second ordre effectuée par M. OGIER en 1980 et 1981 avec un gravimètre Lacoste & Romberg G : 280 stations, situées sur les segments reliant les futures bases du premier ordre ont ainsi été mesurées avec une précision finale voisine de 40 µGals (liaison simple).

Ces réseaux d'ordre 0, 1 et 2 furent complétés par un système de 9 bases d'étalonnage réparties assez régulièrement sur le territoire national et par des stations portuaires (15), aéroportuaires (4) et frontalières (7 + 5 anciennes CGF réoccupées), cf. **Tableau 3.**

En outre 14 anciennes stations IGSN 71 (axe Paris - Bagnères-de-Bigorre) furent remesurées et donc intégrées dans le nouveau réseau.

Les anciens réseaux CGF du troisième et quatrième ordre n'ont pas été remesurés. Seul le réseau de troisième ordre a été recalé dans le nouveau système sur le réseau de deuxième ordre : il consiste en 1800 stations environ et la précision du recalage est estimée à 0,1 mGal. Le réseau de quatrième ordre n'est pas assez homogène pour mériter un tel recalage et il a été simplement converti dans le nouveau système à l'aide de formules de conversion.

5. CONCLUSION

La finalité des mesures gravimétriques est assez variée : parmi les principales applications, où la liaison avec un réseau national de référence soit indispensable, on peut citer :

- la géodésie (calcul de géoïde, déviation de verticale) ;
- la connaissance de g en un point précis (laboratoires de métrologie) ;
- la prospection (recherches pétrolières, minières, géothermiques) et la cartographie géologique pour lesquelles le document utilisé est la carte d'anomalie de Bouguer.

Pour les deux premiers points, il va de soi que le système RGF doit être utilisé ; par contre, pour le dernier point (utilisation de la gravimétrie sous forme de cartes d'anomalie de Bouguer), il est préférable de garder le réseau CGF comme système de référence pour des raisons de cohérence : en effet, on travaille alors sur des cartes à moyenne échelle (1/25 000 à 1/80 000), domaine pour lequel le passage du CGF vers le RGF n'est qu'un décalage d'une quinzaine de milligals : il vaut mieux, dans ce cas, utiliser le système CGF pour pouvoir se servir des mesures antérieures.

TABLEAU 3

Etalonnage Lacoste & Romberg G 225 sur stations absolues.

Stations	Valeurs L.R. - G 225	G absolu (corr. Honkasalo soustraite)
SEVRES-BRUXELLES (2 journées)		
SEVRES A		980 925,970
	+ 0,263	
SEVRES Extérieur		
	+ 198,953	
BRUXELLES		981 117,272
	Δg_r = 191,216	Δg_a = 191,302
	$K_1 = \frac{191,302}{191,216} = 1,000\ 45$	
BRUXELLES-WIESBADEN (1 journée)		
BRUXELLES A		981 117,272
	- 70,431	
KETTENIS		
	- 9,931	
WIESBADEN		981 036,847
	Δg_r = - 80,362	Δg_a = 80,425
	$K_2 = \frac{80,425}{80,362} = 1,000\ 78$	
WIESBADEN-TURIN (5 journées)		
WIESBADEN		981 036,847
	- 95,366	
KARLSRUHE		
	- 406,979	
TURIN		980 534,237
	Δg_r = - 502,345	Δg_a = 502,610
	$K_3 = \frac{502,610}{502,345} = 1,000\ 53$	

$$K_m = \frac{2\ K_1 + K_2 + 5\ K_3}{8} = 1,000\ 54$$

Enfin, il serait souhaitable que ce réseau soit complété par quelques bases absolues, notamment sur des stations d'enregistrement gravimétrique (Strasbourg) et au moins sur les deux extrémités d'une base d'étalonnage.

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A computer method to Determine Terrain Corrections for Gravity Studies, including those for near topography.

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Abstract

A method for determining the terrain correction and complete Bouguer correction for gravity studies is described. Topography surrounding a gravity station is considered to be divided into a set of horizontal pie-shaped segments. Topography within each segment is approximated by a single vertical topographic profile obtained from a contour map using a digitiser with multi-button cursor connected to a computer. The vertical component of gravitational attraction of each segment is calculated separately, then summed to give the total correction. The number of segments can be varied to suit the ruggedness of the topography and the desired precision of the correction. Contributions from bodies of water can be included, and contributions from different parts of the topography can be determined using different densities.

The method uses different topographic information for each determination, and is most suitable where corrections are required for a small number of gravity stations, for widely spaced stations, and for near topography. The method does not entail storing large amounts of topographic information, so is suitable for use with microcomputers.

INTRODUCTION

The most tedious and time-consuming part of gravity data reduction is often the determination of corrections for the gravitational attraction of topography surrounding each gravity station. Various methods for determining terrain corrections have been devised, and many involve supplying topographic information as input to computers. These are programmed to approximate the topography by bodies of simple geometrical form, and to calculate their gravitational attraction. Many of the existing computer methods use the same topographic information for a number of determinations so are efficient when corrections need to be determined for a moderate or large number of gravity stations, or for distant topography. However, if only a few corrections are required, it is often quicker to use a manual method than prepare data for a computer. Also, most existing computer methods are unsatisfactory for near topography because a large amount of input data is required to define the topography in sufficient detail.

In the past the author has found that a combination of methods is usually the most efficient; a computer method for distant topography, and the manual zone-chart method (Hammer, 1939) for near topography. The method described here is designed to complement existing computer methods. It has been developed primarily for use when corrections are required for either a few stations, or widely spaced stations, or for near topography. It can be used to compute either complete corrections, or corrections for only part of the topography.

The method is designed for use with a digitiser used online to a computer. A single computer program is used to control the digitising and use the digitiser output directly to compute the terrain correction.

PRINCIPLE OF THE METHOD

Topography surrounding a gravity station is considered to be divided into a set of pie-shaped segments centred on a vertical line through the station. A digitiser on which topographic maps can be placed is used, together with a transparent overlay on which is drawn a set of equi-spaced radial lines. The overlay is placed on the map, centred on the gravity station location, and the points where each radial line intersects contours and spot heights are digitised. These data are used by the computer to construct vertical sections of the topography, one for each radial line. Each vertical section is taken to represent the average section for a pie-shaped segment of topography bisected by each radial line (Fig. 1a). The vertical component of gravitational attraction for each segment is calculated, and contributions from all segments summed to give the total correction. The number of radial lines, and hence the number of segments into which the topography is divided, can be varied to suit the ruggedness of the topography and the precision with which the terrain corrections are required. Practice shows that between 12 and 16 segments is usually sufficient.

DESCRIPTION OF THE METHOD

A flat-bed or line digitiser fitted with a multi-button cursor is used to convert topographic information on contour maps into digital form. The digitiser is connected to a computer running the program that has been developed to compute terrain corrections. The coordinates of points on the map are determined by moving the cursor to points in turn and pressing a selected button. The button number is sent to the computer together with the coordinates, and this number is used to direct the computer to different parts of the program.

Part of a topographic map on a digitiser, together with an overlay with radial lines, is shown in Figure 1. The scale and contour interval of the map, and the range of distance for which corrections are to be determined, are supplied from the computer keyboard. For each determination the position of the gravity station is digitised first and its height supplied from the keyboard. Topography along each radial line is then digitised, starting at the contour intersection or spot height closest to the gravity station and moving outwards along each line in turn to a distance corresponding to the maximum distance to which corrections are required.

The button used to digitise each contour crossing point depends on whether the elevation, as viewed from the gravity station position, is increasing or decreasing. With the button code shown (Table 1), button 4 is pressed when the elevation is increasing, and button 5 when it is decreasing. With the button code shown, upto 3 contours can be passed over without being digitised. This facility is useful for areas of uniform topographic gradient, and for distant topography that does not need to be defined in as much detail as near topography.

Instances can arise where a contour line at its point of intersection with a radial line, deviates locally from its average trend in that area. In such cases, since each profile is taken to represent that of a segment of topography extending both sides of the radial line, the average position of the contour in the vicinity of the radial line is digitised in preference to the actual intersection point.

The computer calculates the radial distance from the gravity station to each point and the height of the contour that it represents. The height is computed from that of the previous point, or that of the gravity station in the case of the first point along each line, using the button code and contour interval. A vertical topographic section along the radial line is constructed by considering adjacent points to be joined by straight lines (Fig. 2a). Points at radial distances greater than 28.8 km (Hayford Zone L) are lowered and brought slightly closer to the gravity station to take account of the Earth's curvature. This calculation, and that for the vertical component of gravitational attraction of a segment of topography which follows, is performed by a part of the program taken piece-meal from the terrain correction program written by Takin and Talwani (1966). The angle between radial lines on the overlay with this method corresponds to the azimuthal angle in the Takin and Talwani method. The gravitational attraction of segments corresponding to each vertical section are computed separately, then summed to give the total correction.

Corrections are computed for topography over a distance range defined by the radii of two circles centred on the gravity station position. The smaller radius is the minimum distance, and can be zero, and the larger radius is the maximum distance. If the minimum distance is zero, the starting point for each vertical section is the gravity station location (Fig. 2b), otherwise it is a point added by the computer at the minimum distance and with a height obtained by linear interpolation from heights of digitised points on either side (Fig. 2c). Each vertical section is terminated by a point at the maximum distance, again added by the computer with an interpolated height, if necessary.

The correction computed can be the terrain correction alone, or the complete Bouguer correction, including the curvature correction. For terrain corrections alone, a closed vertical section is made by joining the two ends of each topographic profile by one or 2 vertical lines and a horizontal line with the elevation of the gravity station. For the complete Bouguer correction the two ends are joined by a line with zero elevation representing sea level (Fig. 2d).

The gravitational attraction of water in lakes, large rivers and oceans may be computed as well as that for rock. When digitising along a radial line that crosses one or more bodies of water, topographic and bathymetric contour intersections are digitised without differentiation. However, when the intersection of the nearest shoreline to the gravity station of each body of water has been digitised, a cursor button designated to indicate this fact is pressed. The coordinates of these intersection points, and all the following points, until the elevation exceeds that of the corresponding near station shorelines, are used to construct separate vertical sections for the bodies of water (Fig. 3a). The gravitational attraction of segments corresponding to these vertical sections are computed using an appropriate water density, then summed with those for the solid topography.

It is possible to repeatedly change the density used in the calculations to take account of lateral variations in the density of rocks forming topography. When digitising, and a change in density is required, cursor buttons designated for the purpose are pressed and the new value typed from a keyboard. This can be either before topography along a radial line is digitised, or for greater precision, at points along a line. In the case of the former, the attraction of complete segments are computed with the new value of density until it is changed again. In the case of the latter, the segment is divided into parts, the attraction of each part is calculated separately using the appropriate value of density, then summed to give the attraction of the complete segment (Fig. 3b). Only vertical junctions between parts of different density are programmed for.

COMPUTER IMPLEMENTATION

This method was developed some years ago (Sowerbutts 1978) on a PDP 11 computer using a program written in Fortran. The Fortran program is currently used with a VAX computer and a version written in Basic currently used with a 48K Apple II microcomputer.

The program is written so that a drawing of the topographic profile is plotted on the computer screen as digitising proceeds, so an operator can see immediately if an error has been made. In addition, various prompts and instructions are supplied. For example, when digitising along a radial line it is not necessary for an operator to constantly observe if the maximum distance has been reached. After each point has been digitised its distance from the gravity station is calculated by the computer and a sound generated to alert the operator if it is equal to or greater than the maximum distance.

The program is menu driven and includes a number of error checking and error correction facilities. For example, to help the operator determine if an error has been made while digitising a topographic profile the height corresponding to the last point digitised is displayed on the computer screen. This can be compared with the corresponding height on the map by the operator to see if an error has been made. This is in addition to a plot of the topographic profile being produced on the screen. If it is realised that a mistake has been made while digitising, the erroroneous information can be deleted by pressing two cursor buttons in succession, and the correct information provided by redigitising. The first button pressed, number 8 according to the code shown in Table 1, causes control to pass to a part of the program where erronerous information is deleted. The number of the second button pressed depends on the amount of information that is to be deleted; button 1 for just the last digitised point; button 2 for all the information for the current segment; and button 3 for all the information for the current gravity station. It is necessary to use buttons in combination in this way because the total number of different instructions that need to be sent to the computer using the cursor, exceeds the number of cursor buttons.

EVALUATION OF THE METHOD

The program has been tested to check that it works in the way intended, and to give correct results when used with topographic features of simple geometrical shape. It has been evaluated using a number of maps depicting different types of terrain, and by comparison with results obtained using the Hammer chart method. When used with data representing real topography all methods for determining terrain corrections involve approximations, the type of approximation generally being different with different methods. This means that when evaluating a terrain correction method for real topography it is not possible to estimate errors in determinations by comparing test results with absolute values. In the method described here, if the topographic profile for each segment and the rock density are defined precisely, errors in determinations will only arise when topography within segments on either side of the profiles differs from that depicted by the profiles. This will almost always be the case, and so some method for estimating the errors produced by such departures need to be derived. Clearly for most types of topography, errors due to such departures can be reduced simply by reducing the size of the segments. However, this increases the number of topographic profiles that have to be defined by digitising, and hence the amount of work involved. A method is needed for determining the minimum number of segments that are required in order to produce a terrain correction having an error less than a specified value. When testing this terrain correction technique a simple method for doing this was used which works reasonably well. The method entails making a number of terrain correction determinations for a representative point in the area under consideration. First a correction is made using a small number of segments of large size then the number is increased and the terrain correction redetermined. The number of segments is increased repeatedly until increasing the number, and hence reducing their size, does not cause the terrain correction obtained to differ by more than the specified amount. When doing this it has been found convenient to determine a number of values of terrain correction for each different number of segments. For example, for each of the maps considered, 4 separate determinations were made when 8 segments were used. This was done by changing the orientation of the overlay by 11 1/2 degrees between determinations. Additional determinations were made with other orientations of the overlay.

Terrain corrections determined using the computer method for one representative point on each of three maps for a range of segment numbers are given in Table 2. All values have been computed for a density of 2.0 gm/cm^3. Map 1 (UK Ordnance Survey 1:25,000 sheet SH44) covers an area of almost flat terrain and the representative point was taken to be at the map centre. An isolated 60m high hill lies to the east of the representative point and a more extensive 270m high set of hills lie to the north-west. The average terrain correction for this representative point derived from all the separate determinations made is 0.128 mgal. The terrain corrections determined when 8 segments were used range from 0.12 to 0.14 mgal. When values to the nearest 1/100th mgal are considered, the same value for the correction (0.13 mgal) is obtained when 12 or more segments are used in the determination. This result shows that if terrain corrections to an accuracy of 0.01 mgal are required for this area, a minimum of 12 segments must be used for each determination

Map 2 (UK Ordnance Survey 1:25,000 sheet NY50) covers an area of undulating terrain. The representative point is again taken to be at the map centre. This places it on the side of a hill and at an elevation about equal to the average elevation of the terrain contributing to the terrain correction. The average terrain correction determined using the computer method is 0.355 mgal (Table 2). Corrections determined using 8 segments range from 0.333 to 0.359 mgal, and those made using 12 segments from 0.354 to 0.359 mgal.

Terrain corrections for this representative point have also been made using the Hammer chart method. 10 separate determinations for zones E-I were made so results could be compared with those determined by the computer method. The 10 determinations were made using different orientations of the Hammer chart, the chart being rotated 3 degrees between determinations. Since compartments in zones G-I of the Hammer chart cover a radial distance of 30 degrees, this distance was covered in 3 degree steps. The values of terrain correction determined in this way average 0.377 mgal and range from 0.334 to 0.424 mgal.

Map 3 (Peruvian Instituto Geografica Militar 1:100,000 sheet Ambar 22:i) covers part of the Andes. Terrain corrections for a representative point at the bottom of a 1.5km deep valley (grid. ref. 244,8828) near the town of Aco, were determined using the computer method. The average terrain correction for this representative point is 32.68 mgal. The way individual determinations approach this average as the number of segments is increased can perhaps best be appreciated when results are displayed in graphical form as shown in Fig. 4. It is seen that even when 32 segments are used for the terrain correction determination, errors are likely to be of the order of 0.1 mgal. This is simply a reflection of the very rugged terrain of this area.

DISCUSSION

This method for determining terrain corrections has been used extensively by the author for a number of years and found to be a very useful method. The time required to make a single determination is approximately the same as that required to estimate compartment heights when using the Hammer method. The advantage with the computer method is that the terrain correction is given directly, unlike the Hammer method where corrections have to be derived once estimated heights have been obtained.

A moderate degree of mental concentration is required when using this computer method. However, it is found that corrections can be made continuously for about twice the length of time that height estimates can be made for the Hammer method before a break is required.

This computer method can be used to determine complete terrain corrections, or partial corrections if the remaining part is being determined using some other method. If the computer method is used to determine a complete correction, for example out 166.7 km, this would normally be done in stages, with a large-scale map being used for the near topography and a small-scale map for the distant topography. The radial distance ranges over which partial corrections are determined can be chosen to suit the scale of the contour maps available and do not have to be restricted to Hayford zone values.

It is interesting to compare the results obtained by the computer method with those obtained for the same area by the traditional Hammer zone-chart method. Considering the results for Map 2 given here, the average terrain correction determined by the computer method is 0.335 mgal, whereas that determined using a zone chart averages 0.377 mgal. This difference is due entirely to the different ways in which the corrections are determined. It is found for points on other maps that similar differences occur, the values obtained by one method being slightly greater than those by the other for some types of terrain, and slightly less for other types. The zone chart values for

Map 2 obtained by placing the zone chart on the map with different orientations show a difference of up to 12% from the average value. This difference is quite large; the implications perhaps not always appreciated by users of the zone-chart method.

REFERENCES

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SOWERBUTTS, W.T.C., 1978. A computer method to evaluate terrain corrections for gravity studies, including those for near topography. Geophys.J. R. astr. Soc., 53, p.184 (Abstract only)

TAKIN, M. and TALWANI, M. 1966. Rapid Computation of the Gravitational Attraction of Topography on a Spherical Earth. Geophys. Prosp. 14, No. 2, p.119-142.

TABLE 1

CURSOR BUTTON NUMBER	USE IN PROGRAM
1,2 or 3	Pass over 1, 2 or 3 contours without digitising
4	Contour intersection, elevation increasing
5	Contour intersection, elevation decreasing
6,1	Spot height location, supply height from keyboard
6,2	Site of density change, supply new density from keyboard
7	Last point digitised was at start of body of water
8,1	Delete last point digitised
8,2	Delete all information for current profile
8,3	Delete all information for current station

TABLE 2

The columns show terrain correction values obtained by dividing the topography surrounding a representative point on each of three maps into the number of segments given at the head of each column. All terrain corrections given are in mgal for a density of 2.0 gm/cm^3.

NUMBER OF SEGMENTS	8	12	16	24	32	48
MAP 1	0.142	0.132	0.132	0.133	0.129	
ZONES	0.125	0.133	0.129			
E-I	0.127					
	0.122					
	0.129					
	1.127		Average terrain correction = 0.128			
MAP 2	0.377	0.354	0.364	0.356	0.358	
ZONES	0.333	0.359	0.352			
E-I	0.325					
	0.350					
	0.367					
	0.366		Average terrain correction = 0.355			
MAP 3	32.57	33.06	32.30	32.54	32.86	32.72
ZONES	32.02	31.44	33.43	32.96		
A-K	33.77	34.16	33.10	31.76		
	33.58					
	30.61		Average terrain correction = 32.68			

FIGURE CAPTIONS

Figure 1: Annotated sketch of contour map, transparent overlay and 8-button cursor on digitiser table. An overlay with 12 radial lines is shown centred on the point for which a terrain correction is required. Solid circles represent points that have been digitised, the number(s) indicates the cursor button(s) used. The number in brackets is a spot height supplied from a keyboard.

Figure 2: Topography surrounding a gravity station is considered to be divided into a set of pie-shaped segments. (A) The outline of a single segment (dashed). In the method used to compute terrain corrections, topography in the segment is approximated by a single vertical section along its centre (solid). (B) A set of vertical topographic sections representing the input used in the calculation of one terrain correction. The sections are closed by horizontal lines with a height equal to that of the gravity station. (C) The corresponding set of vertical sections used for the calculation of a complete Bouguer correction. The vertical sections are closed by horizontal lines corresponding to a sea-level datum. (D) A set of vertical sections for the topography surrounding a gravity station, excluding topography in the immediate vicinity of the station.

Figure 3: Single closed vertical sections. The gravity station is assummed to be at the left side of each section. (A). Vertical section that includes a body of water. Bodies of water wholly above, wholly below, or partly above and partly below the gravity station are programmed for. (B). Vertical section on which variations in rock density are considered.

Figure 4: Plot showing how the scatter of values of terrain correction for a point in the Andes is reduced as the number of segments used in the determination is increased.

