ASSOCIATION INTERNATIONALE DE GÉODÉSIE

BUREAU GRAVIMETRIQUE INTERNATIONAL

BULLETIN D'INFORMATION

N° 59

Décembre 1986

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. The abstract of a paper should be informative rather than descriptive. It is not a table of contents. The abstract 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. Long papers may include a table of contents following the abstract.

Footnotes. Because footnotes 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 $\bar{x}$,', and $\hat{}$) 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 and superscripts should be clearly noted and easily distinguished. Unusual symbols should be avoided.

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

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 whether 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. 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.

Address :

BUREAU GRAVIMETRIQUE INTERNATIONAL

18, Avenue Edouard Belin

31055 TOULOUSE CEDEX

FRANCE

Phone :

61.27.44.27
61.27.40.72

Telex :

CNEST B 531081 F

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Toulouse

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PART I

INTERNAL MATTERS

We have the unfortunate duty to announce the death of our colleagues Michel Ogier, on August 17, 1986, after a long illness.

Michel Ogier had been working for BRGM since 1970 and in BGI staff since 1980.

Session n° 6 of the 12th IGC meeting held last September in Toulouse was dedicated to him. A summary of his career is given down below the first paper of this session.

French National Colloquium

dedicated to Michel Ogier

RECENT DEVELOPMENTS IN GRAVITY SURVEYING

Date : May 12-13, 1987

Location : BRGM, Orleans

Topics : invited papers on the following items :

- metrology and data bases
- interpretation : new inversion methods
- satellite gravity

Organizing committee :

. J. Goguel,	honorary president
. P. Louis,	president
. G. Balmino,	
. R. Millon,	
. C. Weber,	executive secretary

Expected sponsorship :

- IAG (IUGG, French National Committee)
- "ECORS" program
- "GPF" program

GENERAL INFORMATIONS

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 (59 have been issued as of Jan. 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 :

- *55 French Francs without map,*
- *65 French Francs with map.*

2. HOW TO REQUEST DATA

2.1. Station Descriptions 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.

As of January 1, 1987, the following procedure will be applied :

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

(b) Requests for the full altimeter measurement records will be 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 in view of the categories of users - mostly contributors of measurements and scientists, and also considering the large amount of support of our host organizations.

For these users and untill 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 data contributors, individuals working in universities, such as students, and generally to any person who can contribute to our activities on a data or documentation exchange basis.

The prices given below are in french francs. They are effective January 1, 1987 and will be revised periodically.

3.1. 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.

3.2. 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.

3.3. 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.

3.4. 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°.

3.5. 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°.

3.6. Computation of Mean Gravity Anomalies

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

. minimum charge : 150 F

. maximum area : 40° x 40°.

3.7. Gravity Maps

3.7.1. Catalogue of all gravity maps :

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

3.7.2. 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)

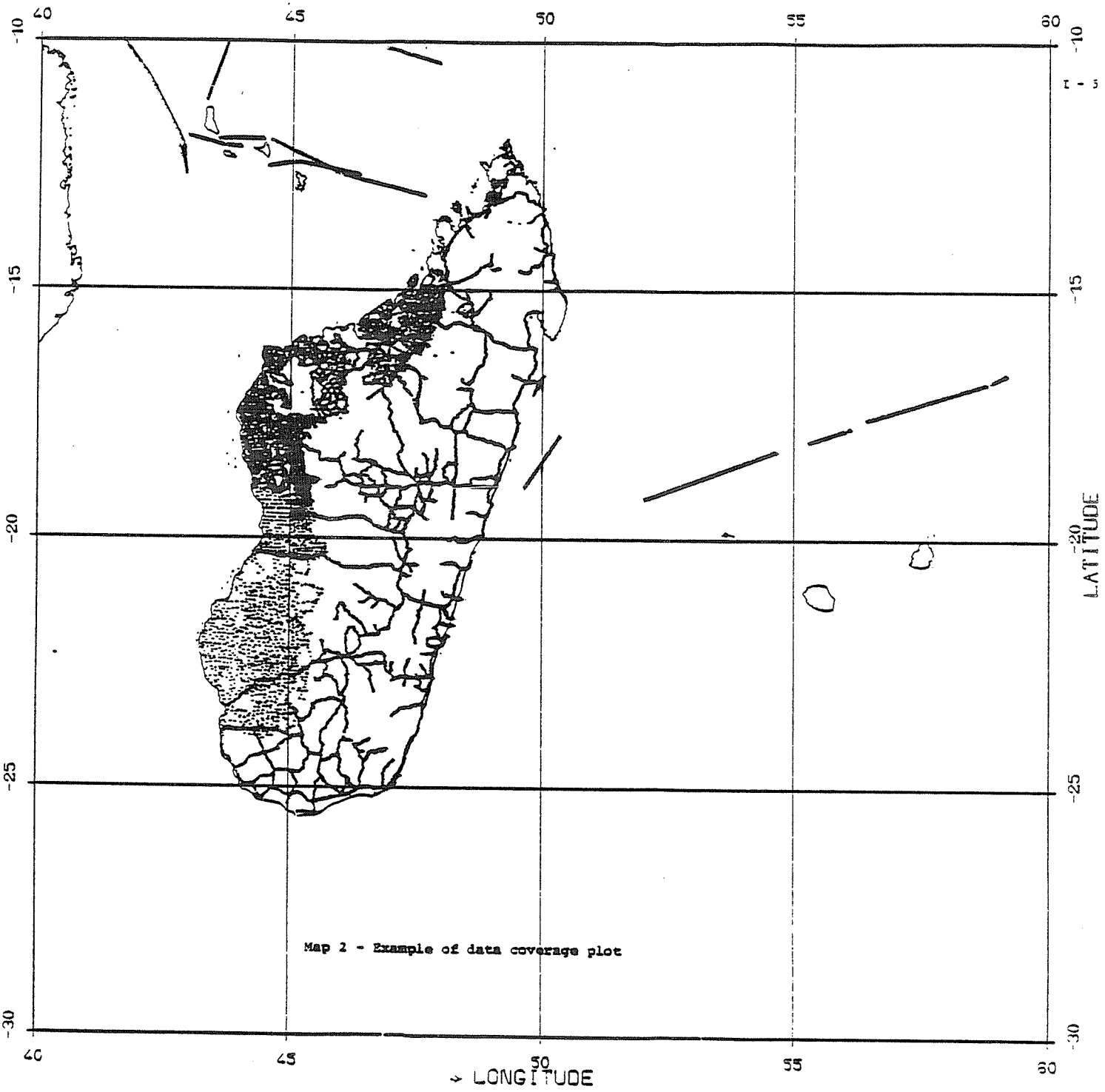
CRUISES prior to	1970	65 French Francs
CRUISES	1970-1975	65 French Francs
CRUISES	1975-1977	65 French Francs

Miscellaneous

CATALOGUE OF ALL GRAVITY MAPS (listing)	1985	200 French Francs
THE UNIFICATION OF THE GRAVITY NETS OF AFRICA (t. 182)	1979	150 French Francs