Figure 1

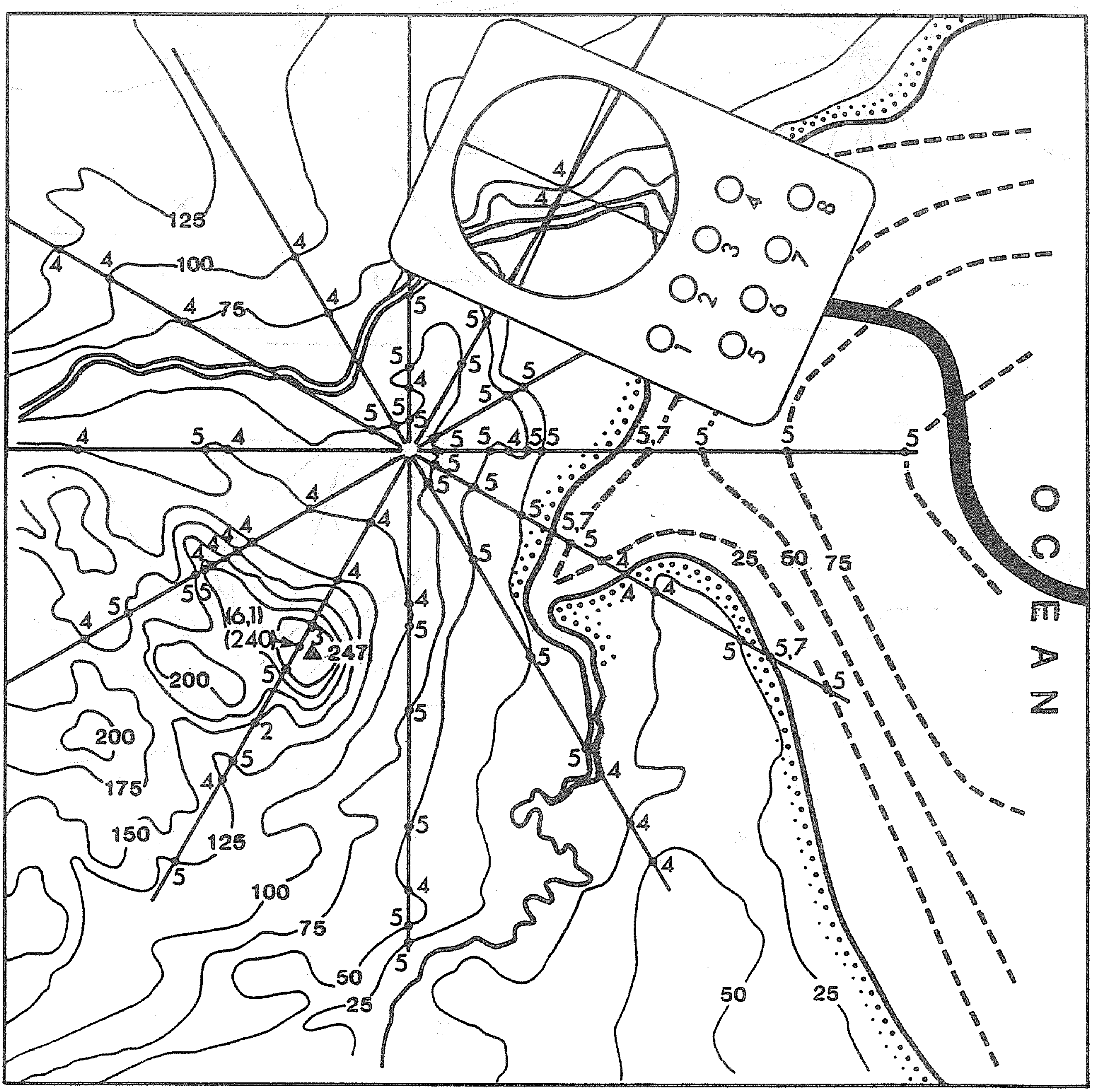


Figure 2

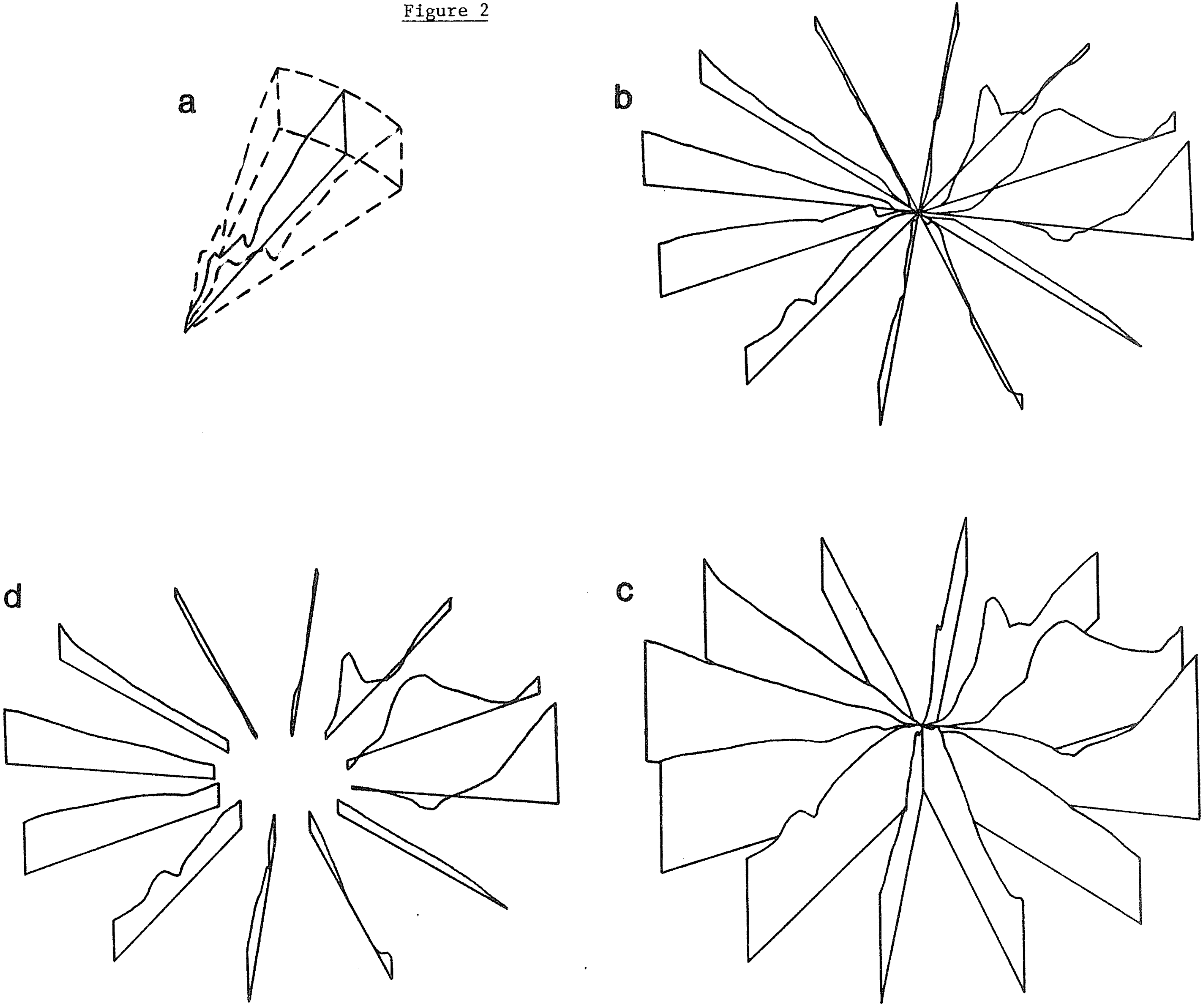


Figure 3

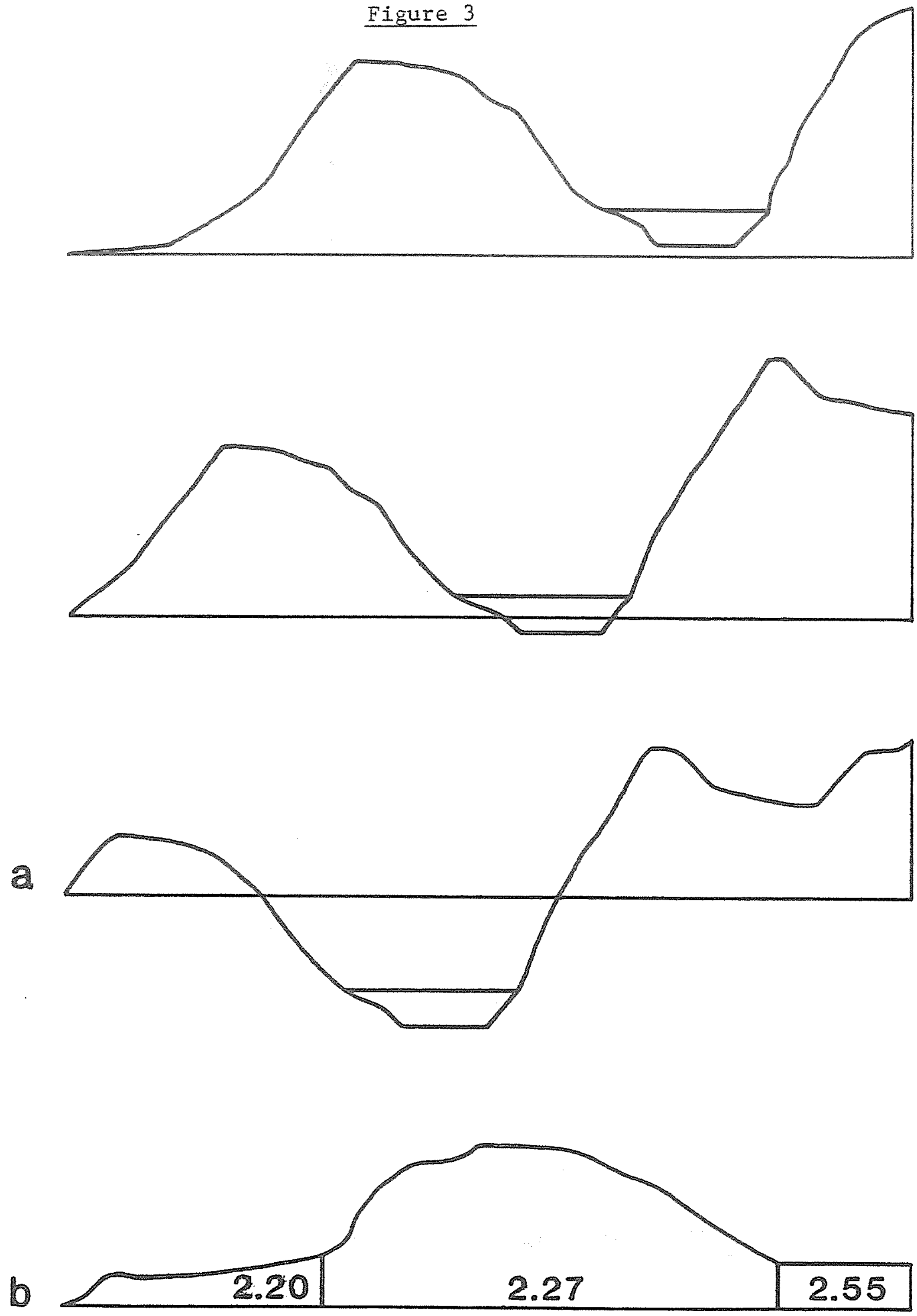
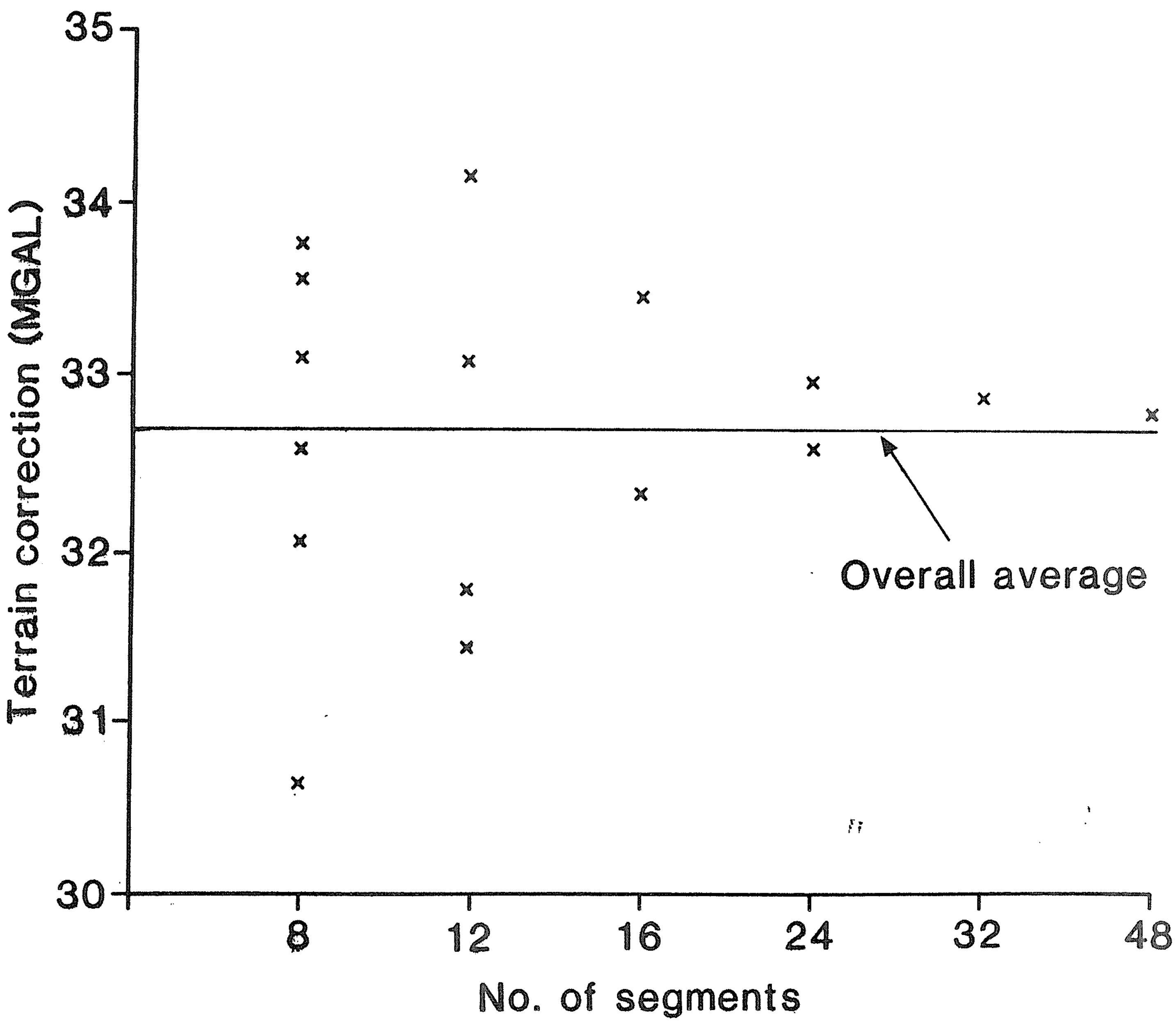


Figure 4



Terrain correction (MGAL)
35
34
33
32
31
30
Overall average
8
12
16
24
32
48
No. of segments

DETAILED GRAVIMETRIC GEOID AND SATELLITE ALTIMETRY SEA SURFACE

OF THE NORTH-WEST PACIFIC OCEAN (KURIL-JAPAN AREA)

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Abstract

We computed the detailed gravimetric geoid of the North-West Pacific Ocean (Kuril-Japan area and vicinity) using 20' x 30' area averaged gravity anomalies and the GRIM 3B global gravity model, and compared this geoid to the sea-surface topography (SST) derived from the Seasat-Geos 3 satellite altimetry experiments. The difference map SST minus gravimetric geoid was constructed. Using numerical experiments, we show that (a) large deviations of 8 to 10 meters in the belt between the island arc and trench arise from the systematic error in the mapping of sea gravimetry, (b) a radius of the Stokes' integration cap should not exceed 10 degrees to supress longwavelength errors of the sea gravimetry. Deviations of the SST from the gravimetric geoid on the level of 2 meters in the vicinity of the Kuroshio current are probably due to the oceanographic effect.

Introduction

The sea-surface topography (SST) is known from satellite altimetry with an accuracy of about 0.3 meter and with a spatial resolution of 30 to 80 kilometers (Marks and Sailor, 1986). This surface deviates from the geoid due to various oceanographic effects. Thus differences SST-geoid bear information on the general circulation of the World ocean, on the dynamics of oceanic fronts and synoptic events. The monitoring of these deviations, which are less than 2 meters (Wunsch and Gaposchkin, 1980) will revolutionize physical oceanography. However, the determination of the oceanic geoid from sea gravimetry is still a problem if an accuracy of about 0.2 meter is necessary (Zlotnicki, 1982). The Stokes'-Molodenski's theory requires that (a) the convolution integral of the measured gravity anomaly be computed over the spherical cap σ_c, (b) distant zones, that is gravity anomalies outside σ_c be computed using the global longwavelength gravity model.

Efforts of many authors have been aimed at optimizing the convolution kernel (Ostach, 1970) and at estimating errors associated with the global field model (Jekeli, 1981).

In this study we show that the accuracy of the gravimetric geoid is limited by the long wavelength errors of gravity measurements and by the errors of mapping gravity anomalies from discrete tracks of the sea gravimetry campaigns. We analyze the long wavelength error for optimal kernels and apply these results to the computation of the gravimetric geoid in the area in the North-West Pacific Ocean.

Data

Sea Gravimetry

For performing Stokes' numerical integration we mainly used the Free-Air Gravity Anomaly Map of Watts, Kogan, and Bodine (1978), as averaged over 20' of latitude by 30' of longitude. Gaps over oceanic and adjacent continental areas were filled-in with 1° x 1° averages. In the studied area of the North-West Pacific, free-air anomalies make a paired belt with an intense high of 300 mgal over the Japan-Kuril-Aleutian island arcs and an intense low of - 250 mgal over the corresponding trenches. This belt is observed against the mild positive regional background over the marginal basins of the Japan, Okhotsk, and Bering seas and over the outer seafloor rises seaward of trenches (Kogan, 1975).

Satellite Altimetry

Fig. 1 shows the SST from the 0°.5 x 0°.5 grid constructed from the combined Seasat and Geos 3 NASA satellites data (Rapp, 1985). An SST high of 25-30 meters over island arcs and a low of - 4 meters over the trenches are observed. Regional SST is positive, decreasing gently from 20-30 meters over marginal seas to zero over the North-West Pacific ocean basin. Essentially the image of SST is a smoothed version of the image of free-air anomalies as it should be.

Note that the studied area is a segment of the global system of positive geoid belts over subduction zones of the oceanic lithosphere.

Computation of the Gravimetric Geoid

The main relation to compute the gravimetric geoid was used as :

$$N(\vec{r}) = R/(4\pi G) \int_{\sigma_c} [\Delta g(\vec{r}') - \Delta g_m(\vec{r}')] \times [S(\psi_{\vec{r},\vec{r}'}) - S(\psi_c)] \, d\sigma(\vec{r}') + N_m(\vec{r}') \qquad (1)$$

where $\vec{r}$, $\vec{r}'$ are radius-vectors of the center of cap σ_c and of a current point in the cap, Δg and Δg_m are measured and global model free-air anomalies, $\psi_{\vec{r},\vec{r}'}$ is the angle made by $\vec{r}$ and $\vec{r}'$, ψ_c is the angular radius of the cap, N is the Stokes' function, and N_m is a model value of the geoid height. We used the GRIM 3B global gravity field model (Reigber et al., 1983).

Two properties of the basic relation 1 should be reminded.

(1) The suboptimal kernel of Ostach-Meissl is used.

(2) In the theory of M.S. Molodenski the measured values of $\Delta g(\vec{r}')$ are convolved while distant zones are accounted for through the coefficients of a series which depend on the cap size. Relation 1 is mathematically equivalent and much more convenient computationally.

To make the Stokes' integration over the cap, average values of Stokes' function over all compartments $d\sigma(\vec{r}')$ for various ψ_c are necessary. Careful calculation of these values is more important for central compartments since $S(\psi) \backsim 2/\psi + 0(1)$ at small ψ such that a value of S in the center of a compartment differs significantly from an average over the compartment. This aspect is either ignored (Marsh and Vincent, 1974), or solved by using smaller central compartments. 2-D numerical integration techniques based on Newton-Lagrange formulas of order up to 17 have also been used (Balmino, 1982) but require much computer time. We preferred to use an analytical approximation in terms of $\vec{r}$ and $\vec{r}'$ for the evaluation of the contribution of the "central" value of S in order to reduce it to the average over the compartment. Thus we were able to employ standard compartments 20' x 30'.