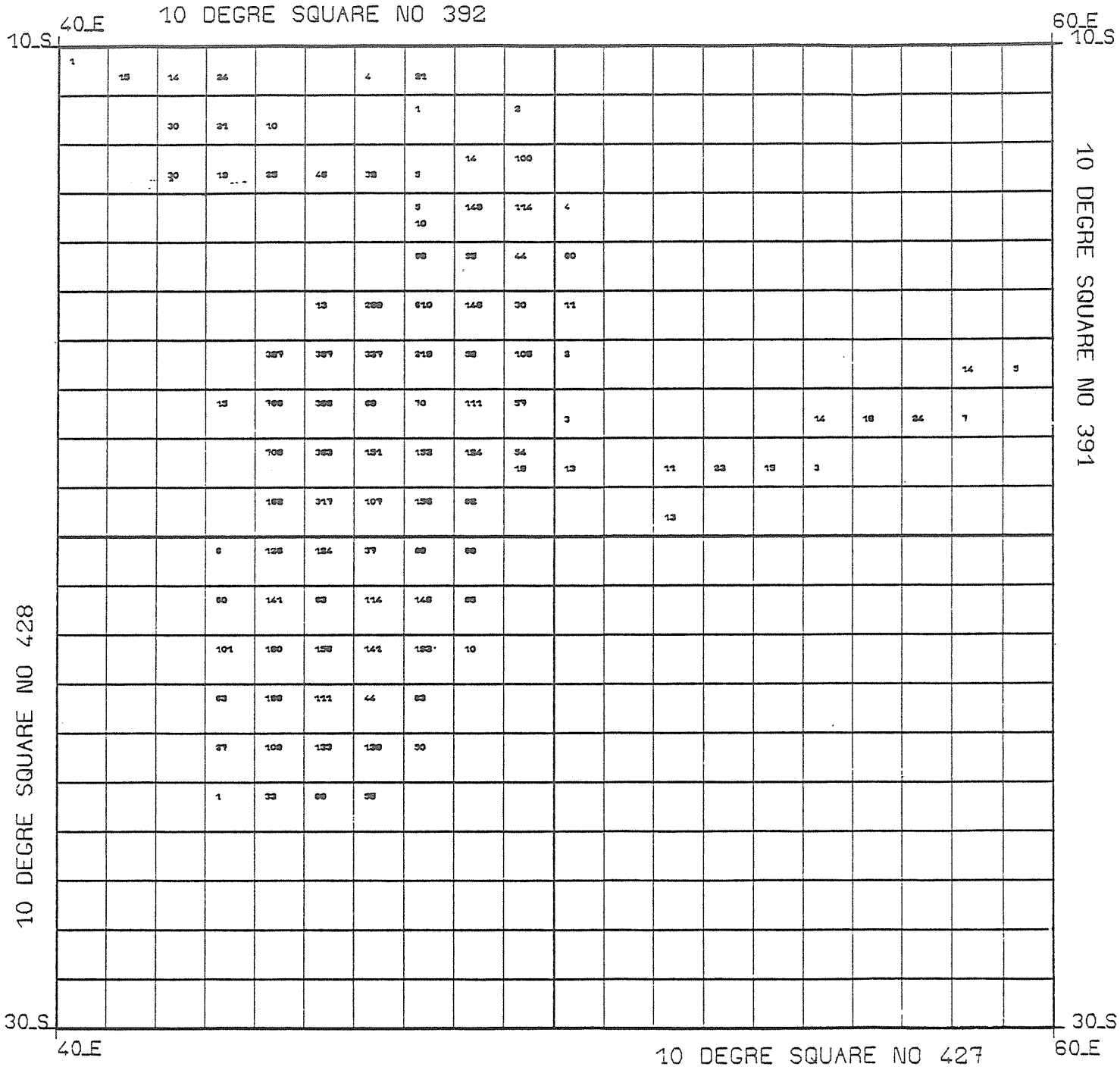
- *Black and white copy of maps : 100 F per copy*
- *Colour copy : price according to specifications of request.*

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



Map 2 - Example of data coverage plot

REPRESENTATION OF EARTH AND SEA GRAVIMETRIC STATIONS



Map 3 - Example of detailed index
(Data coverage corresponding to Map 2)

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

THE 12TH MEETING OF THE

INTERNATIONAL GRAVITY COMMISSION

TOULOUSE 23-26 SEPT., 1986

12TH MEETING OF THE INTERNATIONAL GRAVITY COMMISSION

September 23-26, 1986

Toulouse - France

PROGRAM OF SESSIONS

TUESDAY SEPT. 23

a.m. Administrative Session (Chairman : C. Morelli)

9.30 Opening : Allocution of President of French National Committee of Geodesy and Geophysics
9.45 IGC President report
10.00 BGI report
10.15 WG 1 report
10.25 WG 2 report

10.35 Coffee Break

10.50 WG 3 report
11.00 WG 4 report
11.10 Sub-Commission 1 report : North Pacific Region
11.20 Sub-Commission 2 report : South West Pacific Region
11.30 Sub-Commission 3 report : North America
11.40 Sub-Commission 4 report : Central and South America
11.50 Sub-Commission 5 report : Africa
12.00 Sub-Commission 6 report : Western Europe
12.10 Sub-Commission 7 report : Eastern Europe and USSR
12.20 Sub-Commission 8 report : India and Arab Countries

- End of Administrative Session 12.30 -

Note : *The order of the Scientific Sessions below (and therefore their numbering) was changed to take account of the arrival and/or departure dates of some participants.*

TUESDAY SEPT. 23

p.m. Session 1 : DYNAMIC GRAVIMETRY (Chairman : J.M. Makris)

2.00-2.15 - **1.1. R.K. McConnell and J.M. Woodside**
Compilation of a Marine Gravity Data Base for the East Coast of Canada.

2.15-2.30 - **1.2. Li Xiqi, Liu Ruozang, Liang Chujian, Zhang Shanyan, Zhang Xianlin, Pan Xianzhang**
A New Sea-Air Gravimeter.

2.30-2.45 - **1.3. B.D. Loncarevic**
Four Years Experience with the KSS30 Seagravimeter.

2.45.3.00 - **1.4. J. Fritsch and K.H. Tödt**
Calibration of Seagravimeters KSS30 and KSS31 along the European Absolute Calibration Line.

3.00-3.15 - **1.5. G. Balmino, B. Moynot, M. Sarrailh, N. Valès**
Satellite Altimetry Derived Gravity Anomalies over the Oceans.

3.15-3.30 - **1.6. D.H. Eckhardt**
Status of the Gravity Gradiometer Survey Systems

3.30-3.45 - **1.7. G. Balmino, A. Bernard**
Status of the Satellite Gravity Gradiometer Project GRADIO.

End of Session 1

3.45-4.00 - Coffee-Break

Session 2 : ABSOLUTE COMPARISONS (Chairman : G. Balmino)

4.00-4.20 - **2.1. G. Arnautov, Y. Boulanger, L. Cannizzo, G. Cerutti, J. Faller, Feng Youg-Yuan, E. Groten, Guo Yuguang, W. Hollander, Huang Da-Lun, E. Kalish, I. Marson, T. Niebauer, A. Sakuma, R. Sands, G. Sasagawa, S. Schleglov, Y. Stus, W. Tarasiuk, Zhang Guang-Yuan, Zhou Juing-Hua, M. Zumberge**
Results of the Second International Comparison of Absolute Gravimeters in Sevres 1985.

4.20-4.45 - **Discussion : the Accuracy of Absolute Gravimeters**

4.45-5.00 - **2.2. W. Torge, R.H. Röder, H.G. Wenzel, J.E. Faller**
First Results with the Absolute Gravity Meter JILAG-3.

5.00-5.15 - **2.3. J.E. Faller, T.M. Niebauer**
Past and Future Comparisons : Some Thoughts.

End of Session 2

WEDNESDAY SEPT. 24

a.m. Session 3 : NETWORKS - ACTIVITIES, PROJECTS (Chairman : U. Uotila)

9.00- 9.15 - 3.1. **D. Adjakaye**
The AGSN Project - Problems ; Prospects.

9.15- 9.30 - 3.2. **I. Nakagawa, R. Shichi, S. Nakai, K. Nakamura, T. Higashi, Ruihao Li, Yihui Chen and Dongchu Wang**
International Gravimetric Connections between Japan and China.

9.30- 9.45 - 3.3. **Song Xingli, Hsu Houtze, Hou Shangwei**
On the Adjustment of National Gravity Fundamental Network in China.

9.45-10.00 - 3.4. **G. Boedecker, I. Marson, C. Poitevin, G. Strang Van Hees**
Status of the Unified European Gravity Network UEGN.

End of Session 3

Session 4 : INTERNATIONAL ABSOLUTE GRAVITY BASE NETWORK - S.S.G. 3.87 (Chairman : G. Boedecker)

10.00-10.20 - 4.1. **Xu Shan, Qiu Qixian, Jian Zhiheng, I. Marson, G. Cerutti, F. Alasia, S. Desogus**
Sino-Italian Joint Absolute Gravity Measurements in China.

10.20-10.40 - 4.2. **G. Boedecker**
Status of the International Absolute Gravity Base Station Network.

10.40-11.00 - Coffee-Break

11.00-11.30 - Discussion on IAGBN

End of Session 4

11.30-12.45 - Discussion on Structure and Activities of I.G.C.

WEDNESDAY SEPT. 24

p.m. Session 5 : DETERMINATION OF THE NEWTONIAN CONSTANT. RECENT DEVELOPMENTS (Chairman : J. Tanner)

2.15-2.35 - **5.1. C. Boucher**
Possible Variations of the Newtonian Constant. Determinations of GM.

2.35-2.55 - **5.2. J. Tuck**
Deviations from Newton's Inverse Square Law from Geophysical Observations.

End of Session 5

Session 6 : HIGH PRECISION GRAVITY TECHNIQUES - S.S.G. 3.85 (Chairman : E. Groten)

3.00-3.20 - **6.1. M. Ogier**†
Détermination statistique du gradient vertical de la pesanteur sur le pilier A3 de Sèvres.

3.20-3.35 - **6.2. R.H. Röder, H.G. Wenzel**
Relative Gravity Observations at BIPM, Sèvres in 1985 and 1986.

3.35-4.00 - Coffee-Break

4.00-4.15 - **6.3. A. Kiviniemi, J. Mäkinen**
Observations with a Fully Damped LCR G-gravimeter.

4.15-4.30 - **6.4. Zhou-Kungen, B. Ducarme, C. Poitevin**
Screw Error and Electrostatic Effect on Three LCR Gravimeters with Feedback System VRL 8350.

4.30-4.45 - **6.5. M. Becker, Bakkelid, E. Groten, A. Midsundstadt**
High Precision Gravity Measurements for the Detection of Crustal Deformation by Surface Loads.

4.40-5.00 - **6.6. B. Ducarme, V. Dehante**
Comparison between the Theoretical and Observed Tidal Gravimetric Factors.

End of Session 6

† Our french colleague Michel Ogier died on August 17 and this session was dedicated to him. A paper on some aspects of his work was presented by MM. Millon and Weber from BRGM.

THURSDAY SEPT. 25

a.m. Session 7 : GEOPHYSICAL INTERPRETATION (Chairman : E. Klingelé)

9.00-9.20 - 7.1. **M. Blizkovsky, J. Ibrmajer, S. Olejnik, J. Sefara**
Gravimetric Network and Characteristics of the Geological Structure of Czechoslovakia from Gravity Data.

9.20-9.40 - 7.2. **Jiang Fuzhen, Hsu Houtze**
Gravity Field of Xiang Plateau and its Recent Uplift.

9.40-10.00 - 7.3. **R.G. Hipkin**
Isostacy in Northern Britain

10.00-10.20 - 7.4. **R. Byamungu, P. Louis**
Interprétation de données gravimétriques aux Ruanda, Burundi et Zaire.

End of Session 7

10.30-10.50 - Coffee-Break

Session 8 : EUROPEAN GEOID - GEOID DETERMINATIONS (Chairman : G. Birardi)

10.50-11.20 - 8.1. **G. Birardi**
Present State of the European Geoid.

11.20-11.40 - 8.2. **R.G. Hipkin**
High Resolution Relative Geoid for Northern Britain.

11.40-12.00 - 8.3. **J. Rakotoary, G. Balmino**
First Computation of a Gravimetric Geoid over Madagascar.

End of Session 8

12.00-12.45 - **Presentation of Resolutions (Chairman : J. Tanner)**

THURSDAY SEPT. 25

p.m. Session 9 : SECULAR CHANGES OF GRAVITY - S.S.G. 3.86
(Chairman : Yu. Boulanger)

2.00-2.20 - **9.1. J.E. Faller, T.M. Niebauer**
Status of and Progress Report on the New JILA Absolute Gravimeter.

2.20-2.40 - **9.2. R.H. Röder, W. Torge**
Improved Relative Gravimetric Techniques for Detecting Recent Crustal Movements in Northern Iceland.

2.40-3.00 - **9.3. M. Satomura, I. Nakagawa, H. Tsukamoto, T. Higashi, Y. Fukuda and K. Nakamura**
Secular Changes of Gravity Observed in Kinki District, Japan.

3.00-3.20 - **9.4. F. De Meyer, B. Ducarme**
Long Term Periodical Gravity Changes Observed with a Superconducting Gravimeter.

3.20-3.40 - **9.5. E. Lagios, R.G. Hipkin**
Gravity Changes 1981-6 over the Atalanti Fault System, Greece.

End of Session 9

3.40-4.00 - Coffee-Break

Session 10 : DISCUSSION OF RESOLUTIONS (Chairman : C. Morelli)

4.00-5.00 - **Discussion led by the Resolution Committee**

End of Session 10

FRIDAY SEPT. 26

a.m. Session 11 : LOCAL GRAVITY FIELD DETERMINATION - S.S.G. 3.90
(Chairman : C.C. Tscherning)

9.30-10.00 - 11.1. C.L. Merry
Interpolation of Gravity Anomalies in Southern Africa.

10.00-10.30 - 11.2. D. Arabelos and C.C. Tscherning
Computation of the Gravity Vector from Torsion Balance Data in Southern Ohio Using Collocation.

End of Session 11

10.30-10.45 - Coffee-Break

CLOSING SESSION (Chairman : J. Tanner)

10.45-11.30 - *Proposals and Resolutions*

11.30-11.45 - *Various Items*

11.45-12.15 - *Program of the Next Quadriennal*

End of 12th IGC Meeting

LIST OF PARTICIPANTS

D.E. AJAKAIYE	University of JOS - Faculty of Natural Sciences JOS - NIGERIA
G. BALMINO	Bureau Gravimétrique International 18, Avenue Edouard Belin - 31055 TOULOUSE Cedex - FRANCE
R. BARAUD	Observatorio Nacional - CNPQ Rue General Bruce 586 - SAO CRISTOVAO - 20921 RIO DE JANEIRO - BRAZIL
M. BECKER	Institute of Physical Geodesy - Technical University Petersenstrasse 13 - D-6100 DARMSTADT - F.R.G.
G. BERRINO	Osservatorio Vesuviano ERCOLANO (NAPOLI) - ITALY
G. BIRARDI	University of Rome via Eudossiana, 18 - 00184 ROME - ITALY
G. BOEDECKER	Bavarian Academy of Sciences Marstallplatz 8 - D-8000 MUNCHEN 22 - F.R.G.
C. BOUCHER	Institut Géographique National 2, Avenue Pasteur - 94160 SAINT MANDE - FRANCE
Y.D. BOULANGER	Soviet Geophysical Committee - Institut of Physics of the Earth Molodezhnaya 3 - MOSCOW GSP 1 - U.S.S.R.
A. CERRATO	University of Buenos Aires - Faculty of Engineering Institut of Geodesy Av. Las Heras 2214 - Piso 3 - 1127 BUENOS AIRES - ARGENTINA
G. CERUTTI	Istituto di Metrologia "G. Colonnetti" Strada delle Cacce 73 - 10135 TORINO - ITALY
G. CORRADO	Dipartimento Di Geofisica e Vulcanologia - University of Napoli - L. go S. Marcellino, 10 - 80138 NAPOLI - ITALY
B. DUCARME	Observatoire Royal de Belgique Avenue Circulaire 3 1180 BRUXELLES - BELGIUM
H.M. DUFOUR	Institut Géographique National 2, Avenue Pasteur 94160 SAINT MANDE - FRANCE
D. ECKHARDT	Earth Sciences Division - Air Force Geophysics Laboratory Hanscom AFB - BEDFORD, M.A. 01731 - U.S.A.