In M.S. Molodenski's theory of integration over a cap an estimator is provided for the r.m.s. error in the geoid due to the truncation of the global model. This analysis was later complemented with estimates of errors in the retained harmonic coefficients based on some assumed error model (Jekeli, 1981). We made numerical experiments by calculating geoid heights with various cap sizes and various truncations of the GRIM 3B model (Table 1). It was obvious that if all harmonics up to degree 36 are retained, there is only an insignificant change as compared to the 20th degree first harmonics. Indeed it could be expected that a contribution of higher harmonics decreases rapidly with an increase in degree and order since the Earth's gravitational spectrum is very "red". However its specific structure is not well known and may depend on the mathematical method which was used to develop the field model.

Errors in the gravimetric geoid arising from the errors and incompleteness in gravity measurements are poorly known since there is no reliable model of errors in sea gravimetry. The largest errors in the geoid are due to long wavelength errors in surveying which then appear as a systematic error in the integration over a cap. The importance of this error depends on the kernel and on the cap size. Fig. 2 shows the dependence of the error in the geoid on the systematic error in the gravity anomaly for Stokes' and Ostach-Meissl's kernels over a wide range of the cap size. Because the kernels keep the same positive sign up to large values of ψ, the error in the geoid may reach 2-3 meters even with a small error in the measurements of 1-2 mgal. We cannot rule out a chance that the effect of a systematic error in sea gravimetry decreases with an increase in the cap size. However it is a typical case that the gravity map of a large part of the ocean is based on a single cruise or on a number of cruises with similar gravimeters such that a systematic error on a level about 1 mgal may prevail over wide areas. As shown in Fig. 2, an influence of such error is roughly proportional to the cap size, so that a minimal value of ψ_c should be adopted, which is still supported by the global model used if we neglect their long wavelength error as compared to the gravity measurement errors ; that is we take $\psi_c \leqslant 360°/nmax$ degrees where nmax is the highest degree retained in the model.

Analysis of Deviations : SST Minus Gravimetric Geoid

A systematic error of our marine gravity data set of 1.8 mgal was found with respect to GRIM 3B in this area. It gives rise to a systematic error in marine gravimetric geoid (MGG) which depends on the cap size (Fig. 2). We removed this error from all subsequent comparisons of SST with MGG. Fig. 3 shows a map of MGG and Fig. 4 shows a difference map SST-MGG. These deviations are mostly within 2-meter limit with a notable exception in the trench area where a pronounced narrow belt of positive differences, as large as 8-10 meters, extends parallel to the trench. Largest deviations are roughly in the middle between the trench and the volcanic line of the island arc. It is easy to show that such discrepancies reflect typical errors in contouring the sea gravity data over the island arc. In fact, all ship tracks run through straits of the island arc where the sea floor topography is relatively low. As a result we may expect that such data are systematically biased to low values due to the well-known correlation of the local gravity with the topography. Simple estimates show that an error in the contoured map by 50 mgal across the belt 200-km wide results in a systematic error in MGG of 8 meters.

The differences SST-MGG in the South-Eastern corner of the studied area correlate well with the location and strike of the Kuroshio current. An amplitude of the deviation of 2 meters seems to be a realistic expression of an oceanographic effect.

It should be noted that our map of MGG deviates by more than 10 meters from that of Watts and Leeds (1977). The method of these authors differs from ours in the following respects : (a) Stokes' kernel was used rather than Ostach-Meissl suboptimal kernel, (b) an integration over an irregularly-shaped area was done with a cap size σ_c of about 30 degrees which may result in important systematic errors, (c) the spherical harmonic model GEM 6 was used which was appropriate in 1977 but which is inferior to the later GEM (NASA) and GRIM (German-French) models, (d) 1° x 1° averaged gravity anomalies were used.

Conclusions

1. In order to monitor deviations of the sea-surface topography (SST) from the geoid, it is necessary to have sea gravimetry data with a spatial resolution of 20-30 km and with a systematic error less than 0.3 mgal over areas 2000-km wide.

2. To suppress the effect of systematic errors in sea gravimetry on the marine gravimetric geoid (MGG), a minimal radius of numerical integration should be used up to the limit supported by the global field spherical harmonics model.

3. Spherical harmonics of degree and order higher than 20 in the GRIM 3B global model are of no practical importance in computations of MGG.

4. We computed the detailed MGG of the North-West Pacific Ocean and found deviations of SST versus MGG as large as 10 meters between the Kuril Island arc and trench. We attribute these large deviations mainly to a systematic error in contouring discrete gravity surveys. Deviations over the Kuroshio current seem to be realistic as they seem to reflect the oceanographic effect. Levitus sea surface topography model in spherical harmonics (or in map form) will be used in the future and correlations established by some automatic means.

Acknowledgements

We thank Georges Balmino for making available to us the GRIM 3B global gravity model, and for reviewing the manuscript.

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TABLE 1

Standard deviation between marine gravimetric geoids computed with the GRIM 3B model complete to 20th and to 36th degree and order and with various cap sizes

	20' lat by 30' lon grid				1 by 1 degree grid			
ψ_c (deg.)	10	16	20	24	10	16	20	24
Deviation (meter) (deg. 36-deg. 20)	0.13	0.08	0.05	0.04	0.1	0.09	0.06	0.05

FIGURE CAPTIONS

Fig. 1. Sea-surface topography (SST) from Seasat and Geos 3 satellite altimetry with respect to the IAG80 reference ellipsoid. Contour interval is 5 meter. North-West Pacific Ocean.

Fig. 2 Theoretical dependence of an error in the gravimetric geoid on the systematic error in sea gravimetry for the integration kernels of Stokes and of Ostach-Meissl (continuous curves). Observed values (that is with respect to GRIM 3B) for the North-West Pacific are also shown.

Fig. 3 Marine gravimetric geoid (MGG) over the North-West Pacific Ocean. Contour interval is 5 meter.

Fig. 4 Differences SST minus MGG over the North-West Pacific Ocean. Contour interval is 2 meter.

Figure 1

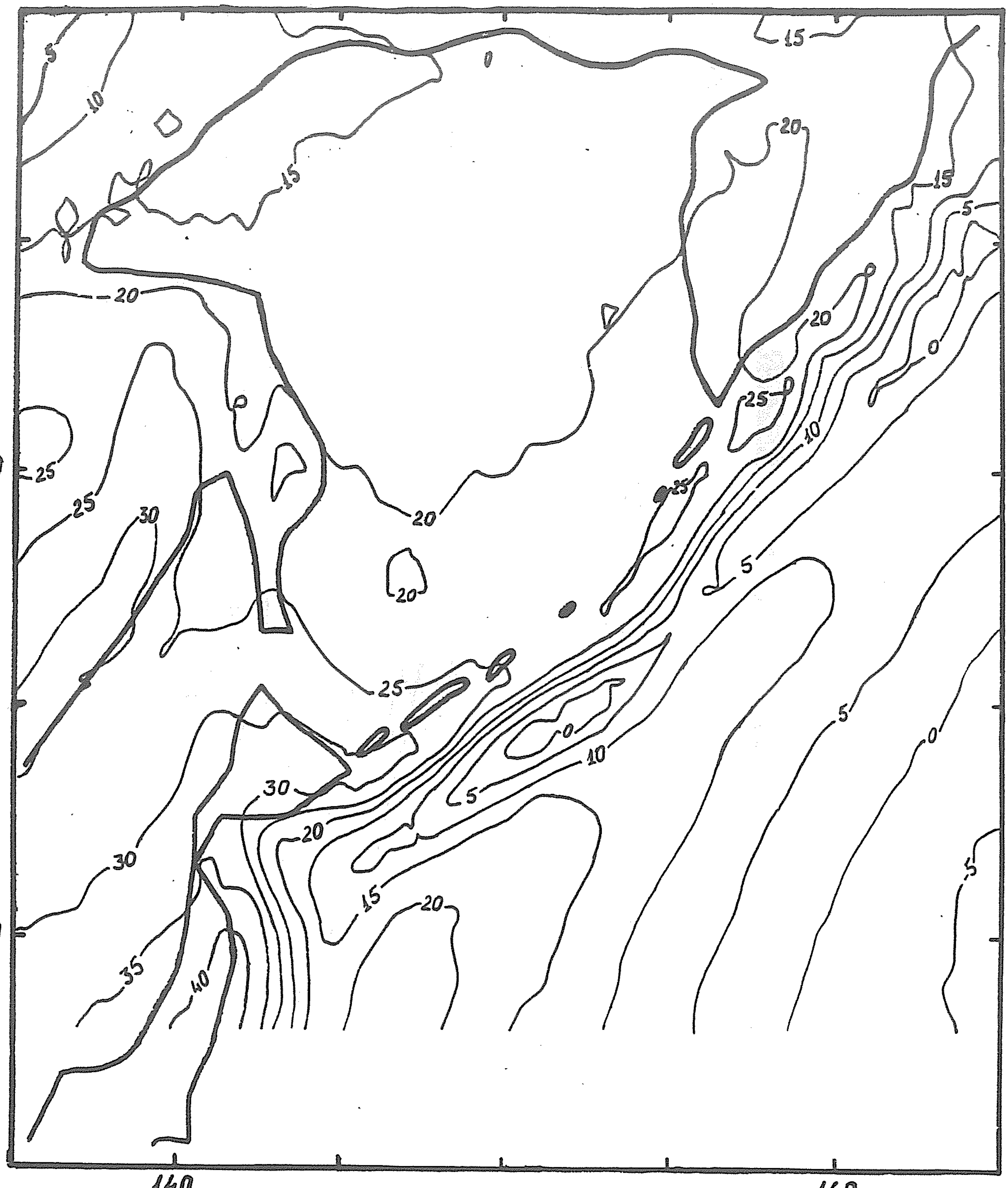

Figure 2

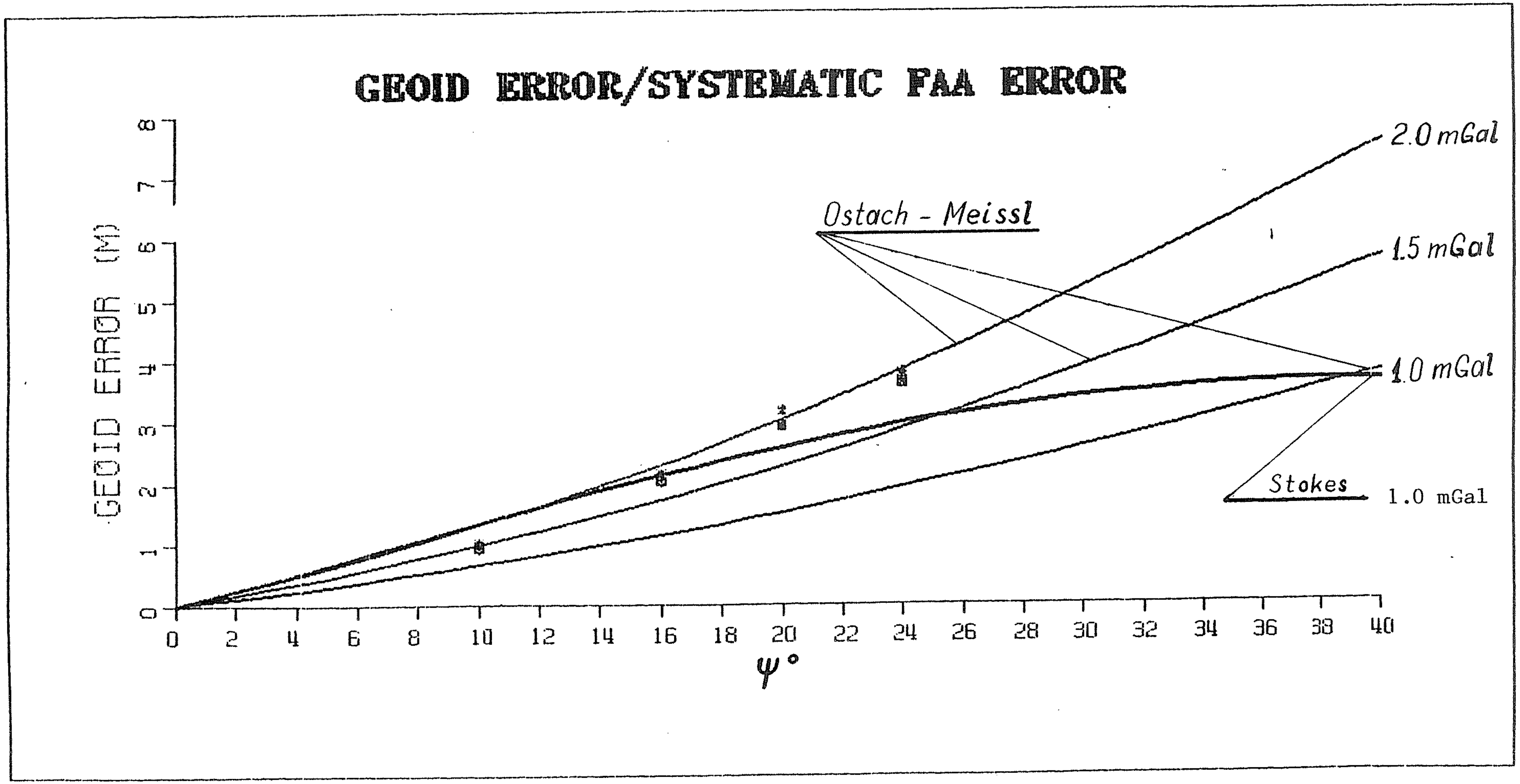
GEOID ERROR/SYSTEMATIC FAA ERROR
GEOID ERROR (M)
ψ°
2.0 mGal
1.5 mGal
1.0 mGal
Ostach - Meissl
Stokes
1.0 mGal

Figure 3

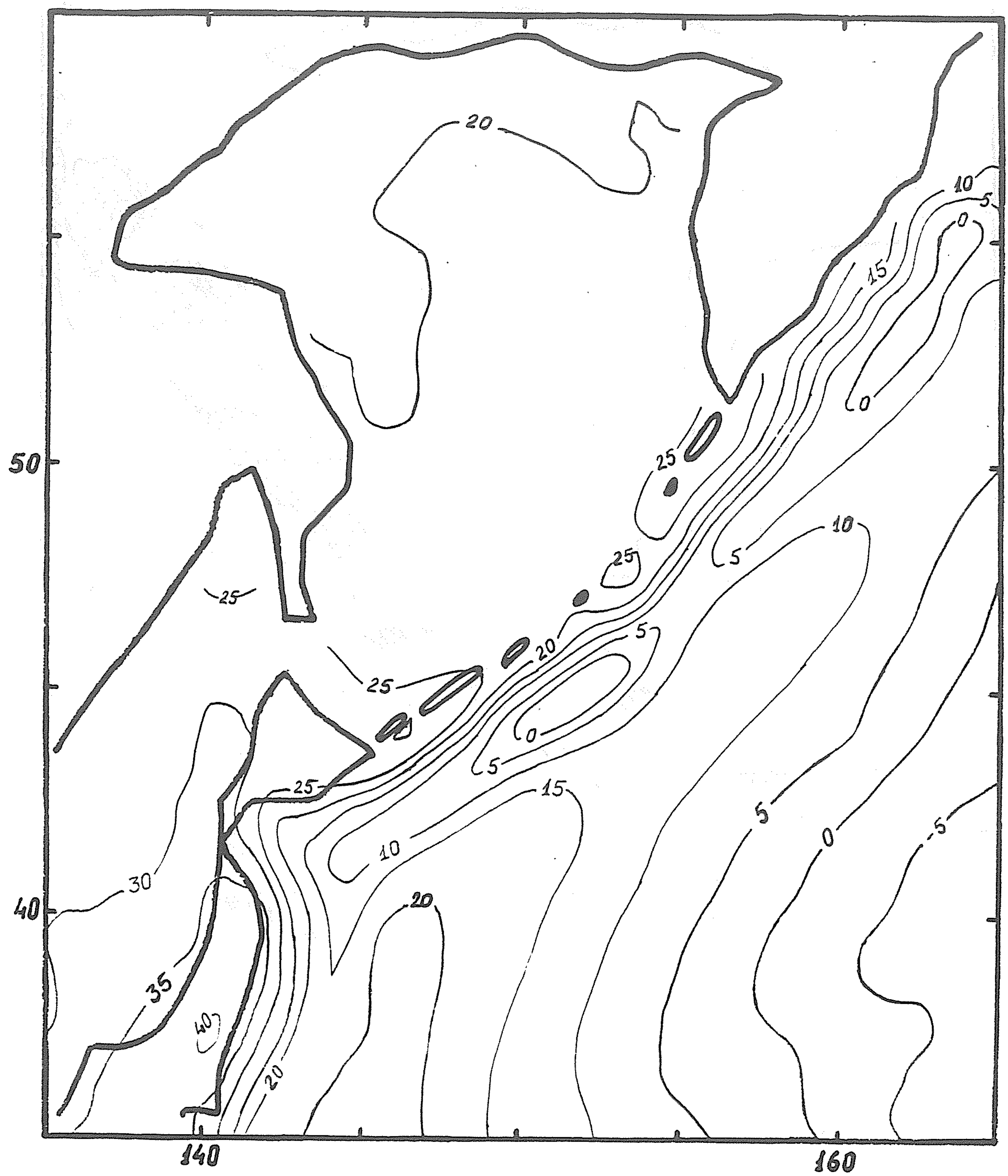

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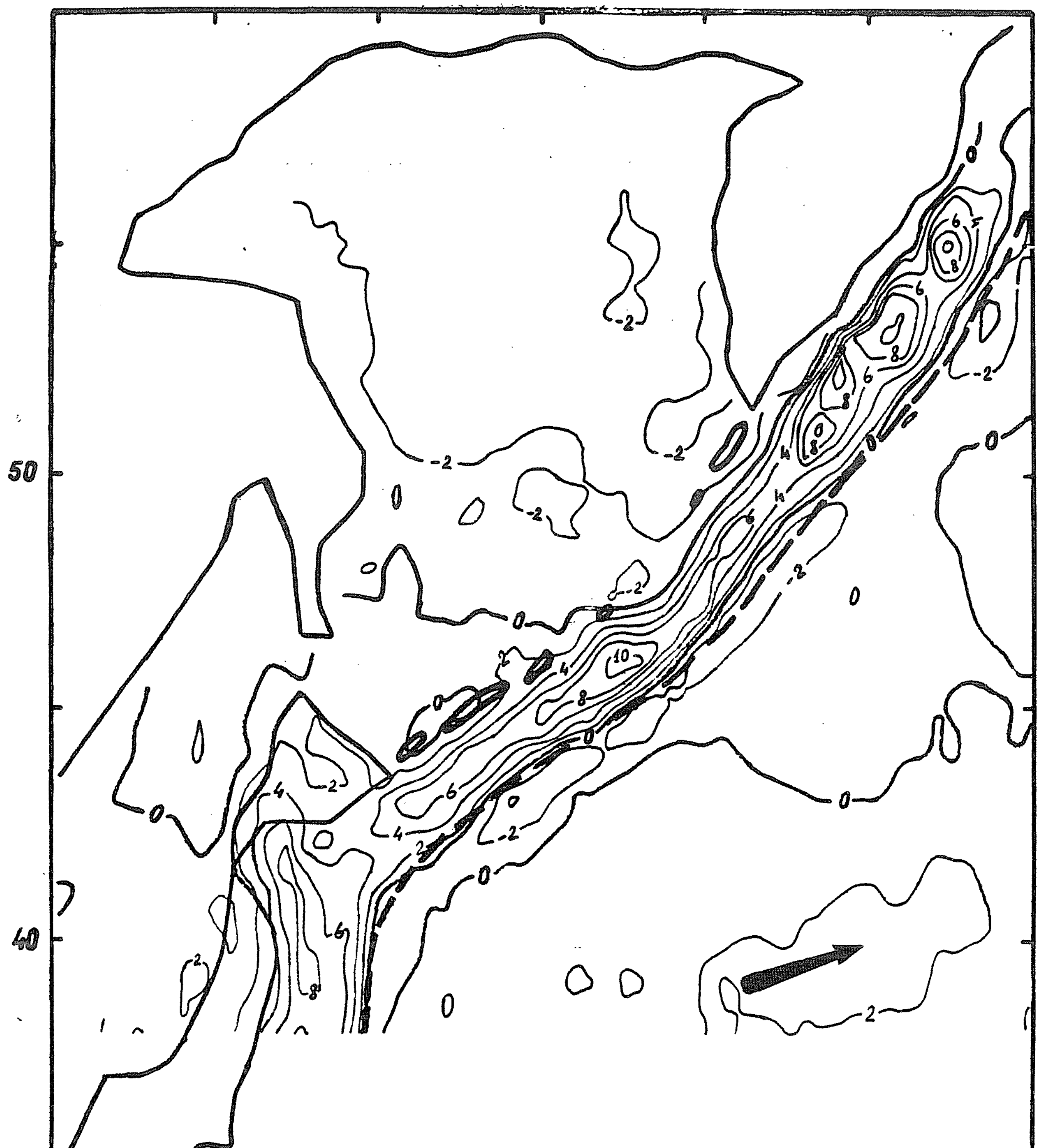
Figure 4



Evaluation of Gravity Data

within the

Department of Defense Gravity Library

By

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June 1987

ABSTRACT

The Department of Defense Gravity Library (DODGL) maintains an automated file of worldwide surface gravity observations. The gravity information in the database has been acquired from numerous sources including many scientific and government organizations, educational institutions, and private companies. To establish the quality of the gravity data in the database the data is subjected to review and evaluation and referenced to a common datum, the International Gravity Standardization Net of 1971 (IGSN 71). The data evaluation process is designed to eliminate duplicate data and reduce errors to a minimum. Error sources include instrument and recording errors, horizontal or vertical positioning errors, data correction (reduction) errors, and uncertainties in base station connections and the IGSN 71. Relationships and fit between individual data sets are also a consideration. Based on results from the evaluation process, gravity data is deleted, modified, or adjusted to obtain the most error free data possible. An accuracy value is assigned to each gravity observation based upon all findings from the evaluation. When the evaluation of a data set has been completed, the database is updated to reflect the evaluated data. Due to ongoing gravity data acquisition, evaluation is a continuing process.