J.E. FALLER	JILA - University of Colorado Campus Box 440 - BOULDER, Co. 80309-0440 - U.S.A.
M. FOURGASTIE	EPSHOM - 13, Rue du Chatellier - B.P. 426 - 29275 BREST Cedex - FRANCE
J. FRITSCH	Bundesanstalt für Geowissenschaften und Röhstoffe Stilleweg 2 - D 3000 HANNOVER 51 - F.R.G.
M. GODIVIER	Office de Recherches Scientifiques et Techniques d'Outre Mer - 70, Route d'Aulnay - 93140 BONDY - FRANCE
B. GONZALEZ	Instituto Geografico Nacional - General Ibanez de Ibero, 3 28003 MADRID - SPAIN
E. GROTEN	Institute of Physical Geodesy Petersenstrasse 13 - D 6100 DARMSTADT - F.R.G.
M. GUTBERLET	Institut für Geodasie und Photogrammetrie Strasse des 17 Juni 135 - D-1000 BERLIN 12 - F.R.G.
L.A. HALLER	Lantmäteriverket S-80112 GAVLE - SWEDEN
R. HIPKIN	Edinburgh University - J.C.M.B. Mayfield Road - EDINBURGH EH9 3JZ - UNITED KINGDOM
H.T. HSU	Institute of Geodesy and Geophysics Chinese Academy of Sciences Xu Dong Lu - P.O. Box 27 - WUCHANG - HUBEI - CHINE
C. KAMELA	Organization for Surveying and Cartography GEOKART 2/4 Jasna Street - 00-950 WARZAW - POLAND
A. KIVINIEMI	Finnish Geodetic Institute Ilmalankatu 1A - 00240 HELSINKI - FINLAND
E. KLINGELE	Institut für Geodäsie - E.T.H.-Z E.T.H. Honggerberg - 8093 ZURICH - SWITZERLAND
D. LAMY	Bureau Gravimetrique International 18, Avenue E. Belin - 31055 TOULOUSE Cedex - FRANCE
N.A.G. LEPPARD	Directorate of Military Survey Elmwood Avenue, Feltham/MIDDLESEX TW13 7AE - UNITED KINGOM
J. LIARD	Geological Survey of Canada 1 Observatory Crescent - OTTAWA, K1A 0Y3 - CANADA
M.M. LISBOA	Instituto Geografico e Cadastral Praca da Estrela - 1200 LISBOA - PORTUGAL
P. LOUIS	Centre Géologique et Géophysique - U.S.T.L. Place Eugène Bataillon - 34060 MONTPELLIER CEDEX - FRANCE

R.K. McCONNELL	Geological Survey of Canada 1 Observatory Crescent - OTTAWA, K1A OY3 - CANADA
J. MAKRIS	Institut für Geophysik - Universität Hamburg Bundesstrasse 55 - 2000 HAMBURG 13 - F.R.G.
I. MARSON	University of Trieste - Ist. Geofisica Applicata Via A. Valerio 10 - 34137 TRIESTE - ITALY
C. MERRY	University of Cape Town - Dept. of Surveying RONDEBOSCH 7700 - SOUTH AFRICA
A. MIDSUNDSTADT	Norvegian Mapping Authority - Statens Kartverk 3500 HONEFOSS - NORWAY
M. MILLON	Bureau de Recherches Géologiques et Minières B.P. 6009 - 45060 ORLEANS CEDEX - FRANCE
C. MORELLI	Universita di Trieste - Ist. di Miniere et Geofisica Applicata P. le Europa 1 - 34123 TRIESTE - ITALY
I. NAKAGAWA	Geophysical Institute - Kyoto University Sakyo-ku - KYOTO 606 - JAPAN
T. NEIBAUER	JILA - University of Colorado Campus Box 440 - BOULDER, Co. 80309-0440 - U.S.A.
S. OLEJNIK	Institute of Geodesy and Cartography - Kostelni - 42 - PRAGUE - CZECOSLOVAKIA
R. PARRA	Instituto Geografico Nacional - General Ibanez de Ibero, 3 28003 MADRID - SPAIN
C. POITEVIN	Observatoire royal de Belgique - Avenue circulaire, 3 - B-1180 - BRUXELLES - BELGIQUE
R. H. RODER	Institut für Erdmessung - University of Hannover - Nienburger Str. 6 - D-3000 - HANNOVER - F.R.G.
D. RUESS	Bundesamt für - und Vermessungswesen - Schiffamtsgasse 1-3 - A-1025 - WIEN - AUSTRIA
M. SARRAILH	Bureau Gravimétrique International - 18, Avenue Edouard Belin - 31055 TOULOUSE Cedex - FRANCE
M. SATOMURA	Faculty of Liberal Arts - Shizuoka University - Ohya 836 - Shizuoka City 424 - JAPAN
G. STRANG.V.HEES	Geodetic Institute - Thijsseweg 11 - NL - 2629 JA - DELFT - NETHERLANDS
J.G. TANNER	Geological Survey of Canada - Room 223 - 601 Booth Street - OTTAWA - ONT.K1A OE8 - CANADA

J. TIPPING	Hydrographic Dept. - Ministry of Defense (Navy) - Taunton, Somerset - UNITED KINGDOM
K.H. TODT	Inst. of Geophysics - University of Hamburg Bundestrasse 55 - 2000 HAMBURG 13 - F.R.G.
W. TORGE	Institut für Erdmessung - Universitat Hannover - Nienburger Str. 6 -D-3000 HANNOVER 1 - F.R.G.
D. TOUSTOU	Bureau Gravimétrique International - 18, Avenue Edouard Belin - 31055 TOULOUSE Cedex - FRANCE
C.C. TSCHERNING	Geodaetist Institut - Gamlehave Alle 22- DK - 2920 - CHARLOTTEENLUND - DANEMARK
J. TUCK	Department of Physics - University of Quensland Brisbane QUENSLAND 4067 - AUSTRALIA
U.O. UOTILA	The Ohio State University - 1958 Neil Avenue Colombus - OHIO 43210 - USA
C. WEBER	Bureau de Recherches Géologiques et Minières B.P. 6009 - 45060 ORLEANS Cedex - FRANCE
H.G. WENZEL	Institut für Erdmessung - Universitat Hannover Nienburger Strasse 6 - D-3000 HANNOVER 1 - F.R.G.
I. WINDLE	University of Leeds - Dept. of Earth Sciences LEEDS - LS2 9JT - UNITED KINGDOM
J. WOODSIDE	Atlantic Geoscience Centre - P.O. BOX 1006 - DARTMOUTH - NOVA SCOTIA - CANADA B2Y4A2

MEETING OF

BGI DIRECTING BOARD

12th IGC, Toulouse, France

September 22, 1986

Present :	J.G. Tanner	(Chairman)		
	D.E. Ajakaiye		I.	Nakagawa
	G. Balmino		M.	Sarrailh
	J.E. Faller		C.C.	Tscherning
	H.T. Hsu		W.	Torge
	D. Lamy		D.	Toustou
	R.K. McConnell		U.	Uotila
	C. Merry		J.	Woodside
	C. Morelli			

1. Chairman's Opening Remarks

Tanner reported that the main project of the International Gravity Commission in recent years has been to support the work of the African Geodetic Commission and its Gravity Network Committee in the development of the African Gravity Standardization net. He summarized the results of the Cairo meeting held in the fall of 1984 and the Paris meeting of May, 1985 and noted that his report on the Commission's activities relating to the development of AGSN is available through the BGI.