INTRODUCTION

The degree of success of many projects which make use of gravimetric data and products is dependent on the quality and consistency of data in the Point Gravity Anomaly (PGA) Master File. The PGA Master File (or PGA Database) is an automated file of worldwide gravity observations. The sources of gravity information contained in the file cover a broad spectrum of the scientific and technical community. Scientific, government, and private organizations send to and exchange data with the Department of Defense Gravity Library (DODGL). Data sources include the United States Naval Oceanographic Office (NAVOCEANO), the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC), the National Oceanographic and Atmospheric Administration (NOAA), the Unites States Geological Survey (USGS), the geophysical exploration companies, universities and institutions involved in geodetic or geophysical research (national and international), state agencies, and agencies of foreign government [Boyer,1974].

A reconciliation or interrelation process is necessary to achieve commonality between data sets within the PGA Master File. To realize this homogeneity, gravity data accessioned to the PGA Database is subjected to examination and evaluation. The primary purpose for an in-depth evaluation of data is quality control. The procedures which constitute the task are designed to ensure gravity data placed in the PGA Database is of an acceptable accuracy, that all data is consistent, and that the most acceptable version of similiar data sets is accessioned [Scheibe et al., 1983]. As a result of this process, erroneous gravity data is removed from the database, identified systematic errors are removed, and all data is tied to the same datum.

All data sets sent to the DODGL are similar in nature. All contain data derived from observed gravity values. However, they are quite dissimilar since the data is collected from a variety of sources and has been surveyed at different times for different purposes under various environmental conditions, using various types of equipment, surveying procedures, and data reduction methods [Boyer,1974].

For evaluation purposes, the earth's surface is divided into regions corresponding to the areas covered by the 1:1,000,000 scale Operational Navigation Charts (ONC) produced by the Defense Mapping Agency Aerospace Center. The ONC areas are evaluated (more appropriately, re-evaluated) periodically. Frequency of evaluation is dependent on the amount of accession activity in the area as well as the current importance of the area (with respect to priority project demands). Determining the order in which ONC areas will be evaluated is a function of allocating the most important areas to the available manpower. Areas with a high degree of accession activity or project priority are evaluated more frequently [Scheibe et al., 1983].

The evaluation process consists of nine stages. These are: (1) assembly of gravity data, associated information, and evaluation aids, (2) knowledge of the surveying organization, (3) a general trend analysis of area and data, (4) elimination of duplicate data, (5) detection and resolution of errors, (6) gravity base station check, (7) estimation of survey accuracy, (8) updating processes,and (9) final operations. These stages constitute a "guideline" for the evaluator. However, cases frequently arise where it is advantageous to perform an evaluation out of any prescribed order. No two ONC areas are alike with respect to geologic structure, topographic setting, and distribution of gravity data. Therefore, no two evaluations are exactly the same. The actual sequence of an evaluation is largely a matter of judgment on the part of the evaluator [Scheibe et al., 1983].

ASSEMBLY OF GRAVITY DATA, ASSOCIATED INFORMATION, AND EVALUATION AIDS

Before beginning an in-depth examination of gravity data, the evaluator assembles materials and information that will be benefical in the evaluation. The information retrieved consists of gravity data from the PGA Master File, survey and source information, base station data, and other pertinent documentation.

Automated Materials

One of the major computer subroutines utilized in assembling data is the "Point Gravity Anomaly (PGA) Select" program. This computer program is designed to iterate through any PGA-structured input file selecting records which satisfy input criteria. Initially, PGA Select is used to retrieve from the PGA Master File all gravity stations falling within an ONC area. It is also used to create secondary, smaller sets of gravity data during the course of evaluation. Output is a file used continually throughout the evaluation process, primarily in updating and plotting.

A data listing is also generated. Information contained in the records retrieved for each gravity station include its geodetic position (latitude and longitude), the source number (a unique four digit code assigned upon acquisition of a data set), observed gravity value, elevation above mean sea level, free-air and Bouguer gravity anomaly values, and the assigned (if any) anomaly accuracies. Print options range in detail from listing only the total stations examined and retrieved to a listing by latitude of all records retrieved and a count of stations falling in each $1^{o} \times 1^{o}$ area.

A second source of information is the "Source File." The type of data stored on this file includes the geographic boundaries of the data set, the accession date, the total number of stations in the survey, the authors (the surveying organization) and the contributing organization (organization sending the data to the DODGL), the title of the survey, and the survey date. A listing is produced by accessing the Source File through the "Gravity Source File List" program by inputting a file of source numbers encountered from the PGA Select.

A third file accessed is the "Reference Gravity Base Station (RBS) File." Information stored on this file includes the location of the gravity base station (both the position and the name), a country code, an adopted gravity value, station accuracy and elevation above mean sea level , the parent base, and a network reference. The "Gravity Base Station Select" computer program uses base station numbers generated by the PGA Select computer program to access the RBS File and produce a listing [Dotson and Reinholtz, 1975].

After generation of the products mentioned above, a "Source and Reference Base Station Comparison" is generated by execution of a computer program of the same name. The unique matching of source numbers and gravity base stations is used to produce a listing of the matches along with free-air and Bouguer gravity anomaly accuracies, if previously assigned.

Nonautomated Materials

Nonautomated documentary materials must also be gathered. ONCs, topographic maps, bathymetric charts, and geologic/tectonic maps are used for orientation, checking gravity station locations and elevations, and general analysis. The "Source File Fact Sheet" provides source and base station information. Attached to this sheet is a graphic representation of the source coverage. Previous "Evaluation Histories" (Evaluation Summary Reports) can be benefical in describing the ONC area, any problems encountered with any source, and the method used to resolve those problems. Evaluation Histories also include a contour plot of the gravity data from the previously evaluated sources. These materials are collected before beginning the evaluation of a new source or are obtained on an "as needed" basis during the course of an evaluation.

Evaluation Aids

There are several evaluation aids produced that assist in the examination and evaluation of gravity data. The "Gravity Station Comparison" computer program creates a cross reference listing of collocated gravity stations within a tolerance set by the evaluator. It is a good check for common, near-common, and duplicate stations. This method of comparing individual sources to all other data on the file is useful because statistical information produced may make station differences and adjustments readily apparent.

A second aid is the output from a software package known as the "OSUCON Plotting" program. It is a graphics package originally designed by The Ohio State University (OSU). The graphic output is commonly referred to as "plots." Evaluators use the contouring capabilities to portray Bouguer gravity anomalies over land while free-air gravity anomalies are contoured when evaluating ocean gravity data. Various scales, contour intervals, and map projections are possible. The contoured plots can be produced in black and white or color. The figurative "work-horse" of the evaluation process is the "plot-by-source" subroutine. This subroutine works from a source-sorted gravity data file using information from the PGA Select program. The gravity station plot is produced in four colors with individual sources (their gravity stations) coded by color and symbol. The distribution and density of gravity data in an evaluation area mandate the scale and projection. An evaluator generally produces as many plots as needed to carry out a point-by-point inspection of the gravity station values in an ONC area.

Additional Information

Three additional sources of information may be beneficial in the gravity data evaluation process. All gravity-related material collected by the DODGL is stored in the "Source Document File." This material includes any data (heights or depths, gravity anomalies, positions, etc.) pertinent for the computation or recomputation of observed gravity value on the PGA Master File. The documents are retained in their original form at an off-line storage site. The material in this file is contained on aperture cards which are reduced, miniaturized versions of the original material. The Aperture Card File is stored within the evaluators' work area. The total holdings of the DODGL are also maintained in the work area as 1: 1,000,000 scale gravity station plots, reflecting the location of each station and its source.

KNOWLEDGE OF GRAVITY SURVEYING ORGANIZATIONS

Every evaluator should have an understanding of the surveying methods used by organizations providing gravity to DODGL. This is especially important within the ONC areas assigned to each evaluator.

Knowledge of the type of organization is very important. Is it a professional gravity surveying organization, a group of students, a research or geophysical company, or is the data from a state or federal program? Different organizations have different guidelines and standards concernings the quality and precision of the gravity data they acquire. For example, the number of internal checks performed and the amount of funds available influence data quality.

The objectives of the organization for obtaining gravity data is another point of interest. Is the gravity data being acquired to support academic research, a federal gravity application program, oil or mineral exploration, or will the data be used simply to support a report (thesis, dissertation ...)? The objective of the gravity survey will generally determine the amount of time and effort that is spent on checks and other quality control measures.

The organization sending data to the DODGL may not be the organization that performed the gravity survey. If the organization is a clearinghouse for gravity data, and problems or questions arise, will it be capable of providing any answers to an evaluator?

An evaluator must have knowledge of the location of a survey. Were the observed gravity stations in areas of easy accessibility? How rough was the terrain? Was the ship in shallow or deep water? How were the positions for the stations determined: precisely or scaled from a map? How accurate are the maps or charts in the area? Have the stations been correctly located? By what method and to what accuracy have station elevations been determined? The answers to these questions reflect upon the accuracy of the survey.

Knowing what instruments were used to gather the data is important. New technology has introduced new instruments with increased capabilities. These tend to improve the accuracy of the data recorded. Each instrument (new or old) has parameters unique to itself and must be operated correctly.

Improved instrumentation (recording devices) and surveying techniques (transportation modes and methods) have increased the speed at which data can be gathered. The date of the survey often puts the techniques and instruments used within the proper timeframe.

GENERAL TREND ANALYSIS

A key factor in any gravity data evaluation is a thorough visual inspection of the gravity anomaly contour plot. An evaluator checks the overall relationship of the gravity data to the ONC area and to itself. Questions raised which need to be answered are concerned with the continuity of the data. Does the general gravity field appear to fit the area? Are the lows and highs where expected? Do magnitude changes occur where they are warranted ? Are the land gravity stations indeed on land and the ocean gravity stations at sea?

In general, gravity anomalies directly reflect the land and ocean bottom surfaces. For example, on continents, the Bouguer gravity anomaly should be less than the free-air gravity anomaly and with increasing (higher) elevation usually becoming regionally more negative (lower magnitude). The type of topography present in an area (mountains, plains, etc.) will affect the gravity value and the gravity anomaly. Local geology such as rock type, block faults, sedimentary basins, etc. also influence the gravity anomaly value.

In ocean areas, there is a correlation between free-air gravity anomalies and the topography of the ocean bottom (bathymetry). For example, the gravity anomaly will show a rapid downward trend over trenches with a minimum near the trench axis. Along mid-ocean ridges, the free-air gravity anomaly values are uniformly more positive, by approximately 20 to 30 milligals, than those over the adjacent ocean floor. Over seamounts, the free-air gravity anomaly also becomes more positive as the apex is approached. There is generally a free-air gravity anomaly high near the edge of a continental shelf and a low along the base of the continental slope [Dehlinger, 1978]. This is called "the edge effect."

It is expected that the gravity anomaly field will show appropriate changes over the topographic and bathymetric surfaces. If an evaluator is aware of possible local irregularities in those surfaces, abrupt changes in the gravity field will not incorrectly be thought to be erroneous gravity data. An evaluator refers to available topographic maps or bathymetric charts of the area to check for features that can be expected to produce changes in the gravity anomaly field.

ELIMINATION OF DUPLICATE GRAVITY DATA

Definition

Situations may arise where identical or nearly identical data sets are encountered. It is important to differentiate between duplicate data and common stations.

Common stations are gravity stations where two or more independent measurements (different surveys) have been made at or near the same site. The station positions and elevation are essentially the same. This situation arises most often when different surveys make a gravity measurement at the same elevation markers ("benchmarks"). This practice is designed to assist in maintaining vertical control throughout a given survey. It is not uncommon for intersecting or overlapping surveys to occupy a single benchmark station [Scheibe et al., 1983]. Duplicate data sets are data from two or more sources that are, for all intents and purposes, exactly the same. Latitudes, longitudes, and elevations of corresponding stations are so similar they are considered to be the same set of data.

Duplicate data sets result from reprocessing the same observational data set. The measurements are not independent. They may occur when an organization supplies the DODGL with a data set, but then performs any one of numerous modifications and re-submits the data at a later date, this time with the modifications. Or, an agency can can submit a set of data, perform additional station readings over the area, and then submit the final data set. The first set of data will also be included in the second submission. A third method of acquiring duplicate data occurs when two or more organizations supply the DODGL with the same data. The situation is complicated if one of the organizations furnishes the data with additional stations over the area or if any of the organizations modify the data in any way prior to submission.

Detection

Detecting and differentiating between duplicate data and common stations is aided by the plot-by-source gravity station plot. The plotting routine assigns a unique symbol to the records from each source in the ONC area. By referring to this plot an evaluator can discern where collocation or duplication occurs, the sources involved, and the extent to which it occurs.

The Gravity Station Comparison listing is also used in the identification of common stations and duplicate data. The routine lists, as mentioned previously, a cross-reference of facts for gravity stations which are located within a specified distance of each other. This includes the difference in gravity values for collocated stations. By using this listing an evaluator can determine whether the collocations are common to a degree indicative of duplication. This is detectable when most, if not all, stations from one source consistently collocate with another source. Identical geodetic coordinates, station elevations, and station sequence numbers occur in instances of duplicate coverage [Scheibe et al., 1983].

Resolution

In most cases, common stations demonstrating the desired consistency in gravity values are retained by the evaluator. This action assists in the determination of a correct gravity value in future evaluations where additional collocation may require a decision regarding source reliability.

Some of the duplicate data is discovered and eliminated prior to file accession. But more frequently, all data is placed on the PGA Master File and it is the evaluators' job to locate and eliminate the duplication.

Duplicate data can be resolved and eliminated in various ways. Elimination depends on whether the data was received from a collection agency or the original surveying organization, the extent of duplication, and the modifications performed and their validity. Final determination is left to each evaluator on a case by case basis.

When deciding which source or sources to delete (or a portion of a source), an evaluator attempts to retain a source in order to preserve its individuality rather than combining several surveys under one source number.

GRAVITY DATA ERRORS

An evaluator has the responsibility to locate, analyze, and when possible, rectify inconsistent gravity data within an ONC area. Inconsistent data takes the form of abnormal gravity values which cannot be explained by topography, bathymetry, or geologic structure [Scheibe et al., 1983]. The abnormal gravity values are considered to be errors. There are three general classes of errors: systematic errors, blunders, and random errors. Systematic errors are those errors which tend to follow some fixed "law", which may be unknown. This error occurs with the same sign and often with a similar magnitude. A blunder can be defined as a gross mistake. Blunders are generally caused by carelessness. The residual errors, the errors remaining after all other errors have been eliminated or resolved, are considered random errors [Greenwalt and Shultz, 1962; DoD Glossary, 1981].

A primary task of gravity data evaluation is the detection and elimination, if possible, of all known systematic errors and blunders so that any unresolvable but uneliminated are random in nature. These random errors, often small in magnitude, are then reflected in the accuracy values assigned to the gravity data.

Error Sources

There are numerous error sources within gravity data sets. These include instrumental errors, recording and transcription errors, positioning errors, datum errors, and errors in the surveying procedures [Woollard, 1967 ; Boyer, 1974; Scheibe et al., 1983].

Horizontal positioning errors directly propagate into gravity anomaly errors. The horizontal position error has a north/south sensitivity of 1.3 sin 2Ø mgal per statute mile, where Ø is the geodetic latitude of the gravity station. (This is equivalent to 1.5 sin 2Ø mgal per arc minute of latitude. These values are found by derivations of the normal gravity formula.) Longitudinal errors may also occur, although they will not be directly evident in erroneous gravity anomaly values. The geodetic coordinates of the gravity station may have been determined using misread instrument measurements or from an incorrectly scaled map or chart. A station may have been improperly identified leading to an erroneous location. Horizontal positioning errors may take the form of transposed digits, misaligned decimals, or the use of incorrect signs with the coordinate (wrong hemisphere or quadrant).

Gravity station elevations, with respect to mean sea level, are determined by conventional (spirit) leveling, map and chart interpolation, altimetry (barometric), or trignometric leveling. Each elevation determinaton method has different accuracy limitations. Vertical positioning errors are created when map or chart information is unreliable or is incorrectly interpolated. When other methods are used, errors are due to instrument mishandling or misreading, or by erroneous interpretation of the measurements. A vertical positioning error may also be due to the use of incorrect elevation units. Errors can also be made when converting feet to meters, feet to fathoms, or meters to fathoms. The errors have a tendency to occur in areas of low elevation or shallow water where a small change in gravity anomaly magnitude is visible after a unit conversion is performed. In addition, errors can occur if a conversion is not made where necessary or if a conversion is applied twice.

A large group of gravity data errors are created by instrumental difficulties. A "tare" is defined as a disruption or rent in a data set. Tares are created by gravimeter malfunction. Improper handling of the instrument will cause abnormal readings. The gravimeter could have been dropped or jarred. It could have stopped (off heat), become stuck, or it could simply have been misread. Other errors may be due to off-leveling effects or poor calibration. Effects from vibration or magnetics may be included. Atmospheric effects such as pressure and temperature disturb instrument measurements. Many other types of instrumental error are possible [Woollard, 1967].

Survey procedures and techniques are a possible source of error. Measurement patterns, such as the loop or leap-frog technique, should have been followed. A gravity survey should have a number of reference points. Inaccurate or insufficient ties may lead to errors. Although an evaluator cannot and does not presuppose improper surveying methods, he/she must be aware of all possible causes of inconsistent gravity data.

Gravity survey measurements include corrections for instrument drift, luni-solar effects, and vehicle movement (e.g., the Eotvos correction in ocean data). If any of these corrections are applied incorrectly or inaccurately, errors are created.

Gravity data errors are also due to incorrect datum referencing. These types of errors are generally synonymous with a gravity base station error. A gravity base station error may be created by using an incorrect reference value. The value may have been overly corrected, under corrected, or double corrected to comply with the present reference system (IGSN 71). A datum referencing error is commonly called a "datum shift."

Error Detection

The detection of abnormal gravity values is largely a manual process requiring an evaluator to visually inspect a gravity anomaly contour plot. Erroneous gravity values, reflected in the anomalies, may be apparent on the contour plots where abrupt isolated changes of the gravity gradient immediately surrounding the suspect data will cause irregularities (a non-smoothness) in the contouring pattern. (See Figures 1 and 3.)

Horizontal positioning errors have a tendency to show as skews in the contour pattern. Station alignment is usually along lines of communication in land surveys. The majority of surveys follow roads, railroads, streambeds and shorelines. Alignment may also be in a gridded or linear pattern. This is often the case with ship survey tracks. Misalignment of survey tracks at sea or traverses on land may be evident with the aid of color and symbol coding of individual sources on the gravity anomaly contour plots. Additionally, number sequencing of gravity stations within a source may be indicative of misalignment. Irregularities in sequence numbers within traverse lines, or track numbers within ocean surveys, may occur without reason and the stations in error, those belonging in the break area, are found elsewhere on the plot.

Positioning errors are often difficult to locate using contouring alone. For example, a misplaced point may have an anomaly value that, by chance, fits into the gravity anomaly pattern at its erroneous location. A comparison between a PGA Select listing and a source's original data listing may be necessary.

Elevation errors may be difficult to detect. When an elevation error is present, the gravity anomaly will appear to be larger or smaller than expected for the gravity station elevation or depth. Referral to topographic maps or bathymetric charts is necessary. The gravity anomalies should be manually computed and compared to the values given on the PGA Master File. Common stations are also checked for discrepancies using the Gravity Station Comparison listing.