2. Director's Report

Balmino presented a report on the activities of BGI over the period January, 1983 to September, 1986. There was a wide-ranging discussion of this report, the major points of which are summarized below :

Data Acquisition and Processing

Tanner expressed concern about the duplication of effort involved in the compilation of world-wide gravity data sets at several institutions around the world. He suggested that the Directing Board may have to make a major effort to elicit support for the BGI if it is to be recognized as a major force in gravity data acquisition, management and dissemination. Tscherning felt that more pressure should be exerted on contributors to provide data in BGI format but Balmino noted that BGI requests to 150 countries had yielded few contributions in <u>any</u> format. Tanner noted that the establishment of region Sub-Commissions had been an attempt to address this problem by funnelling information to the BGI but few of the sub-commissions had functioned effectively. Balmino pointed out that the BGI strategy had been to concentrate on data collection in one area at a time, Africa being the current priority. He noted, however, a major problem in establishing contacts in third world countries. Uotila suggested that

personal visits by BGI personnel would yield the greatest volume of data and that a more aggressive approach should be followed to obtain travel funds. Balmino noted that DMA has a contract to obtain gravity data in six or seven West African countries and that BGI will involved in the evaluation of these data. Morelli advised the Board that the University of Leeds is compiling a gravity map of Africa and that the BGI will receive a copy of the data. He expressed the view that the Working Group concept has been successful in world-wide data acquisition projects in the past (e.g. IGSN71) and should be exploited again to help the BGI gather data. Torge suggested that through more agressive marketing of its products and services, the BGI would likely encourage users to contribute data since they would perceive a longterm benefit for themselves.

Request Processing

Balmino presented statistics on requests processed. Tanner, Morelli and Tscherning described several complaints which they had received concerning response time and data quality. In responding, Balmino noted that complaints resulting from loss of material in the mail were unavoidable but agreed that the loss of their data base programmer has severely curtailed request processing activity during the past year. He noted that some of the complaints had not previously been brought to his attention. On the positive side, he reported that major users (e.g. Boulanger - compilation of maps for North Atlantic and Pacific ; Makris - compilation of 1/1.000.000 map of Mediterranean) were quite satisfied with BGI service. The DB recognized that there had been a deterioration in BGI service in recent months. It was agreed that :

a) DB members should bring user complaints promptly to the attention of the BGI Director.

b) BGI would follow up on requests to ensure that material had been received.

c) BGI would endeavour to fill all requests within one month.

d) BGI would give priority to request processing over all other activities.

Other

Tanner requested that Balmino look into the possibility of funding to bring experts to the BGI as a way to build up experise.

Tscherning stressed the necessity ot have quality estimates on data distributed by BGI so that the quality of products derived by BGI or users could be easily computed.

Balmino agreed to look into both of the above topics.

There was a discussion of the BGI project to digitize world-wide bathymetry from GEBCO charts. Some members of the board felt that this activity should have a much lower priority, or be deferred until the current gravity data base was restored to effective operation. The Board requested that W.G., examine the data base problem and make recommendations before the end of the week.

Publicizing BGI Products and Services

After a discussion on the need for wider advertisement of the BGI the Board decided that BGI should compile and distribute a three page brochure showing coverage of gravity anomaly and base station data held and providing ordering information for users. It was suggested that a version of this brochure be submitted to EOS. Faller and Torge were asked to confer with delegates and compile recommendations for submission to the Bureau.

3. Agreements of Assistance

Balmino reported that as of August, 1985 the informal data sharing agreement with DMA had been discontinued at their request.

An agreement has been reached to transfer marine gravity adjustment software from the Geological Survey of Canada. A two week orientation for BGI personnel scheduled for May, 1986 in Ottawa has been rescheduled to November, 1986 at the request of the GSC.

4. Role of the BGI

After a review of the activities and organization of BGI as laid out in the IAG Statutes, the Board agreed that the general objectives should remain unchanged but that priority should be given to acquisition and distribution of land and marine anomaly data and base station information.

The Board recommended that W.G.1 review the current data base structure and operation from the technical point of view and make recommendations to the Director.

With respect to distribution of software developed by BGI the Board recommended that BGI ask W.G. 1 to review potentially useful packages before releasing them to the user community.

5. Formation of a Geoid Commission

Tanner noted that this subject had been discussed one year ago by the IAG executive and that Special Study Groups from Section 3 and Section 4 had recommended the formation of a Geoid Commission at a meeting in Florence earlier this year. Members of the Directing Board were encouraged to pass comments directly to the Secretary of Section 3.

6. Reports of Working Groups

W.G. 1 - Data Processing

McConnell reported on changes and progress with respect to data/software agreements (see item 3. above) and noted that W.G. 1, in the absence of a specific project on which to work, had been relatively inactive. He suggested that an appropriate new initiative would be to collaborate with BGI in the production of a Gravity Map of the World in one sheet. This

product suitable for publicizing BGI. The Board asked that W.G. 1 formulate a specific proposal by the end of the week.

W.G. 2 - World Gravity Standards

Uotila reported that W.G. 2 had also been relatively inactive for the same reasons as W.G. 1. After some discussion, the Board asked Uotila to confer with colleagues and make recommendations for new activities for W.G. 2 with respect to absolute measurement programs and to make a proposal, if appropriate, by the end of the week. Tanner and Balmino agreed to consult with Sub-Commission presidents on how best to collect information on new base nets and in general how to elicit better response from member countries with respect to data contribution to the BGI.

W.G. 3 - Data Presentation

Boulanger presented a number of recently published coloured gravity maps of the North and South Atlantic and other areas. He acknowledged the good cooperation received from the BGI in providing data for these maps.

W.G. 4 - Gravity Anomaly Prediction

This Working Group has been inactive and was dissolved by the Board. Tanner invited members to send comments and ideas for coordination of activities in this area to the president of Section 3 for consideration next year in Vancouver.

MINUTES OF MEETING OF

WORKING GROUP 1

Held at BGI, Toulouse, France

23 Sept., 1986

Present :

R.K. McConnell (Chairman)
C.C. Tscherning
H.G. Wenzel
G. Balmino
M. Sarrailh

1. Assistance to BGI Re Data Evaluation

(a) GSC (Ottawa) will train BGI personnel (Sarrailh) in use of marine gravity editing and adjustment software during a two week period in November, 1986. Software will then be installed on BGI computer. In addition to a block of marine gravity data, Sarrailh will bring to Ottawa a 10° x 10° block of data from Africa. GSC will try out their existing data editing software to see if it is of value to the BGI. If so, GSC and BGI will try to set up a working arrangement to make use of the software an on-going basis.

(b) Tscherning and Wenzel agreed to collaborate on reporting errors already detected in the BGI Scandinavian data set. BGI will send all European data to IFE, Hannovre for computation of a new European geoid. Result of the data evaluation will be sent back to BGI.

2. Gravity Map of the World

It was recommended that a gravity map of the world in one sheet be produced during the coming year mainly as a vehicle for advertising the products and services available from the BGI. GSC (Ottawa) could collaborate on the project by assisting with data editing and producing colour screens.

3. Observations and Recommendations Regarding BGI Operations

The untimely departure of J.F. Isaac and the resulting 18 month delay in getting the data base software back into operation has been a serious blow to the effectiveness and reputation of the BGI. While it is not clear that the Directing Board could have helped resolve the problem, the seriousness of the situation should have been brought to their attention.

The Working Group makes the following recommendations :

(a) The Director of BGI should seek approval from the Directing Board to defer or even discontinue the GEBCO digitizing project. Manpower

currently devoted to this project should be diverted to data evaluation.

(b) BGI's first priority should be data evaluation until the current backlog is removed. Second priority should be request processing and third priority data acquisition.

(c) BGI should publish a catalogue of goods and services including in this booklet a request and format for data contribution.

(d) Formats for data contribution should be published in the Geodesist's Handbook.

(e) BGI should distribute their catalogue and periodic data announcements on an expanded mailing list including, for example, geophysical contractors.

(f) W.G. 1 should review data formats before its next meeting.

(g) W.G. 2 should meet up to twice yearly to offer advice and assistance until the present crisis is resolved.

R.K. McCONNELL

MEETING OF

BGI DIRECTING BOARD

12th IGC, Toulouse, France

September 25, 1986

Present :

J.G. Tanner (Chairman)
W. Torge
J.E. Faller
C. Morelli
G. Balmino
U. Uotila

1. Report of Working Group 1

McConnell tabled the minutes of the September 23, 1986 meeting of W.G. 1 and stressed the urgency of improving service at BGI. He observed that BGI had experienced a considerable shock from losing a key person who left behind little documentation concerning maintenance and operation of the data base and that the organization was just now recovering. Termination of the arrangement with DMA whereby they provided data evaluation services has placed an additional load on BGI. Although BGI can now handle requests fairly effectively again there is a large backlog of data evaluation. Balmino has proposed to develop additional software over the next three months to help deal with the evaluation problem. A new employee of BRGM (one of BGI supporting agencies) (Ravatin) will arrive at BGI shortly to undergo training.

After some discussion the Directing Board accepted all of the W.G. 1 recommendations. (For details of recommendations see minutes of W.G. 1 meeting). With respect to the GEBCO digitizing project it was decided to defer activity for one year, divert manpower from that project to gravity data evaluation, and reassess the need for digital bathymetry after one year.

With respect to the Gravity Map of the World proposal it was agreed that the project should go ahead. McConnell with attempt to locate a suitable base map and will prepare, by the summer of 1987, a prototype colour plot from a tape of data to be supplied by BGI.

2. Report of Torge/Faller re Publicizing BGI

In each issue of the Bulletin d'Information should appear informations for requesting : the Bulletin itself, data, maps, services... Main formats for data exchange should also be repeated.

- A "flyer" containing these informations should also be systematically sent with any provision of data following a request (a nice cover is desirable, in colour - cost permitted).

- BGI should prepare an advertisement for publication in EOS.

- The presentation of BGI activities in the Geodesist's Handbook should be re-written.

3. Business re Sub-Commissions

It was agreed that BGI would send out sets of base station descriptions and corresponding principal facts to the presidents of the Indian, North Pacific, European, African and S.W. Pacific Sub-Commissions and request that an attempt be made to report on the status of these stations including modifications to descriptions or gravity values. Descriptions for new stations which have gravity values in the IGSN 71 system or referred directly to absolute measurements would be welcomed.

4. Other Business

The next meeting of the Directing Board will be held on Sat., August 8, 1987 in Vancouver.

UPDATED LIST OF OFFICERS AND MEMBERS OF

I.G.C., B.G.I. Directing Board and Working Groups

I.G.C.

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
W.	Torge	(F.R.G.)	President Section III
C.C.	Tscherning	(Denmark)	Secretary Section III
G.	Balmino	(France)	Director BGI

Nominated Members :

J.	Woodside	(Canada)
C.	Morelli	(Italy)
I.	Nakagawa	(Japan)
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 3 : Data Presentation

Chairman :	Y.D.	Boulanger	(U.S.S.R.)
Members :	H.	Kautzleben	(G.D.R.)
	R.H.	Rapp	(U.S.A.)
	O.	Williams	(U.S.A.)

. WG 4 : Gravity Anomaly Prediction

Ceased its activities and has been suppressed.

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*	E.	**Kausel**	(Chile)
. *Africa*	R.O.	**Coker**	(Nigeria)
. *Western Europe*	G.	**Boedecker**	(F.R.G.)
. *Eastern Europe and USSR*	Y.D.	**Boulanger**	(U.S.S.R.)
. *India and Arab Countries*	M.G.	**Arur**	(India)

NARRATIVE ANALYSIS

C.L. Merry

Introduction

The 12th meeting of the International Gravity Commission (IGC) took place in Toulouse, France, over the period 23-26 September, 1986. This meeting was preceeded, on 22 September, 1986, by a meeting of the Directing Board (DB) of the Bureau Gravimetrique International (BGI). The meeting of the IGC took place in the Henri Fabre Lecture theatre of the Formation Internationale Aeronautique et Spatiale (F.I.A.S.), and was attended by 62 scientists from 26 countries.

SUMMARY OF PROCEEDINGS

Day one : 23 September 1986

The meeting, opened with a short welcoming address, read by Dr. G. Balmino (Director, BGI) on behalf of the President of the French National Committee for Geodesy and Geophysics. The remainder of the morning was then taken up by administrative matters, in a session chaired by C. Morelli. The president of the IGC (J. Tanner) presented his report, as did the director of the BGI (G. Balmino). Reports were also presented on the activities of the various Working Groups and Sub-Commissions. All these reports will be published in the Bulletin d'Information of the BGI, and will not be repeated here. Some points worthy of note are :

(i) WG 4 (Gravity Anomaly Prediction) will be disbanded, as its activities are largely covered by a number of special study groups of the International Association of Geodesy (IAG).

(ii) the main task of WG 2 (Gravity Standards - Networks) will become the realisation of the International Absolute Gravity Base Network (IAGBN), and the chairmanship will change from U. Uotila to G. Boedecker.

(iii) the Sub-Commissions need to become more active in the furnishing and validation of data for the BGI. As an additional responsibility the Sub-Commissions should ensure that the base station status and descriptions are updated regularly.

The Scientific Sessions started in the afternoon of 23 September 1986.

Session 1 : *Dynamic Gravimetry* (Chairman : *J.M. Makris*)

The first paper, by **R.K. McConnell and J.M. Woodside**, was presented by McConnell, and was entitled : *Compilation of a Marine Gravity Data Base for the East Coast of Canada*. This dealt with the homogenisation of 2,3 million data values from more than sixty separate surveys, producing results consistent, in the authors' estimation, to 3-3,5 mgal. The next three papers dealt with the design and testing of new sea gravimeters (**Li Xiqi, Liu Ruozang, Liang Chujian, Zhang Shanyan, Zhang Xianlin, Pan Xianzhang** : *A New Sea/Air Gravimeter* ; **B.D. Loncarevic** : *Four Years Experience with the KSS30 Sea Gravimeter* ; **J. Fritsch and K.H. Tödt** : *Calibration of Sea Gravimeters KSS30 and KSS31 along the European Absolute Calibration Line*).