Gravity stations subjected to the effect of tare are usually found visually on the gravity anomaly contour plot due to unusual patterns in the contouring produced as a result of the effect of the error on the gravity anomalies. A tare could appear as a sudden change in anomaly values from one station to another within the same survey traverse. Or, the gravity anomalies along a traverse will all have the same value, indicative of a possible stuck gravimeter.

A scale change error is discovered by having numerous comparisons of near-common or common stations between a "new" source and previous, reliable, evaluated sources [Estes, 1971]. The new source's observed gravity value may agree with another source's value at one station or ship track crossing but the gravity differences will tend to increase or decrease along the survey track as the new source continually crosses the reliable sources. Scale changes are caused by the instrument, and are due to spring or calibration problems.

Datum shifts may be apparent from an inspection of the gravity anomaly contour plot. The contour pattern will change as a shift is encountered. This is dependent on the scale of the plot, the contour interval used, and the magnitude of the errors. The resultant, general pattern will be a group of contours set within smoother surrounding contours. (See Figures 1 and 2.)

Limitations within the contouring subroutine algorithm prevent some or all of the abnormalities from being reflected in the contour pattern. This may require the evaluator to inspect the gravity anomaly value at each data point (gravity station) annotated on the plot. This is done visually and with the aid of listings from the Gravity Station Comparison and PGA Select computer programs. Topographic maps or bathymetric charts are also referenced. A source's orignal data listing is used to verify station positions and observed gravity values.

Resolution

It may be possible to correct positioning errors, both horizontal and vertical, when a correction is apparent and justifiable. Justifiable meaning, if corrected, the data will fit the general trend. With some positioning errors, a valid assumption on the cause of error cannot be made and no correction is possible. In such instances, the gravity stations are deleted from the evaluator's data file.

A tare is an instrumental error that is more often than not unresolvable since the exact cause of the error is untraceable. In such cases, the gravity stations affected by the tare are deleted.

The Gravity Station Comparison listing can be beneficial in detecting scale changes, datum shifts, and other systematic errors. Common and near-common stations are cross-referenced and the differences between the Bouguer and free-air gravity anomalies at such stations are noted. Variations in the magnitude and consistency of the difference may be indicative of an error. Many times the gravity anomaly difference between common stations is used as the adjustment or correction to be applied to all gravity stations within a source. At other times, the datum shift can be determined graphically from the contour plot.

Gravity station differences for common or near-common stations, when analyzing ocean gravity data, are usually found by comparing ship track crossings from a new source and a reliable, previously evaluated source. Numerous comparisons are needed to make a valid adjustment. When the track crossing differences are consistent in magnitude and direction, an adjustment is made to the new source's observed gravity values by the addition or subtraction of that difference. Again, this adjustment may be applied to an entire survey or to only the stations along a particular track. If the track crossings are inconsistent in magnitude, but similar in direction a scale change error may be evident in the data. An evaluator will need to refer to the observed gravity values for confirmation. If a scale change is verified, a Least Squares Adjustment may be utilized to correct the gravity values [Estes, 1971]. When a scale change is not evident, the gravity stations along the survey track(s) are considered to simply be "bad" stations and are deleted from the evaluator's working file.

A typical datum shift an evaluator encounters is the translation of data from the Potsdam Reference System to the IGSN 71. The reference gravity base stations used for the gravity data in the DODGL are IGSN 71 stations. When Potsdam RBS values have been used by the surveying organization, the source's gravity stations must have an adjustment applied in order to convert the values to IGSN 71. The nominal correction applied is -13.7 mgals. But, in specific cases, the actual value of the correction may differ somewhat from the nominal value. This correction is normally applied to the gravity data by pre-accession analysts, but it may be overlooked or not be readily apparent in which case the final adjustment or "fitting" of the data to the IGSN 71 is left to the evaluator. (See Figures 1 and 2.)

Another example of a systematic error is in data sent in by geophysical exploration companies. Such companies are primarily interested in the small differences that occur between gravity values from point to point over a survey area. For that reason, the companies may establish their own referencing systems. These systems are not based or related to any national or international system (Potsdam, IGSN 71, etc.), although occasionally they are referenced to a normal (theorectical) gravity value. The company is only concerned with the magnitude of the differences in gravity values at field stations from values at established starting points. The values of gravity at these starting points usually are not referred to the same gravity datum. Datum changes generally occur with respect to latitude. These pre-established values essentially create numerous "floating" datums within one source. In order to resolve the discrepancies between an arbitrary datum and the IGSN 71, the starting point value must be determined using common stations or gravity anomaly map comparisons. This problem may be originally discovered by pre-accession analysts, but it may be the evaluators' job to complete the gravity data adjustment.

Most systematic errors can be corrected in some manner and the corrected data retained on file. One type of systematic error that always requires deletion of the stations involved occurs due to "ship cornering." Although survey tracks at sea appear linear in form, readings are continuous throughout a ship's turn (changing direction). Errors occur during the turns due to acceleration problems. These errors are reflected in the measured gravity values collected during the ship's change of course. The existence of this erroneous gravity data in a data source will be apparent from changes in the contour patterning. In most cases, the organization performing the gravity survey will delete the turn stations prior to forwarding their data to the DODGL. However, sometimes all or part of the data gathered during the ship's cource change is still present. The "bad" stations at the turns are identified by noting when the readings fluctuate from readings preceding and following the turn. The gravity measurements stabilize once the ship is back on course. The erroneous gravity stations are deleted from an evaluator's working file.

Sometimes, the "new" unevaluated gravity source receives an adjustment with the adjustment based on its fit and relationship to other data in the area, i.e. gravity data that has been previously evaluated (the "old" sources). Othertimes, the unevaluated source may tie and correlate better to the area (geologically, topographically, and geophysically) than previously evaluated sources. In such cases, the previously evaluated sources are re-evaluated, an adjustment performed if necessary, and new gravity anomaly accuracies assigned if warranted. The determination that a new gravity source is more accurate than one previously acquired is dependent upon the quality of the survey: the date, the organization, the instrumentation and survey methods used, etc. (See section titled "Knowledge of Gravity Surveying Organization.")

If an error is found during the gravity data evaluation process an attempt is made to correct it. The correction or adjustment should bring the data set into proper fit with the surrounding gravity field. (See Figure 4.) When the data is not correctable or an error is untraceable, the data is considered for deletion. An unresolved error is often considered a blunder and portions or all of a source are sometimes deleted. (See Figure 5.) However, the need for coverage and station density may force the stations in question to be retained. When this occurs, the anomaly accuracies assigned to the gravity data reflect the presence of the unresolve error.

GRAVITY BASE STATION CHECK

A gravity base station is a reoccupiable station having an accepted value of observed gravity. A gravity base station check is performed to verify that each gravity source is referenced to at least one base station and the base station is referenced to the IGSN 71.

Ideally, the information necessary for verification includes the station name and number (Bureau Gravimetrique International, BGI; or DOD), the geographic location, and the gravity value obtained, or used, during the survey. The ideal is not always attainable. Many gravity sources may include only a portion of the information while others may not provide any information. Source documents, aperture cards, other reference materials, and the DOD Gravity Base Station File are utilized and analyzed for base station verification. These materials are also used to establish the relationship between the survey value and the IGSN 71 value, if the latter exists.

In ideal situations, verification of a base station and its value is relatively simple. When documentation exists for the value of the field base station, an evaluator has only to check the difference (if any) between this value and the corresponding IGSN 71 value. Verification is made that the difference has been applied to all stations in the source [Scheibe et al., 1983]. When multiple base stations are used in the survey, the evaluator must verify that appropriate adjustments were correctly applied to corresponding segments of the survey.

A typical occurrence is when a field base station is referenced to the Potsdam System. All gravity stations in the survey must then be adjusted in order to reference them to the IGSN 71. (See section titled "Detection of Errors", datum shifts.) Generally, surveys made prior to the early 1970's were referenced to Potsdam. Many, but not all gravity surveys made since then are on the IGSN 71. (See section titled "Detection of Errors", geophysical companies.)

Data verification is complicated when the gravity sources do not provide complete information. Surveys may be referenced to gravity base stations not included in or tied to the IGSN 71. The gravity survey documentation must be analyzed in an attempt to locate base stations common to both the survey network and the IGSN 71, and to determine an adjustment relationship. The DOD gravity base station assigned to the source by the evaluator and the information describing the indirect tie to the field gravity base station is included in the Evaluation History. (See section titled "Final Operations.")

Instances occasionally occur where an organization does not provide any associated information with the gravity data forwarded to the DODGL. Therefore, no identifiable field gravity base station exists. However, it may be possible to use the Gravity Station Comparison listing to assign a base station value to the source based upon station commonality with other sources. In some cases, a reference gravity base station cannot be assigned.

All efforts are made to establish a base station for the gravity data. The source and related documentation search is exhaustive and if possible, the surveying organization is contacted and additional information requested.

GRAVITY ANOMALY ACCURACY ESTIMATION

Gravity anomaly accuracies are a function of the factors affecting gravity anomaly computation. These factors are related to both theoretical and observed gravity. Errors due to theoretical gravity are those due to uncertainies in the position (geodetic latitude) of the gravity stations. The errors contributed by observed gravity are functions of the errors that may occur in all aspects of accomplishing the observations. These include gravimeter malfuncton, calibration errors, data recording errors, surveying procedures, positioning errors, elevation errors, and any other blunders or tares.

Land Gravity Surveys

For land gravity surveys, the accuracy of Bouguer gravity anomalies is of primary importance. The general equation for the accuracy of the Bouguer gravity anomalies, based on the uniform incorporation of all factors influencing the accuracy, has the form :

$$\sigma_{BA}^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 \qquad (1)$$

where:

σ_{BA} = Bouguer gravity anomaly accuracy (on land).

σ_1 = Gravity Base Station accuracy, obtained from the RBS File.

The RBS accuracies are based upon the errors in the absolute datum and the accuracy with which the Gravity Base Station is tied to the IGSN 71. Its value usually ranges from $\pm$ 0.2mgal to $\pm$1.0 mgal (1 sigma), although some base station accuracies are larger than $\pm$ 1.0 mgal.

σ_2 = Internal accuracy.

The following errors are incorporated within an internal accuracy value:

(1) instrumental errors related to instrument type, its calibration, and pressure and temperature effects;

(2) errors in the adjustment to a Gravity Base Station such as the number of ties to the station, the length of the survey, and the method of the survey;

(3) the reliability of survey and computation procedures which are dependent upon the purpose and date of the gravity survey, the organization, the instruments used, and the techniques utilized. The internal accuracy generally does not exceed $\pm$ 1.0 mgal.

σ_3 = (kh)

where:

k = A constant, 0.1967 [Heiskanen and Moritz, 1967].

h = Accuracy of gravity station vertical position (elevation).

This value is dependent upon the errors in the methods used to determine the height of the gravity station above mean sea level. Elevations determined by conventional (spirit) leveling are more accurate than elevations obtained by trignometric leveling, altimetry, or interpolated from topographic maps. The quality of the gravity station elevation has the most effect of the error sources on the overall accuracy of the gravity anomaly. For example, the difference between an elevation accuracy of $\pm$ 5 meters and $\pm$ 10 meters, with all other variables remaining constant, will change the accuracy of a Bouguer gravity anomaly on land by 1 mgal.

$$\sigma_4 = (np)$$

where:

n = The change in theoretical gravity per minute of geodetic latitude.

This value is tabulated and available to the evaluator.

p = Accuracy of gravity station horizontal position (geodetic latitude).

The error in geodetic latitude is determined by knowing the horizontal geodetic datum involved, the surveying method(s) used to determine the gravity station position, or the map accuracy, if the position of the gravity station was interpolated from a map.

[Greenwalt and Shultz, 1962; DODGL communications, 1985].

Often an error value can not be reasonably assigned to some of the variables in the above error equation. In such cases two other approaches to accuracy determination are available for use. One is considered to be an Indirect Method, the other is call the Logical Method.

The Indirect Method utilizes a known error (the accuracy of other sources) and common stations. The error equation for the Indirect Method is :

$$\sigma_{BA}^2 = \sigma_K^2 + \sigma_{\delta\Delta g}^2 \qquad (2)$$

where:

σ_{BA} = Bouguer gravity anomaly accuracy (on land).

σ_K = A known error in other gravity anomalies (the best accuracy of any source), frequently taken as the mean of known accuracies of all evaluated gravity sources in the area.

$\sigma_{\delta\Delta g}$ = Standard deviation of the differences of common gravity stations.

$$\sigma_{\delta\Delta g}^2 = \sum_i (\delta\Delta g_i - \overline{\delta\Delta g})^2 / (n - 1)$$

where:

$\delta\Delta g$ = The difference between gravity anomalies at a common station.

$\overline{\delta\Delta g}$ = The mean of the differences.

n = The number of stations in the comparison.

[Greenwalt and Shultz, 1962; DODGL communications, 1985].

The Logical Method involves numerous factors, but is not mathematically formulated. It relies on estimating the accuracies based on all influences acting as a whole. These influences include the survey date, the reputation of the organization, the type of survey instrumentation used, the method of determining positions and elevations, and the relationship of the gravity anomalies to the terrain and to other sources in the same area.

It is desired that Bouguer gravity anomaly accuracies range between ± 1 and ± 5 mgals. For error magnitudes larger than ± 5 mgals the gravity data may or may not be usable depending on project requirements and the geographic area of interest.

To compute the accuracy of the free-air gravity anomalies for land data, the constant "k" in Equation (1), the Direct Method, is taken as 0.3086. When using the indirect or logical approaches, the product of elevation accuracy and the Bouguer plate constant, 0.1119, (which is also the difference between 0.3086 and 0.1967) determines the value to increase the Bouguer gravity anomaly accuracy to obtain the free-air gravity anomaly accuracy.

Ocean Gravity Surveys

For ocean gravity data, the free-air gravity anomaly accuracy is of prime importance. The "direct" formulation is inadequate for estimating the accuracy of ocean gravity data because it does not contain an expression for errors related to the Eotvos effect. The Eotvos correction is a significant source of error in ocean gravity surveys. The correction must be applied in the reduction of gravity data taken from moving platforms (the ship) to obtain observed gravity values. The correction accounts for the gravitational effect of the motion of the ship with respect to the rotating earth. Uncertainty in latitude, velocity, and azimuth will create errors in the correction value. The form of the gravity data seen in the DOD Gravity Library does not lend itself to an analysis of any inaccuracies related to the Eotvos effect [Boyer, 1974].

This leads to a modification of the direct approach. The basis for the approach lies in three assumptions: (1) that the differences in gravity anomaly values at ship track crossings are the results of combined errors in gravimetry and navigation; (2) that the errors associated with each gravity anomaly value in the survey form a normally distributed population; and (3) that the differences at crossings, considered as errors, are a statistical sample from that population. The three assumptions allow the use of a simplified version of the direct equation, namely the Indirect Method. The expression related to track crossings results from considering that h=0, that internal accuracy (i) is related to gravimetry accuracy, and that position and Eotvos error are related to navigation error [DODGL comunications, 1985]. The Indirect Method involves the known error, as in land gravity surveys, with the common station factor being replaced by a ship track crossing factor based on the above assumptions. The error equation for the oceanic free-air gravity anomalies has the form :

$$\sigma_{FA}^2 = \sigma_K^2 + \sigma_{\delta\Delta g}^2 \qquad (3)$$

where:

σ_{FA} = Free-air gravity anomaly accuracy (ocean data).

σ_K = Known error (the best accuracy of any source), frequently taken as the mean of the known accuracies of all evaluated gravity sources in the area.

$\sigma_{\delta\Delta g}$ = Standard deviation of the gravity anomaly differences at ship track crossings.

$$\sigma^2_{\delta\Delta g} = \sum_i (\delta\Delta g_i - \overline{\delta\Delta g})^2 / (n - 1)$$

where:

$\delta\Delta g$ = The difference between gravity anomalies at the ship track crossing.

$\overline{\delta\Delta g}$ = The mean of the gravity anomaly differences

n = The number of ship track crossings used in the comparison.

[Greenwalt and Shultz, 1962; DODGL communications, 1985].

The Logical Method used to assign accuracies to ocean gravity anomaly data involves all the factors and influences used with land gravity data. For ocean gravity surveys, the instrumentation used for navigation is also of concern and the gravity data is correlated with the bathymetry instead of terrain.

The accuracy of oceanic gravity anomalies will tend to be larger (worse) than the accuracy of land gravity anomalies. This is due to higher error tolerances being allowed for ocean gravity data with respect to the corrections applied for uncertainties in navigation, cross-coupling, and the Eotvos effect. For ocean gravity data, free-air gravity anomaly accuracies range from $\pm$ 2 mgals to as much as $\pm$ 20 mgals.

UPDATING PROCESS

Types of Alterations

Any correction or modification to a gravity station or group of stations in an ONC area may be made as they are discovered. Or, all data alterations may be applied at one time. Many evaluators feel it is safer and less complex to perform the modifications a few at a time, as an ongoing process, throughout an evaluation. Modifications are made to the ONC area file using data updating subroutines.

Typical revisions to the ONC area file include deletion of individual stations from a single source or multiple sources, deleting a group of stations from a source, deletion of an entire source, corrections to stations, either individual or a group (A delete/add. This includes non-routine corrections such as depth corrections. Depending upon the area encompassed, an evaluator or a pre-accession analyst may be the responsible party.), performing a datum adjustment, performing a scale adjustment, adding or correcting a gravity base station, or assigning free-air and Bouguer anomaly accuracies [Dotson and Reinholtz, 1975].

Procedure

The Department of Defense Gravity Services Branch utilizes both a Digital Eguipment Corporation VAX 11/780 Computer and a Sperry 1100 Series Computer. Whereas the functions are similar between the VAX 11/780 and the Sperry 1100 computer programs, the difference lies in the format of the input data. The Sperry 1100 programs use PGA-structured files as input. The VAX 11/780 programs must be accessed by using a "Select File", a 23-word-per-record unformatted file. There are presently four computer programs utilized when updating an ONC area file.

The "Point Gravity Anomaly Edit-Sort" computer program consists of two separately execute subroutines. The edit phase checks data input for valid characters and format. These edited records are then sorted in the sort phase according to sorting criteria; by quadrants, within each quadrant, then by eight degree bands of latitude, etc. The sort phase may immediately follow an edit phase, or the edited data may be sorted at a later date.

The sorted data from the PGA Edit-Sort is utilized as input into the "Point Gravity Anomaly Update" computer program. This program uses the data to create changes to an ONC area file. These changes are commonly in the form of gravity record deletions and additions. The changes are reflected in the sorted data records.

Evaluators also utilize the delete capabilities of the "Point Gravity Anomaly Merge/Delete" computer program to delete gravity records from an ONC area file. Deletion is accomplished by source and/or geographic area. This is often referred to as "block deletion."

Gravity station modifications are performed with the "Point Gravity Anomaly Maintenance" computer program. Modifications involve datum adjustments, updating reference base station information, and assigning accuracies to the free-air and Bouguer gravity anomalies [Dotson and Reinholtz, 1975].

Table 1 gives the type of alteration and the most commonly utilized program sequence.

Table 1. Computer Programs Used in the Updating Process

PROGRAM SEQUENCE	TYPE OF CHANGE	COMPUTER PROGRAM
1	Deleting individual stations	a. PGA Edit-Sort and PGA Update b. PGA Maintenance (if only a few stations are involved)
2	Deleting part of a source or an entire source	PGA Merge/Delete
3	Correcting individual stations	PGA Edit-Sort and PGA Update
4	Datum adjustment	PGA Maintenance
5	Scale adjustment	A Least Squares Adjustment, then PGA Edit-Sort and PGA Update
6	Updating RBS information	PGA Maintenance
7	Assigning gravity anomaly accuracies	PGA Maintenance

FINAL OPERATIONS

Packaging

When an evaluator is satisfied that all updating has been completed in an ONC area, preparations are made to finalize the evaluation. This entails the assembly of all materials and information to be forwarded to the immediate supervisor for checking. The materials needed to update the PGA Master File are then forwarded to the DOD Gravity Services Library Section.

First, a gravity anomaly comparison, or "differences", program is executed. This computer program, The "Point Gravity Anomaly Compare", compares the final ONC area PGA-structured file to the original ONC area file. The output from this comparison lists the sources that underwent any updates and the types of modification performed. This list enables the evaluator to ascertain that all desired alterations to the ONC area file have indeed been performed.

A check is performed on the final data file using the computer program "Point Gravity Anomaly Sequence Check." This program checks the final, evaluated stations for proper sorted order (sequence) and format to successfully update the PGA Master File. The check also detects those records with geodetic positions outside the legitimate boundaries of the ONC. At the user's option, the computer subroutine can be used to build a new ONC area PGA-structured data file, omitting records which are out of sequence or that have unacceptable geodetic coordinate [Dotson and Reinholtz, 1975].

As a final check, the Source and RBS Comparison Program is executed. The computer program lists the source number, the RBS, the total number of gravity stations, and the assigned gravity anomaly accuracies for all sources on the final ONC area data file. This listing allows the evaluator to verify that all sources have indeed been evaluated. This is apparent by the presence of gravity anomaly accuracy values. Gravity base stations are also checked for proper assignment.

Using the final ONC area file and the OSUCON plotting software, a gravity anomaly contour plot is produced. Such a plot simply shows the gravity anomaly contours. If desired, a four color, symbol coded, annotated gravity station plot can be made. If mandated by the number of stations or their density, numerous contour plots can be produced at scales that will allow illustration of individual stations.

When all details of the evaluation have been resolved a report is compiled. The "Gravity Evaluation Summary Report" is a written history of the ONC area gravity data evaluation. A geographic and geologic description of the area is included with a narrative of all sources in the area. This narrative, by source number, includes background information on each source (i.e., the author, survey date, instrumentation, type of navigation, survey procedures, RBS information, etc.) and a list of all modifications or alterations performed on the data (within each source). All actions performed and any conclusions or recommendations are described.

The aforementioned materials (the PGA Compare, the PGA Sequence Check, the final Source and RBS Compare listings, the final ONC area plot(s) of gravity anomalies, and the Gravity Evaluation Summary Report) are packaged together. The original Gravity Source Select List and Source and RBS Comparison listings are also included in the history package. These two listings document the sources selected from the PGA Master File at the time of initial retrieval. The ONC and other maps and charts used in the evaluation process are also packaged. An evaluator forwards this package to one of the Evaluation Managers (A Section Supervisor.)

All actions and operations taken over the course of the evaluation are reviewed and justification stated. After the supervisor is satisfied that all aspects of the evaluation were performed acceptably, the final ONC area file number or name (as appropriate), the original Source and RBS Comparison Listing, the geographic boundaries of the ONC, and the PGA Sequence Check are forwarded to the PGA Database Manager. The remaining materials in the history package are maintained in storage for historical and reference purposes.

PGA Master File Updating

The final step in the gravity data evaluation process is the responsibility of the Database Manager. Upon receipt of the final ONC area data file the Database Manager will delete data from those sources initially retrieved from the PGA Master File by the evaluator. Limiting the deletion process in such a manner ensures that any new data accessioned after the initial retrieval will be left intact. In the same operation, data on the final data file is merged into the PGA Master File. Both the deletion and merging processes are performed by the PGA Merge/Delete computer program [Scheibe et al., 1983].

Upon completion of the merge/delete process, the affected gravity data sets now contain newly evaluated or re-evaluated data. At this point, the gravity data evaluation process is considered to be complete. The data in the PGA Master File covering the evaluated ONC area is now commonly referenced and is an adjusted representation of the data in the area.

The dynamic nature of the PGA Master File seldom permits this up-to-date status to remain for long. On-going gravity data acquisition necessitates a periodic review of the ONC areas. The frequency of review is determined by accession activity and project priorities. It is important to keep in mind that the end product of any evaluation process is temporary rather than permanent [Scheibe et al., 1983].

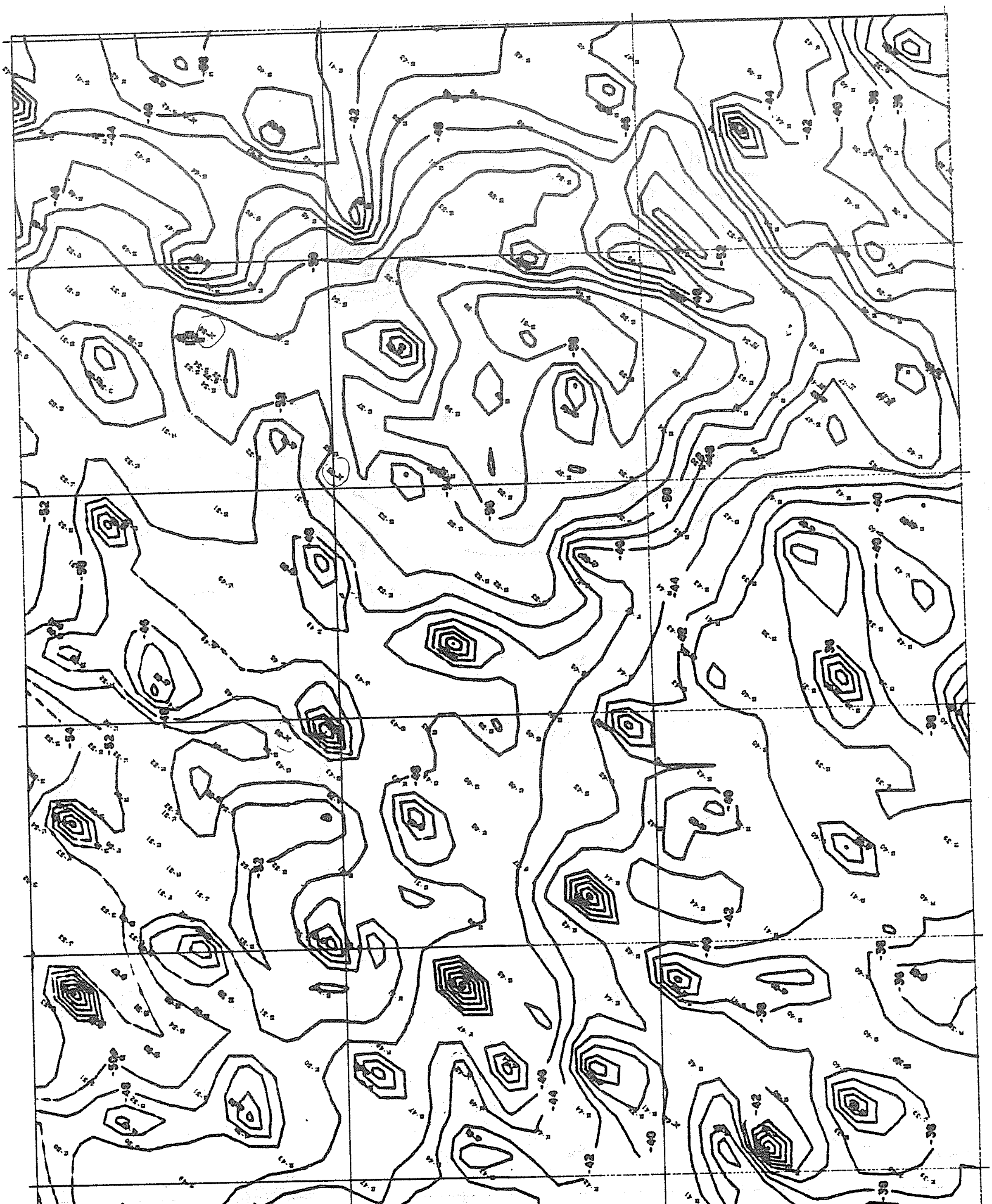
Figure 1. Bouguer gravity anomaly contour plot reflecting a datum error in Source X data.

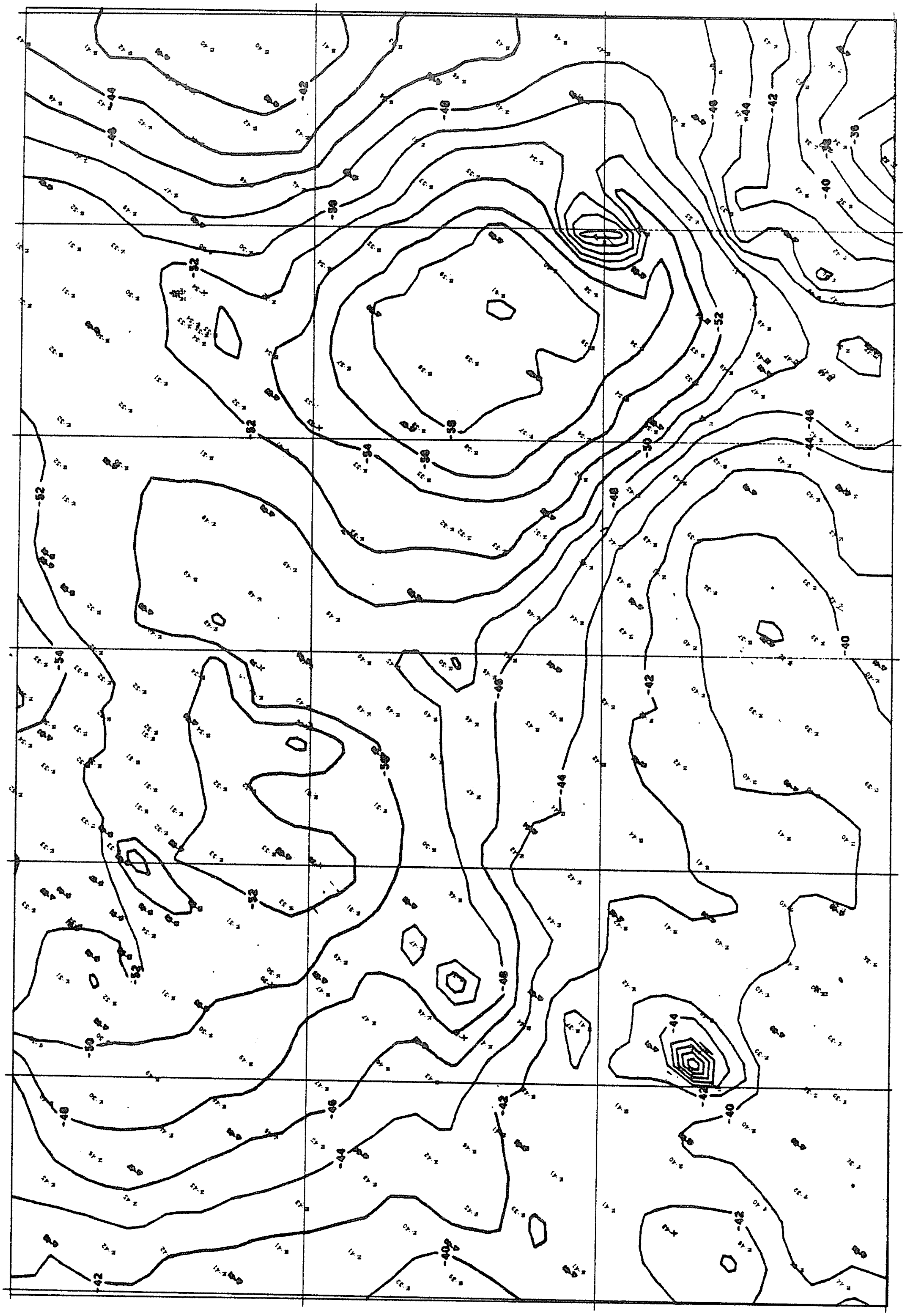
Figure 2. Representation of data from Figure 1 after a -13.7 milligal datum adjustment was applied to gravity data from Source X.

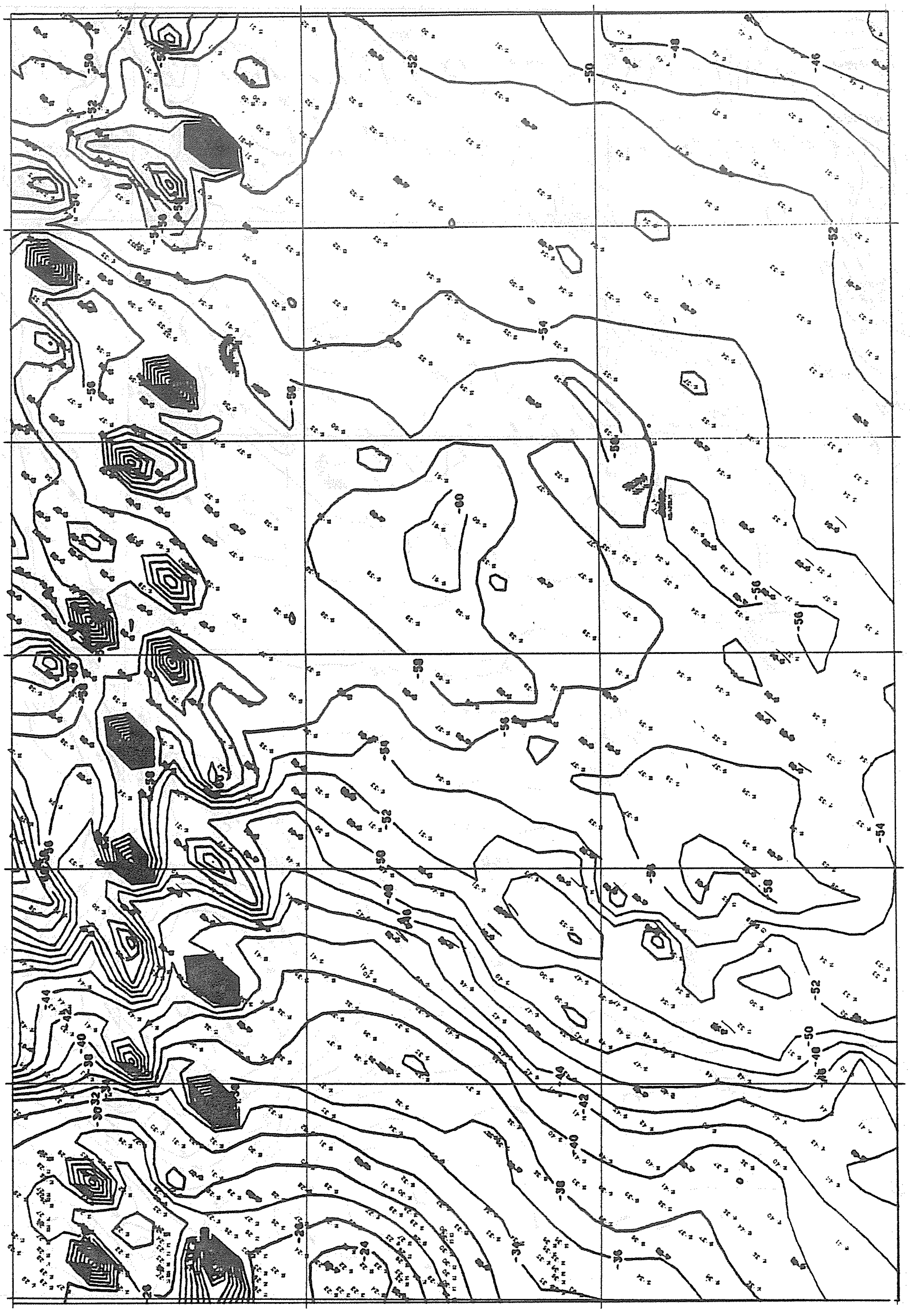
Figure 3. Bouguer gravity anomaly contour plot reflecting an error due to the double reduction of Source Y data.

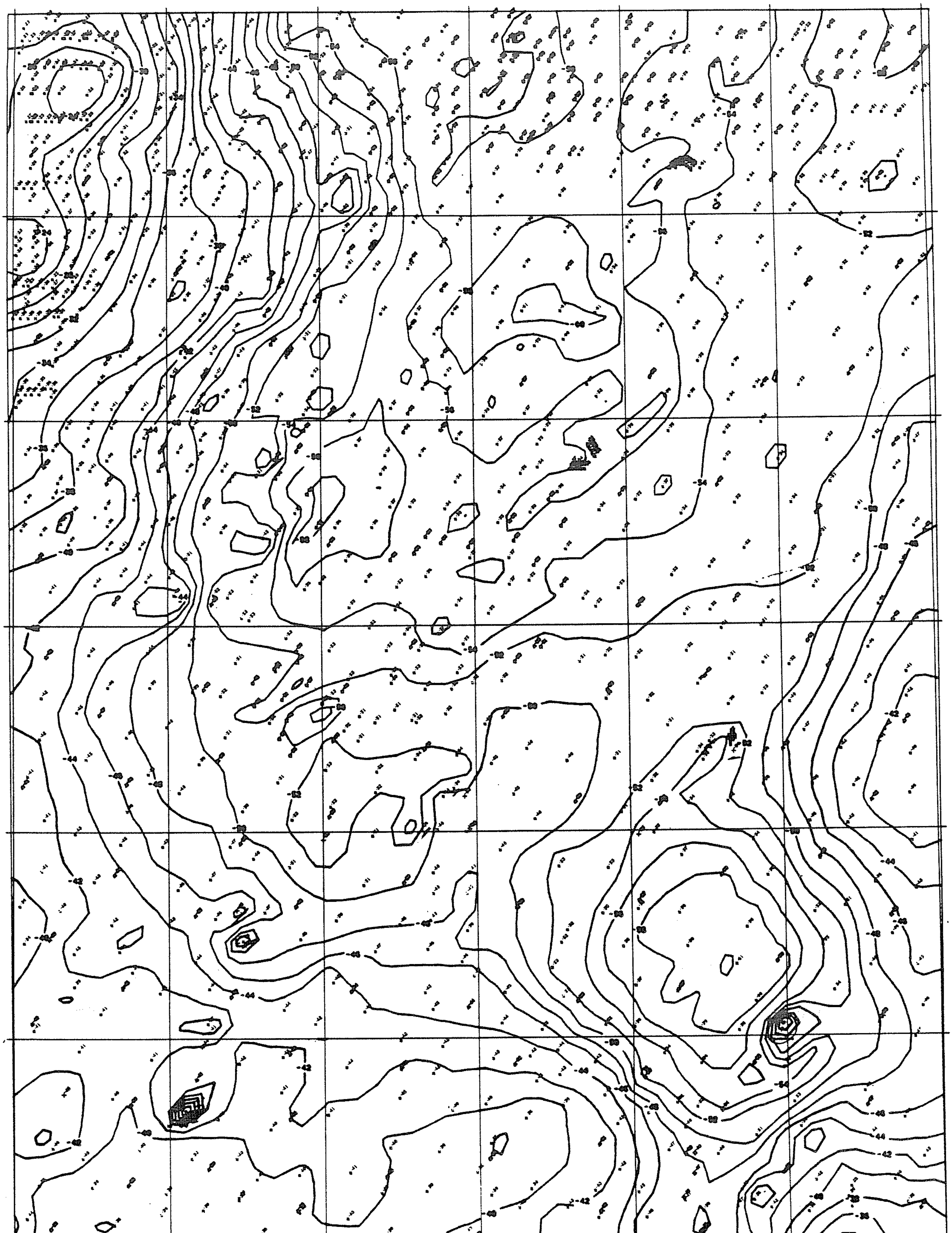
Figure 4. Representation of Figures 1 and 3 using corrected gravity data from Sources X and Y.

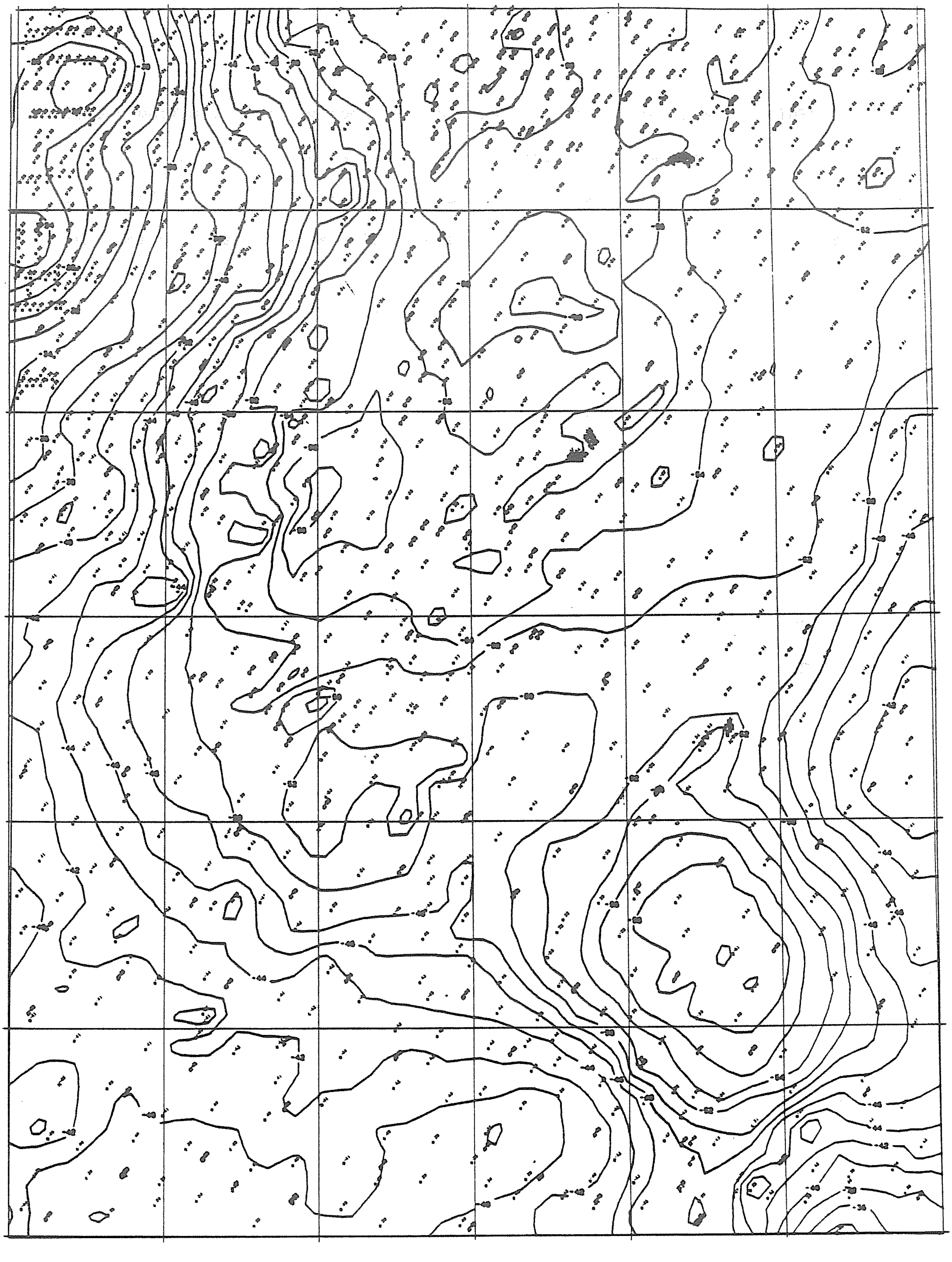
Figure 5. Reflects Figure 4 after the deletion of four "bad" gravity stations.