The first of these, presented by **H.T. Hsu**, described the new Chinese CHZ sea gravimeter, which employs the vertical zero length spring principle. Laboratory and field tests (car and ship) indicate a consistency of better than 1,5 mgal. **J.M. Woodside** presented **Loncarevic**'s paper, which dealt with the evaluation of the Canadian KSS30 and KSS31 sea gravimeters. Based upon the analysis of crossover differences, the author finds a consistency of 0,5 mgal for the KSS30 and 0,3 mgal for the KSS31. **K.H. Tödt** presented the third paper on this topic, and stressed the importance of a reliable calibration factor for surveys which covered a large latitude range. Calibration of Bodenseewerk KSS30 and KSS31 sea gravimeters over the range from Hammerfest to Catania yielded calibration factors with accuracies of the order of $0,4 \times 10^{-4}$ to $0,6 \times 10^{-4}$. No non-linearities in these factors could be detected. The next paper (**G. Balmino, B. Moynot, M. Sarrailh, N. Valès** : *Satellite Altimetry Derived Gravity Anomalies over the Oceans*), was presented by **G. Balmino**. The inverse Stokes'operator together with a high order reference field (modified GRIM 3-L1) was used to produce 15' x 15' mean free air anomalies from SEASAT sea surface height data. Comparisons at the 1° x 1° mean anomaly level with other derived data sets indicate an RMS discrepancy of 6,5 mgal. Systematic discrepancies in some areas (northern Pacific Ocean, Eastern Mediterranean Sea) need to be resolved. **D.H. Eckhardt** presented his paper on *Status of the Gravity Gradiometer Survey System*, in which he reviewed the design principles for an airborne gradiometer system and discussed the precision requirements. An interesting analogy between least squares adjustment and electrical circuit design was presented. With adequate control points at the perimeter of the survey area and flying at an altitude of 500 m it should prove possible to determine gravity disturbances to 0,8 - 2,0 mgal, and deflections of the vertical to 0",2 - 0",4. First field tests of the prototype system should take place before mid-1987. The final paper of the session (**G. Balmino and A. Bernard** : *Status of the Satellite Gravity Gradiometer Project GRADIO*) was presented by **G. Balmino**. In this paper the downward continuation problem was discussed, and the conceptual design for the gradiometer presented. The target launch for this system is 1995.

Session 2 : *Absolute Comparisons* (Chairman : *G. Balmino*)

The first paper in this session, presented by **Y. Boulanger**, dealt with the *Results of the Second International Comparison of Absolute Gravimeters in Sevres, 1985*. The principal authors (editors) of this paper are **Y. Boulanger, J. Faller, and E. Groten**. In this intercomparison six absolute meters were employed during June and July 1985. All the measurements were referred to one site (pillar A) using a microgravimetry network especially measured for this purpose.

Comparison of the results indicated a discordance between that of the BIPM instrument and those of the others. A lively discussion followed, in which **J. Faller** presented A. Sakuma's (BIPM) viewpoint regarding the discrepancy. It would appear that great care must be taken in measuring the vertical gravity gradient, and that certain systematic errors may still be present in some instruments.

Following this paper, **W. Torge** presented the *First Results with the Absolute Gravity Meter JILAG-3* (authors : **W. Torge, R.H. Röder, H.G. Wenzel, J.E. Faller**). Excellent results have been obtained using this instrument (which did not take part in the Sevres intercomparison). Measurements have been made at some 15 sites in Europe, with a precision of 1 to 5 microgal, a probable accuracy of 10 microgal. Comparison at sites occupied by the Italian apparatus indicates a systematic difference of less that 4 microgal. The final paper in this session (**J.E. Faller and T.M. Niebauer** : *Past and Future Comparisons -Some Thoughts*) dealt with some of the possible causes of systematic errors in absolute meters. The susceptibility of these instruments to tilting was emphasised. In discussion, the poor environmental conditions at Sevres were generally agreed upon.

Day Two : Wednesday 24 September, 1986

Session 3 : *Networks - Activities, Projects* (Chairman : *U. Uotila*)

D. Adjakaiye presented the first paper of this session (*The AGSN Project - Problems and Prospects*). The problems of coordinating the African Gravity Standardisation Network between more than fifty countries were discussed. As an example, the establishment of the Nigerian national gravity base network, which required the cooperation of 19 Nigerian states, was presented. The general conclusion was that absolute gravity measurements should take place as soon as possible, and that national networks should be linked to these stations.

The second paper (**I. Nakagawa, R. Shichi, S. Nakai, K. Nakamura, T. Higashi, Ruihao Li, Yihui Chen, and Dongchu Wang** : *International Gravimetric Connections between Japan and China*) was presented by **I. Nakagawa**. This paper described the LaCoste and Romberg (LCR) gravimeter measurements made between Japan and China, with the primary purposes of improving the IGSN71 in this area, and of establishing a calibration line in China between Beijing and Guangzhou. The next paper (**Song Xingli, Hsu Houtze, Hou Shangwei** : *On the Adjustment of the National Gravity Fundamental Network in China*) dealt with the same region, and was presented by **H.T. Hsu**. Absolute measurements were made at 11 sites, using both the Chinese and Italian instruments, and LCR connections between these and 46 other sites were also made. A combined adjustment of these data resulted in the absolute measurements at three of these sites being rejected and the network readjusted. The accuracy of the final result was estimated to be about 8 microgal.

The paper on the *Status of the Unified European Gravity Network - UEGN* was jointly presented by all four authors (**G. Boedecker, I. Marson, C. Poitevin, G. Strang Van Hees**). Progress in compiling the data for this project has been slow, and the paper concentrated on the proposed tidal correction model and adjustment procedures. Lack of time precluded a discussion on some aspects of these models.

Session 4 : *International Absolute Gravity Base Network*
(Chairman : *G. Boedecker*)

This session started with the presentation by **G. Cerutti** on the *Sino-Italian Joint Absolute Gravity Measurements in China*. (authors : **Xu Shan, Qiu Quixian, Jian Zhiheng, I. Marson, G. Cerutti, F. Alasia, S. Desogus**). This paper generated a lively discussion concerning the criteria for site selection. One school of thought propagated the viewpoint that ease of access should be the main criteria proposed in the paper should prevail.

Session 4 was followed by a discussion, chaired by J. Tanner, on the structure and activities of the IGC. The concepts of structuring the IGC in terms of regions or by problems were compared. The general feeling appeared to be that both types of breakdown could be catered for in terms of the present regional sub-commissions and problem-related working groups. The publication policy of the Bulletin d'Information of the BGI was discussed, with a number of recommendations concerning format, refereeing, distribution and priorities being made to the DB. With regard to the 12th IGC meeting, the scientific papers (or their abstracts) would be published in the regular Bull. d'Inf., and the abbreviated national reports in a special issue of the Bull. d'Inf. Up to four papers from the 12th IGC meeting would be recommended for publication in the Bulletin Geodesique. Consideration would be given to more widely advertising the services of the BGI.

Session 5 : *Determination of the Newtonian Constant* (Chairman : *J. Tanner*)

Two papers on this topic were presented. The first, by **C. Boucher** was entitled : *Possible Variations of the Newtonian Constant, Determinations of GM*. The possibility that G is time, space and material dependent was discussed in a relativistic frame. Lunar occultations and other observations indicate that the ratio G/G may be of the order of $2,5 \times 10^{-11}$ y^{-1}. **J. Tuck** (*Deviations from Newton's Inverse Square Law from Geophysical Observations*) dealt with the practical aspects of determining G from observations at different depths inside Australian mines. He also described the recently-completed balance system deployed in a large hydro-electric water reservoir.

Due to time constraints the discussion on this topic was postponed to the morning of Friday 26 September 1986, but was no less lively for its delay. Eckhardt, Faller, Tuck and Tscherning contributed to a debate in which such diverse techniques and tools as lunar laser ranging, balloon gravimetry, torsion balances and pendulums were proposed for the purpose of detecting the spatial and material dependence of G.

Session 6 : *High Precision Gravity Techniques* (Chairman : *E. Groten*)

The first paper of this session was to have been delivered by **M. Ogier**, who died on 17 August 1986. A short tribute in his honour, describing the work of M. Ogier was presented in its place by **M. Millon and C. Weber**. **R.H. Röder** presented the next paper, co-authored with **H.G. Wenzel**, on the *Relative Gravity Observations at BIPM, Sevres, in 1985 and 1986*. In this paper he described the extraordinary care that is required to achieve sub-10 microgal accuracy relative measurements with the LCR gravimeters. Even then up to 9 microgal discrepancies gravity differences occur between the 1985 and 1986 surveys. **A. Kiviniemi** presented an interesting paper on *Observations with a Fully Damped LCF G-Gravimeter*. Because of the problems associated with measurements on the floating ice of the Gulf of Bothnia (accurate levelling not possible) the instrument must be heavily damped. It then becomes insensitive to tilt, and

also to gravity changes. This problem can be overcome by measuring the speed of movement of the beam when the spring tension is changed - this is proportional to the real gravity reading. Tests carried out over known gravity ranges indicate that this method can give very good results.