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CHINA GRAVITY BASIC NET 1985

by

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Abstract

The China Gravity Basic Net 1985(CGBN85) which comprises 57 gravity stations (including 6 absolute gravity stations), was measured with La-Coste & Romberg gravimeter model G(LCR-G). Precise relative connections were also made between CGBN85 and several existed international standards. In total about 11000 observations were obtained. A whole adjustment was made by applying the parameter adjustment method, taking into account of scale functions for each LCR-G meter. The new national-wide CGBN85 with an average internal accuracy of ±8 microgal [10^{-8} ms^{-2}] was then establihed and has being used, since its official appraisal, in gravimetric practices for two years, which shows that CGBN85 meets the requirements of modern earth science. The author discusses briefly in this paper the key problems arised during the establishment of CGBN85, the characters of LCR-G meters, and the adjustment of large scale gravity net etc.

Introduction

The previous China Gravity Basic Net 1957(CGBN57) established in 1957 consisted of 22 basic gravity stations and 80 first-order ones, which were based on Potsdam system with its well known systematic error of about 13.5 mgal [10^{-5} ms^{-2}], and measured with the relative accuracy ±0.15 and ±0.25 mgal respectively. CGBN57 will obviousely never meet the requirements of geophysics, geology and geodesy.

Since 1981, organized by China National Bureau of Surveying and Mapping (CNBSM), 11 absolute gravity stations were determined and the high precise relative measurement campaigns with 9 LCR-G gravimeters were carried out through the cooperations with the organizations domestically and abroad. In order to put CGBN85 to be on a reliable base, an international relative connections was made with 6 LCR-G meters between CGBN85 and several existed international gravity standards located in Paris, Hongkong, and Japan, where 23 gravity values are available and reliable. All those works mentioned above formed the basic structure and its external checking conditions of CGBN85. Besides, all the stations were linked to the national levelling net by third or fourth order of levelling surveying for the altitudes.

I. Field Observation Campaigns

1.1 Absolute determinations and the gravimetric standard

A modern gravimetric standard should have two basic elements: starting point and scale. It, hence, consists of at least two reliable absolute gravity stations. One who plans the distribution of absolute stations and the structure of relative gravity net including its mathematic model of adjustment should take the defination of the gravimetric standard in mind. From 1981 to 1983, 11 absolute gravity stations were determined by using the apparatuses of Torino Metrological Institute (IMGC) from Italy and of China Metrological Institute (CMI). In the other side, as what mentioned above, CGBN85 has been connected with several well known international standards: Paris Severs A3, IGSN71 and Japan national gravity standard (Fig. 1, Table 1). It is obvious that, after the whole adjustment which is based on the known gravity values given jointly by what listed above, the base of CGBN85 is expected to be reliable (Table 2).

1.2 Relative gravity measurements and data pre-processing

An optimal design was made in 1982 by taking the accuracy and economical cost as a criterion function in order to scheme out the CGBN85 and the distribution of the known stations in it, taking into account of the flights of CAAC because the gravimeters were transported mainly by its air services. All the field campaigns were carried out in 1983 and 1984 including the international connections (Fig. 1 and Fig. 2).

Some experiments were made and a precise operating procedure was excecuted so as to eliminate the disturbances caused by the local magnetic field, atmospheric pressure, environmental temperature, battary voltage, vibration of transportations etc. It was found during the field campaigns that there exist probably some linear relation between the displacement sensitivity(S) and gravity(G) as $S_i-S_j=-0.00009(G_i-G_j)$, here i and j are two stations, G in mgal. This change of sensitivity introduces no damage to the observations while the zero reading method, which always keeps the beam level for each reading, is used.

Data pre-processing added to the field observations the corrections for instrument height, theoritical tidal with a factor of 1.16, reduction to standard atmospheric pressure and zero drift of gravimeter. Tare were rejected by judging the drift which should be less than 60 microgals in a loop within one day and by judging the rate of the drift over time difference obtained experiencely depending on what sort of vehicle was employed to transport the instruments. After careful studies of several models of the drift, an average linear model was applied for the corrections in each back and forth tie within one day, as:

$$di = K*dTi$$

$$K=\sum_{i=1}^{n} dZi / \sum_{i=1}^{n} dTi$$

here di is the drift correction, K the average drift rate, n the number of closed reading in an independent tie, dTi and dZi the differences of time and reading at number i closing.

II Adjustment

There were two key problems which should be carefully treated in the adjustment, first, an apt mathematical model with optimal parameters for discribing the scale functions of every LCR-G meter, and secondly, the choice and weighting of absolute or known gravity stations.

2.1 The scale function of LCR-G and its determination

It is well known by now that the milligal value table of gravimeter given by LCR-G manufacturer is not accurate enough for a precise gravimetric net. Generally speaking, the relationship between the milligal value and the reading of LCR-G meter can be described by a scale function as follows:

$$Gi = F(Ri) = Go+\sum_{k=1}^{Pk} Ek*Ri^{k} + \sum_{n=1}^{Pn}[Xn*\cos(Wn*Ri)+Yn*\sin(Wn*Ri)] \qquad (2-1)$$

here

Gi gravity value at station i

Go constant wating for fixing

Ri reading of LCR-G meter

Ek polynomial coefficent

k degree in the polynomial

Pk, Pn numbers of the polynomial and periodic terms

n sequential number of periodic terms

Xn = An*cos(Fn), Yn = An*sin(Fn)

An, Fn amplitude and phase of the periodic term number n

Wn frequency of the periodic term number n

The fixed periods which were introduced necessarily in CGBN85 are listed here in the counter's unit,

No 457 and before	1205.98	602.99	70.94	35.47
No 458 and after	220.00	110.00	73.33	36.67

F(Ri) is then the scale function. Actually, formula (2-1) is often given in the form of gravity difference to simplify some problems in data processing. From (2-1) we have at stations i and j

$$Gi - Gj = F(Ri)-F(Rj) = \sum_{k=1}^{Pk} Ek(zi^{k} - zj^{k}) + \sum_{n=1}^{Pn} \{Xn[\cos(Wn*zi)-\cos(Wn*zj)]+ +Yn[\sin(Wn*zi)-\sin(Wn*zj)]\} \quad (2-2)$$

The unknown parameters Ek, Xn, Yn in formula (2-2) can be determined accurately by several methods, such as direct calibration in laboratory conditions or on the very precise field gravity baselines comprising some absolute stations covering thousand mgals for determining mainly the polynomial and on the short baseline with the gravity point intervals dense enough to decide the periodic terms. Unfortunately, both of the direct methods were not available in China until 1986. The parameters of sacle function had to be, therefore, taken as the unknowns in the adjustments. In fact, it is also possible to determine them with a satisfied accuracy in a large scale of gravity net as CGBN85 because as many as 9 LCR-G meters were employed with their reading positions distributing wildly and densely on the counters of the meters (Fig. 2). All the unknowns for gravimeters were established very carefully by taking into account of the results of the residual analyses of adjustment, which demanded that there should be no systematic tendence after correction of scale function.

Further more, the formula can be given to correct the manufacture's milligal value table as soon as the parameters are determined. Let z and Z be the readings in milligal before and after the corrections, and let $Z_j=0$ in (2-2)

$$Zi = F(Zi)-F(0)=\sum_{k=1}^{Pk} Ek*zi^{k} + \sum_{n=1}^{Pn} \{Xn[\cos(Wn*zi)-1]+Yn*\sin(Wn*zi)\} \qquad (2-3)$$

By the law of error propagation, ignoring the relations among the parameters of Ek, Xn, Yn, one easily get the error for those corrections of reading(Z) and reading difference(dZi_j)

$$Mzi^2 = \sum_{k=1}^{Pk} Mek^2*zi^{2k} + \sum_{n=1}^{Pk} \{Mxn^2*[\cos(Wn*zi)-1]^2 + Myn^2*\sin(Wn*zi)^2\}$$

$$Mdzi_j^2 = \sum_{k=1}^{Pk} Mek^2(zi^k - z_j^k)^2 + \sum_{n=1}^{Pn} \{Mxn[\cos(Wn*zi)-\cos(Wn*zi)]^2 + \qquad (2-4)$$

$$+Myn^2[\sin(Wn*zi)-\sin(Wn*z_j)]^2\}$$

$$Man=\pm\{Xn^2*Mxn^2+Yn^2*Myn^2\}^{1/2}/An$$

$$Mfn=\pm\{Xn^2*Myn^2+Yn^2*Mxn^2\}^{1/2}/An^2 \qquad (2-5)$$

here Man, Mfn are the errors of the amplitude and phase. With the help of (2-4), we can take a look at how accurate the scale functions will be. As a matter of fact, when Z_j=3000 (average reading in China), the scale functions' errors are generally less than 10 microgal for a gravity difference of 1000 milligals(Fig. 6).

2.2 The choice of absolute and known gravity values and adjustment computation

The known gravity values given by absolute determination and the international standards available were considered as the directed observations and were weighted in the adjustment. The choices and weights of them were depended on their accuracies and distributions in CGBN85. Let relative observation equation have the unit weight, the ratio of prior weight is about Pr:Pk:Pa = 1:2:4. Pr, Pk, Pa are the weights for the relative, known and absolute observation equations respectively. This ratio was adjusted according to the results of repeated tests of adjustment. Finally 11 knwons were chosen from 34 of them and were weighted (Fig. 1). The observation equations are as follows:

for the absolute: $V1=G-Ga$, Pa (2-6)

for the known standards: $V2=G-Gk+k$, Pk (2-7)

here V residual of adjustment, G unknown gravity value, Ga,Gk gravity observations, k systematic deviation of Gk to absolute system (determined directly by the absolute apparatus).

For the relative gravity observation equation, from formula (2-2)

$$V3=G_j-G_i+[F(z_i)-F(z_j)] \qquad Pr=1 \qquad (2\text{-}8)$$

with the simultaneous equations of (2-6),(2-7),(2-8), the least square parameter adjustment method was applied, totaly 867 relative observations and 11 weighted knowns, taking the 57 unknown station gravity values in China and 23 ones abroad, including 56 unknown parameters of the 9 LCR-G meters' scale functions for the final adjustment computation.

It is important to select the parameters of scale function for each gravimeter. We had to make a good compromise for the following factors: the residuals of adjustment, apposite distribution of the knowns and the positions of the readings on the meters' counters, [PVV] and the errors of the unknowns, while keeping the number of the unknowns as less as possible. The introduction of the high power terms of the polynomial in scale function should be very carefully when the changes of known gravities do not cover as large as the changes of the unknown ones because of the unstability of the high power terms in this case. Another reason is that the error of scale function increases quickly as the high powers of the readings are employed(Fig. 6).

Numbers of ways of adjustments, formed by the conbinations of weightings and selecting the parameters in scale functions etc., were tried. It is not possible to list all of them. We point out here only that: a) the adjustment might have a loss of 30% accuracy if the scale functions had not been considered. b) the difference between the gravity values at Sevres A3 given by the absolute determinations and by the adjustment is only 15 microgal when A3 was taken as an unknown station, that is, in the northen part of CGBN85 from Beijing to the northest station, there was about 800 milligal free of known stations, which shows that the external checking is perfectly consistence.

III Some Remarks and Conclusions

3.1 The real accuracy of CGBN85 given by the comparations with the existing known standards

From table 1, the most of the differences of the gravity values between the adjustment and the knowns are less than 20 microgal, with the average of -7 microgal and the mean square root of ±22 microgal; and from table 2, it is easily to find out, by paying attention at the differences between CGBN85 and each known standard no matter the latter took part in the adjustment or not, that all the discrepences are completely within the accuarcy estimated. The CMI apparatus has a deviation only -4 microgal with the light weight ratio of 3%; Only -9 microgal discrepence with IGSN71 which were nought weighted; A little bigger of -15 microgal for the standard given by Nagakawa [2]. In conclusion, CGBN85 is well consistent with the existing international systems.

3.2 By using a linear transformation at dozen of coincided or linked stations, 13.53 mgal in systematical difference and 0.0002 in scale are found between the former CGBN57 and CGBN85.

3.3 Altogether 5 absolute determinations from the 11 ones were rejected because of their rather big corrections. The reasons of that perhaps by the ideas of author are: a) the long period change of the earth gravity field and the regional change caused by the weathers' conditions, such as the variation of the level of underground water, both of them can be as big as the order of tens of microgal; b) the absolute gravity determination are damaged sometime by environmental conditions which might introduce a dangerous disturbance without being discovered by the determiners.

Finally, we would like to express our gratitude and appreciation to all the organizations and personnel in China and abroad who help establish CGBN85 through their close cooperations.

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TABLE 1.

DIFFERENCES BETWEEN VALUES
OF KNOWN AND ADJUSTMENT

unit in mgal

City	Go	Mo	P	Go-G	M	Go from *
Beijing	980119.646	±0.010	5.0	0.003	±0.005	(1)
Qingdao	979802.584	0.010	3.0	-0.019	0.007	(1)
Shanghai	979395.979	0.010	0.0	-0.071	0.007	(1)
Zhengzhou	979630.051	0.010	0.0	0.076	0.008	(1)
"	979630.148		0.0	-0.021	0.008	(2) **
Xi'an	979466.925	0.010	0.0	0.124	0.007	(1)
Wuchang	979348.797	0.011	0.0	0.088	0.007	(1)
"	979348.858		0.0	0.027	0.007	(2) **
Nanning	978750.244	0.010	3.0	0.026	0.006	(1)
"	978750.276		0.0	-0.006	0.006	(2) **
Changsha	979133.549	0.010	0.0	-0.068	0.007	(1)
Guangzhou	978815.719	0.010	4.0	0.000	0.005	(1)
"	978815.657		0.0	0.062	0.005	(2) **
Fuzhou	979000.999	0.011	3.0	0.023	0.006	(1)
Kunming	978347.798	0.017	2.0	-0.024	0.008	(1)A, (2)
"	978347.979	0.012	0.0	-0.201	0.008	(1) group B
"	978347.738	0.020	0.0	0.040	0.008	(1) group A
"	978347.858	0.013	0.0	-0.084	0.008	(2)
Tokyo NARTA	979857.332		2.0	-0.010	0.005	(6)
Tokyo B	979788.783		2.0	-0.029	0.005	(6)
"	979788.719		0.0	0.035	0.005	(5)
Tokyo C	979763.210		0.0	-0.039	0.007	(6)
"	979763.189		0.0	-0.018	0.007	(5)
Tsukuba	979951.237		0.0	0.027	0.007	(4)
Mizusawa A	980147.925		0.0	-0.005	0.011	(6)
Mizusawa B	980146.376		0.0	-0.024	0.011	(6)
Mizusawa C	980146.466		0.0	-0.015	0.011	(6)
Kyoto C	979707.732		0.0	-0.003	0.007	(6)
"	979707.750		0.0	-0.021	0.007	(5)
Kyoto A	979707.228		2.0	-0.001	0.007	(6)
"	979707.270		0.0	-0.043	0.007	(5)
Kyoto J 7900	979708.143		0.0	-0.007	0.008	(6)
Paris R	980915.490		0.0	0.015	0.008	(5)
Paris S	980917.930		0.0	-0.014	0.008	(5)
Sevres A3	980925.913		5.0	0.008	0.006	(3) ***
HongKong J7904	978757.436		0.0	0.011	0.007	(6)
Hongkong J7903	978761.160		0.0	-0.008	0.008	(6)
Hongkong J7902	978754.464		2.0	-0.010	0.006	(6)
Hongkong B	978755.882		0.0	-0.026	0.008	(6)
"	978755.871		0.0	-0.015	0.008	(5)

* Refer to second column in table 2.

** Go - the known gravity value, but Go from (2) were the result of experiment, determined in 1983 with the apparatus of model NIM-I, final result will be determined with a new model which is now available.

*** Given by Boulanger [5]

Note: at Kunming on the same site in a cave where the condition was terrible, and between observation groups A and B, the apparatus was wholly re-adjusted.

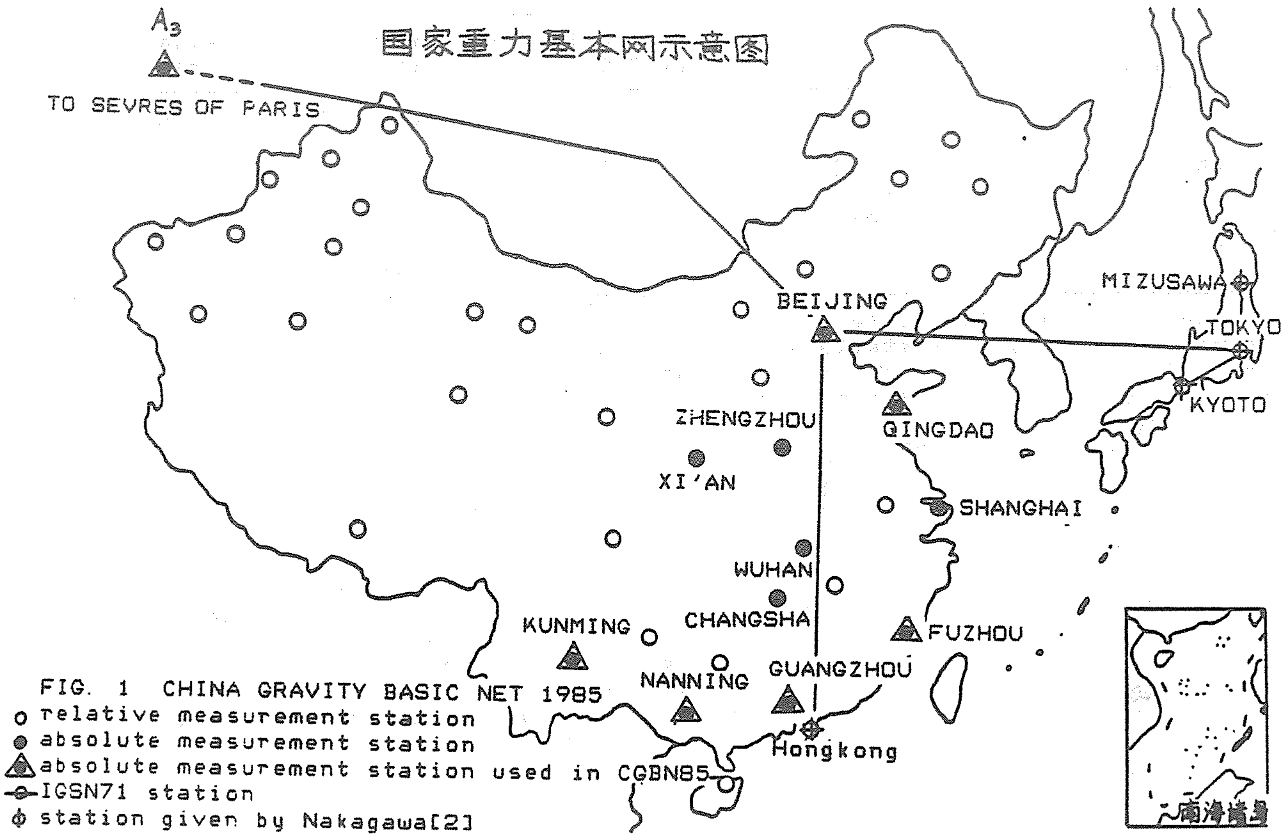


FIG. 1 CHINA GRAVITY BASIC NET 1985
o relative measurement station
● absolute measurement station
▲ absolute measurement station used in CGBN85
-⊖- IGSN71 station
ϕ station given by Nakagawa[2]

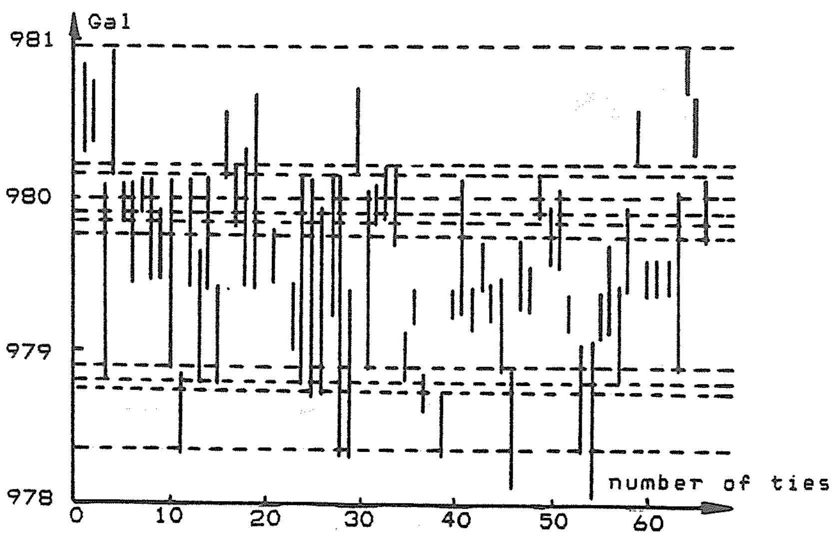


FIG. 2 SOME GRAVITY DIFFERENCES OCCUPIED BY CGBN85
solid line - coverage of a gravity difference
broken line - absolute gravity value

TABLE 2 COMPARISONS BETWEEN THE EXITED STANDARDS AND CGBN85

The existed Standards	No	Gravity diff. mgal	No of S.C.	No of S.A.	Mo ugal	Sume of Weight	Weight ratio	Average diff.
Abs. apparatus IMGC	(1)	1772	11	6	±11	19	0.58	+1.4
Abs. apparatus CMI	(2)	1282	5	1	14	1	0.03	-4.4
Abs. apparatus at sevres A3	(3)	0	1	1	3	5	0.15	+8.0
Abs. apparatus JGI *	(4)	0	1	0	20	0	0	-25.0
IGSN71	(5)	2163	7	0	<100	0	0	-8.7
Given by Nagakawa [2]	(6)	1395	13	4	<30	8	0.24	-15.1
						total: 33	average:	-7.3

*Japan Geographic Institute
No of S.C. - number of stations coinsided with CGBN85
No of S.A. - number of stations used as knowns in the adjustment of CGBN85
Mo - accuracy given by determiner

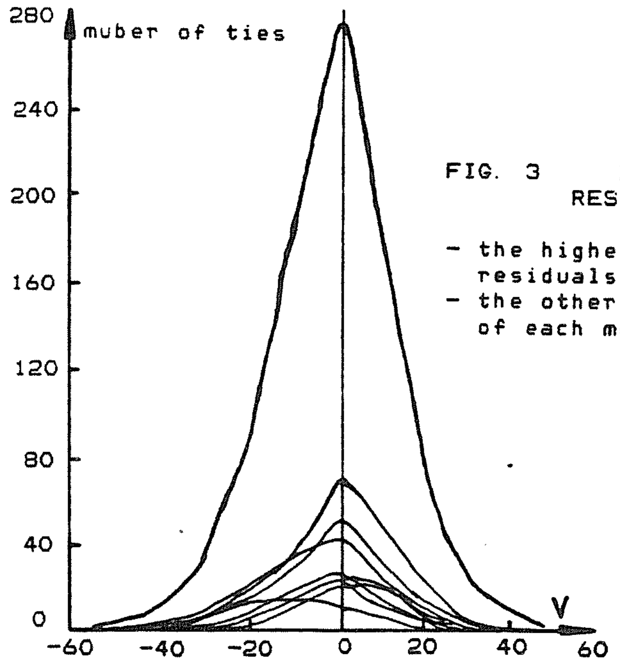


FIG. 3 DISTRIBUTION OF THE RESIDUALS IN THE ADJUSTMENT
unit in micgrogal
- the highest curve is the total residuals of the 9 meters
- the other curves are the residuals of each meter respectively

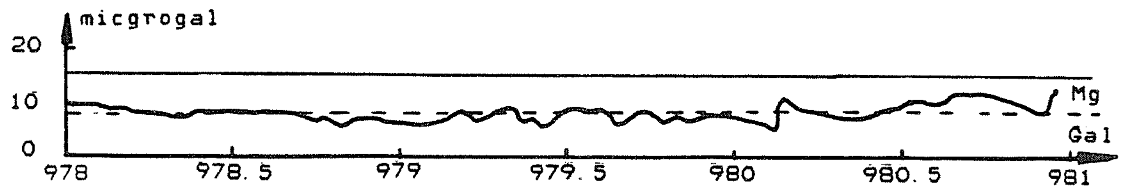


FIG. 4 MEAN SQUARE ERRORS DISTRIBUTED WITH GRAVITY VALUES
straight line - average of mean square error
broken line - unit weight mean square error
curved line - the mean square error(Mg)

TABLE 3

THE PARAMETERS

GIVEN BY THE ADJUSTMENT

unit in microgal

Ins.	No of ties	Sv	V_s	Linear coef. 10^{-6}	Quatratic coef. 10^{-10}	Periodic terms 1206/220 A	F	603/110 A	F	71/73 A	F	35/37 A	F
G 85	205	±13	127	-499±20	1818±32	15±2	-108±10	10±2	125±12	20±2	-29±5		
G147	38	10	-134	345±6		11±5	-81±19						
G570	50	13	21	453±6		8±4	-74±29						
G584	135	14	-320	385±5		8±3	-82±15	3±2	-139±52	4±2	53±29	11±2	152±10
G589	141	13	55	489±6		5±2	-43±28	3±2	163±47	9±2	95±15		
G596	48	15	-59	576±6									
G625	87	15	37	384±6		5±3	-108±34	3±3	66±55	7±3	-137±26	8±2	6±23
G676	83	16	-83	544±6		16±4	-122±15	8±3	-96±24	10±3	100±19		
G681	80	11	58	586±6		1±4	-46±43	9±3	84±24	9±3	138±21	7±2	-132±19

in the table, Sv - standard deviation of residuals for each gravimeter
V_s - Sume of residuals for each gravimeter
A, F - amplitude and phase(degree) of periodic term

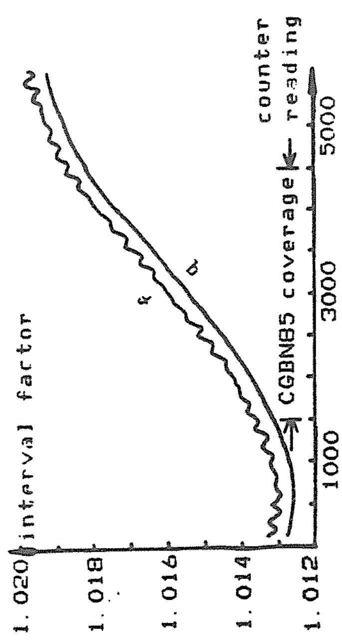
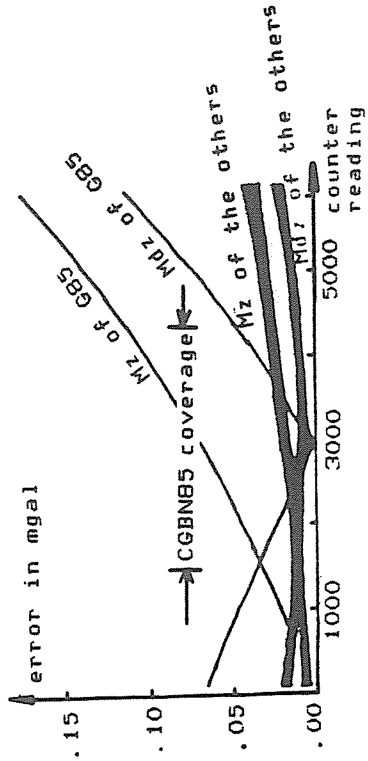


FIG. 5
q - interval factor of G-570 by LCR-G manufacture
f - interval factor after correction of scale function



Mz - error of corrected reading
Mdz - error of corrected reading difference with a reading fixing at 3000

FIG. 6
note: the error of G-85 is much bigger than the other 8 meters because of the error of the quatratic term in the polynomial of scale function, which increases quickly wiht the readings

ON CHINA GRAVIMETRIC STANDARD

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Abstract

Since a new China Gravity Basic Net1985(CGBN85) has been established in 1985, with an accuracy of ±0.02mGal, China gravimetric standard has, in its development, two stages for last 30 years, the previous one was established in 1957 (CGBN57). there are, therefor, several problems faced: how to estimate the error in the previous standard and to transform it into the new one; how to utilize CGBN85 as a gravimetric standard, for example, to control a new China Gravity First-order Net(CGFN) ect. General principles are discussed breafly in view of the author in this paper. After careful studies, it is found that there exsisted in CGBN57 not only the well known basic error because of Postdam system but also a scale error of about 0.02% in gravity differences. A combined adjustment is suggested in order to uniformise CGBN85 and the new CGFN etc.

I. Historical development and present state of gravimetric standard in China

Modern gravimetric standard supplys the starting gravity value and the gravimetric scale to a country, which consists of a system of at least two gravity stations and is usually as a national gravity basic net. Since the begining of this centry, two international gravimetric standards have been adopted: the Postdam system in 1909 previously and the International Gravity Standardization Network 1971 at present. The first China Gravity Basic Net1957 (CGBN57) was established in 1957. It consisted of 22 basic stations on the base of Postdam system with relative measurement accuracy of ±0.15 mGal [10^{-5} ms^{-2}][1]. Based on it, China Gravity First-order Net1957(CGFN57) was there and several hundred thousand gravimetric points of various order were determined. From 1981 to 1985, headed by China National Bureau of Surveying and Mapping, the new China Gravity Basic Net1985(CGBN85) was establised. CGBN85 consists of 57 basic stations (including 6 absolute gravity stations), 9 LaCoste & Romberg gravimeters(LCR-G) were used and altogether 23 international known gravity stations were connected through 4 routs; its standard is then defined by the absolute gravity determinations[2] and also the international known values. Parameter adjustment method was applied, taking into account of scale functions for the LCR-G. Observational equations for the absolute, known gravity values and relative measurements were as follows[3]:

$$\left.\begin{aligned}
&Pa, \quad V1 = G-Ga \\
&Pk, \quad V2 = G-Gk+k \\
&Pr=1, \quad V3=Gj-Gi+\sum_{k=1}^{Pk} Ek(zi^{k}-zj^{k})+\sum_{n=1}^{Pn}\{Xn[\cos(Wn*zi)-\cos(Wn*zj)]+ \\
&\qquad\qquad +Yn[\sin(Wn*zi)-\sin(Wn*zj)]\} \\
&An = (Xn^{2}+Yn^{2})^{1/2}, \qquad \tan(Fn) = Yn/Xn
\end{aligned}\right\} \quad (1)$$

here, the significances of the terms are the same with those in reference [3]. The scale function of LCR-G given by the adjustment can be applied to correct the manufacture's milligal value table with a formula as:

$$Zi = \sum_{k=1}^{Pk} Ek*zi^{k} + \sum_{n=1}^{Pn}\{Xn[\cos(Wn*zi)-1]+Yn*\sin(Wn*zi)\} \quad (2)$$

$$Mzi^{2} = \sum_{k=1}^{Pk} Mek^{2}*zi^{2k} + \sum_{n=1}^{Pn}\{Mxn^{2}*[\cos(Wn*zi)-1]^{2}+Myn^{2}*\sin(Wn*zi)^{2}\} \quad (3)$$

here, Z, Mz are the reading corrected and its error, which is in the same scale with CGBN85. Accuracy analyces[3] show that the error of relative gravity differences measured by LCR-G is within ±0.015mGal, the error of scale function of LCR-G for a gravity difference of 1000mGal is usually within ±0.01mGal; the error of gravity values of CGBN85 is ±0.02mGal and CGBN85 is adopted as the China national gravity standard in the end of 1985.

II. Accidental and systematical error in CGBN57 and its standard transformation

CGBN85, with its reliable and precise standard, can be applied to analyse the errors in CGBN57 and to transform the latter to the new standard: firstly, by using the 18 gravity values of the coinsidend stations in the two systems, a re-adjustment is carred out with all the same observations of the previous CGBN57; secondly, special studies are made in the both sorts of data: the relative data for finding the accidental and systematic error of instruments used, and then the gravity values given by the two adjustments in order to find the basic error, meanwhile to set up a model of standard transformation. Again, the parameter adjustment method is used in the re-adjustment computation, relative observational equation is in the form as:

$$P_{ij}, \quad V_{ij} = G_j - G_i + E_l * dZ_{ij} \qquad (4)$$

here, dZ is average of observations by 9 ГАЭ-3 gravimeters, E_l is an average instruments' linear scale factor, l is sequencial number of groups of E. Study shows individual scale calibrations were performed for every duration of field measurement campaign and the scales could be divided into two groups which differed from each other obviously. The result after careful analyse is that the accidental error in relative measurement for a back and forth tie of the average of 9 ГАЭ-3 gravimeters was ±0.04 - 0.06mGal, and exsisted there also the average scale error of gravimeters about $1.6*10^{-4}$

It is well known that there is a basic error of about 13.5 mGal in Postdam system. Let G57, G85 are respectively the gravity vaules given by the original adjustment and the re-adjustment, then the difference D between them is in a tendence with the change of gravity as in Fig. 1. Obviously, D=G85-G57 goes up with the increase of gravity and the largest difference is up to 0.8mGal, more over than the error of measurement.

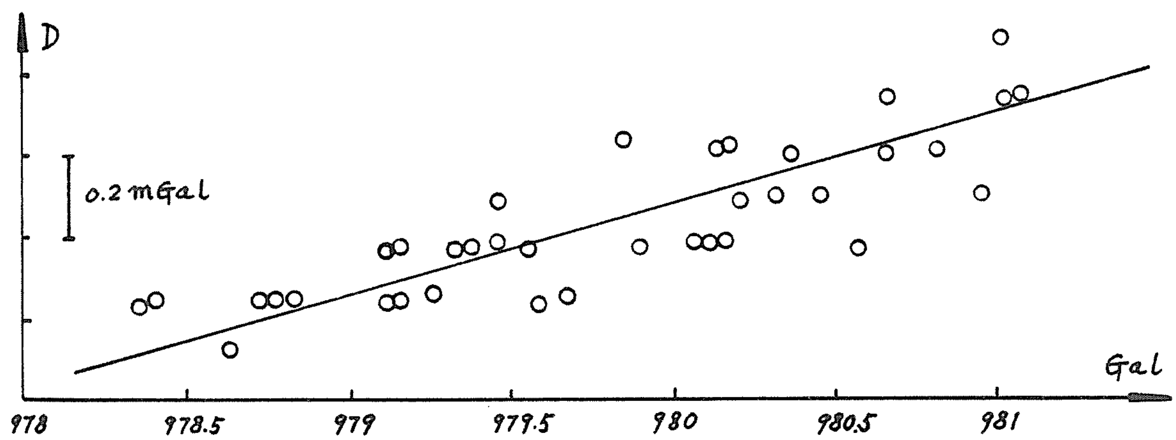

FIG. 1 Differences between CGBN85 and CGBN57

It is possible to divide D into three parts, Do the basic error, Dk the scale error in gravity, and Dq an unlinear term relating to position of gravity station, which can be discribled as the foulling formula:

$$G85 = G57+D = G57+Do+Dk+Dq$$

$$= G57+Do+\sum_{u=1}^{Pu} Ku*(G57-Go)^{u} + \sum_{\substack{i=1\\j=1}}^{n,m} Qij*dB^{i}*dL^{j} \qquad (5)$$

$$dB = B-Bo, \quad dL = L-Lo$$

here, L, B are the longitude and latitude of station, Go is a constant waiting for determining, Lo,Bo longitude and latitude of central station. this formula can be considered as the approching relation between the previous and the present gravity standards, with the practical formula as:

$$G85 = G57+A*H \qquad (6)$$

$$A = (1, G57-Go, C)$$

$$C = (dB, dL, dB*dL, dB^2*dL, dB^3, dL^3)$$

$$H = \begin{bmatrix} Do \\ \hline K \\ \hline \\ \\ G \\ \\ \\ \\ \end{bmatrix} = \begin{bmatrix} -13.56 \\ \hline 0.000189 \\ \hline -0.006502 \\ 0.005374 \\ 0.001441 \\ -0.00008039 \\ 0.00001801 \\ -0.00001521 \end{bmatrix}$$

Dk changes between ±0.4mGal, Dq between ±0.17mGal. The error of formula (6) is about ±0.04mGal. That means, the computation of system transformation for the gravity vaule with the accuracy lower than CGBN57 can ignore the unlinear term Dq and the error is about ±0.1 mGal in that case.

III. Precise additional absolute and relative gravity measurements and their standard

Precise additional measurements here mean: on the base of CGBN85, the new CGFN, national gravity baselines and various local gravimetric controlling nets etc. which are determined with an accuracy about or even higher than that of CGBN85, and are called afterwards attaching net for an abbreviation. It is no daubt that the classical adjustment with fixing condition is never right for processing of an attaching net. A reasonable method should be an adjustment based on CGBN85 and meanwhile avoid or weaken the error influence of it. With the help of theory of modern co-relating adjustment in groups, the adjustment of CGBN85 can be considered as the " first group adjustment ", and then by taking into account of the result of " first group ", the second group, that is, the attaching net, can be adjusted. Let the result of second group is dX2, then X = Xo+dX1+dX2 = X1+dX2. It can be proven[4] that this result is equivelance to the combined adjustment of CGBN85 and the attaching net as a whole. Let L1,L2 are the observations of CGBN85 and the attaching net respectively, the observation equations are:

$$P1, \quad V1=a*dXa+b1*dXb \quad +l1 \qquad (7)a$$

$$P2, \quad V2= \quad b2*dXb+c*dXc+l2 \qquad (7)b$$

$$l1=a*\overset{o}{Xa} + b1*\overset{o}{Xb} + d1 - L1$$

$$l2=b2*\overset{o}{Xb} + c*\overset{o}{Xc} + d2 - L2$$

here, dXb is common unknown of the two nets, dXa,dXc are non-common ones, and all the characters in (7) are the matrix of concerning values with the meanings well known as the applications in the text book as [4]. Let dXb1,dXb2 are the common unknowns in first and second groups, then dXb= dXb1+dXb2. In accordence with the theory of generalized least square method[4], the normal equation, solution and accuracy can be derived as following:

$$\left.\begin{array}{l}
\begin{bmatrix} \hat{P2} & b2^T*P2*c \\ c^T*P2*b2 & c^T*P2*c \end{bmatrix} \begin{bmatrix} dXb2 \\ dXc \end{bmatrix} + \begin{bmatrix} b2^T*P2*\hat{l2} \\ c^T*P2*\hat{l2} \end{bmatrix} = 0 \\
dXb2 = -\hat{P2}^{-1}*b2^T*P2*(c*dXc+\hat{l2}) \\
dXc = (Kcb*b2^T+Kcc*c^T)*P2*\hat{l2} \\
Kcc = [c^T*P2*c-c^T*P2*b2*\hat{P2}^{-1}*b2^T*P2*c]^{-1} \\
Kcb = -Kcc*c^T*P2*b2*\hat{P2}^{-1}
\end{array}\right\} \quad (8)$$

$$\hat{P2} = Pxb1 + b2^{T} * P2 * b2 \qquad \hat{l2} = l2 + b2 * dXb1$$

$$Uo = [(V1^{T} * P1 * V1 + V2^{T} * P2 * V2 + dX2^{T} * Px1 * dX2)/r]^{1/2}$$

$$Mxi = Uo * (Qxi)^{1/2}$$

here, Pxb1 is the prior weight of dXb1, Uo is the unit m.s.r.e., r is freedom degree, Mx, Qx are m.s.r.e and inverse of weight matrix of the unknowns.

The field work of the new CGFN will be completed in 1988. However, let Uo=±0.02mGal, it is possible to give the expected accuracy of it, with the method mentioned above, by considering the designed confrigura- tion of the CGFN. And the result of computation shows that the average error in gravity value of CGFN is expected to be 20-30% lower than CGBN85, while the present accuracy of CGBN85 will be then about 10% higher.

For conclution: as the standards of China gravimetry, the CGBN85 has an accuracy of ±0.02mGal; CGBN57 has a basic error of about 13.56 mGal and a scale error of 0.0002 in gravity value; it is expected to transform CGBN57 into CGBN85 with an accuracy of ±0.05mGal; the average accuracy of the new CGFN is expected about ±0.03mGal.

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