The next paper (**Zhou-Kungen, B. Ducarme, C. Poitevin** : *Screw Error and Electrostatic Effect on Three LCR Gravimeters with Feedback System VRL 8350*) was presented by **B. Ducarme**, and describes the capacitive transducer system developed at ICET. This system has been used to determine periodic screw errors (with periods around 1 counter unit) of amplitude 1 microgal with a precision of 0,25 microgal. The linear range of the feedback system is, however, limited to 2 mgal (the Hannover feedback system has range of 20 mgal). This paper was followed by one on *High Precision Gravity Measurements for the Detection of Crustal Deformation by Surface Loads* by **M. Becker, S. Bakkelid, E. Groten and A. Midsundstadt**, presented jointly by the last two authors. This project is in the initial phases and involves repeated precise levelling and gravity at the site of a large water reservoir still under construction. The 1985-1986 gravity measurements indicate that an accuracy of 6-8 microgals has been achieved. The design accuracy is 3 microgals, as the expected loading effect is only 10 microgals. A second paper presented by **B. Ducarme** in this session, co-authored with **V. Dehante**, was on the *Comparison between the Theoretical and Observed Tidal Gravimetric Factors*. This important contribution, which formed the basis for a later resolution of the meeting, discussed the definition of the tidal gravimetric factor in Wahr's earth model, and proposed a revised definition which is more consistent with observations.

Day Three : Thursday 25 September 1986

Session 7 : *Geophysical Interpretation* (Chairman : *E. Klingele*)

S. Olejnik presented the first paper in this session (**M. Blizkovsky, J. Ibrmajer, S. Olejnik, J. Sefara** : *Gravimetric Network and Characteristics of the Geological Structure of Czechoslovakia from Gravity Data*). This paper reviewed the updating of the Czech gravity network and detail survey, the gravity map production, and analysed the Bouguer gravity anomalies in terms of the known physical structures. In the next paper (**Jiang Fuzhen, Hsu Houtze** : *Gravity Field of Xiang Plateau and its Recent Uplift*), presented by **H.T. Hsu**, different data types in the Tibetan plateau region were analysed. These data consisted of gravity measurements, geoidal heights (GEM 10B, and astrogravimetric levelling) and precise levelling. It appears that the deepest level of the Mohorovicic discontinuity is reached under this plateau, not under Chomolungma (Mt Everest), indicating that isostatic equilibrium has not been achieved. The land uplift in the Lhasa region is about 10 mm per year, and there is a possible small decrease in gravity. Continuing the theme of isostacy, **R. Hipkin** (*Isostasy in Northern Britain*) used a Fast Fourier Transform Technique on a dense gridded Bouguer anomaly and elevation model to determine the isostatic response function in this region. Analysis indicates sources at depths of 9 km and 24 km. The session was completed by a paper (**R. Byamungu and P. Louis** : *Interprétation de données gravimétriques Ruanda, Burundi et Zaire*) presented by **R. Byamungu**. This paper dealt with the interpretation of several gravity profiles across the East African Rift Valley.

Session 8 : *European Geoid - Geoid Determinations* (Chairman : *G. Birardi*)

G. Birardi presented his report on the *Present State of the European Geoid*, which summarised the proceedings of the International Symposium on the

Definition of the Geoid, held in Florence during May 1986. One of the outcomes of that meeting was a proposal that a permanent Geoid Commission be established by the IAG. This proposal received some support at this IGC meeing, and the president of Section 3 (W. Torge) solicited comments on the proposal before he makes his recommendation to the IAG executive committee.

The remainder of this session was taken up with the presentation of papers on regional geoids for two widely separated parts of the Earth. **R.G. Hipkin**, in his paper : *High Resolution Relative Geoid for Northern Britain*, returned to Stokes'original work for inspiration, using Bouguer anomalies (which very smoothly) in Stokes'formula, and computing a corrective term using a dense DEM. The resultant geoid is essentially a relative one, as no account is taken of the influence of distant zones. **G. Balmino** (co-author : **J. Rakotoary**) presented the *First Computation of a Gravimetric Geoid over Madagascar*. The approach used was more conventional, employing a high order (n = 180) reference field together with Stokes'formulation applied to reduced 15' x 15' mean free air anomalies in the inner zone. Different reference fields produced up to 50 cm biases in the geoid.

Session 8 was followed by a short presentation of the four submitted resolutions. Two of the resolutions were adopted nem. con., while the other two were referred back to the resolutions committee, for further discussion.

Session 9 : *Secular Changes of Gravity* (Chairman : *Y. Boulanger*)

T. Niebauer started this session with a paper, co-authored by **J. Faller**, on the *Status of and Progress Report on the New JILA Absolute Gravimeter*. A total of six of these instruments have been constructed, at a cost of approximately $130 000 each. Niebauer identified the sources of small systematic errors (which still have to be eliminated) as : timing biases in the fringe detection ; recoil of the dropping chamber ; and the laser source not being in a vacuum. A relationship of approximately 0,4 mgal/mbar with atmospheric pressure has been identified, although the determination of the exact value is complicated by the highly variable pressure regime around Boulder.

A group of three papers in this session dealt with the detection of secular changes of gravity using LCR gravity difference measurements. **W. Torge** (co-author : **R.H. Röder**) discussed *Improved Relative Gravimetric Techniques for Detecting Recent Crustal Movements in Northern Iceland*. **M. Satomura** (co-authors : **I. Nakagawa, H. Tsukamoto, T. Higashi, Y. Fukuda and K. Nakamura**) presented a paper on *Secular Changes of Gravity Observed in Kinki District, Japan*, and **R.G. Hipkin** (co-author : **E. Lagios**) described *Gravity Changes 1981-86 over the Atalanti Fault System, Greece*. Improvements in the observing and data processing techniques for the northern Iceland survey (electrostatic feedback system, better calibration) allow 5 microgal relative accuracy to be obtained. Comparison of 1985 with 1981 results show good correlation with levelling results. In the Japanese analysis, the major source of gravity change appears to have been variations in lake water level. In Greece the apparent gravity change (40 microgal) could not be correlated with water table changes, nor with any ground movement. Discussion of this paper centred around the possibility of instrumental errors.

Sandwiched between these papers was one presented by **B. Ducarme**, co-authored by **F. De Meyer**, on *Long Term Periodical Gravity Changes Observed with a Superconducting Gravimeter*. In this paper, a new working unit, the nanogal, was introduced - the instrument has a resolution of 10 nanogal ! However, the

long term stability, after removal of systematic effects (including those of the atmosphere, and polar motion) is in the region of 4 microgal.

Session 10 : *Discussion of Resolutions* (Chairman : *C. Morelli*)

Resolutions 1 and 3 had been approved earlier in the day. Resolution 4 was resubmitted in a simpler form and accepted without discussion. Resolution 2 required further simplification, but was then approved with no votes against. The sull texts of the final resolutions are reproduced elsewhere in the Bulletin d'Information.

Session 11 : *Local Gravity Field Determination* (Chairman : *C.C. Tscherning*)

Only two papers were presented in this session. The first of these, by **C.L. Merry**, dealt with the *Interpolation of Gravity Anomalies in Southern Africa*. A high order reference field (1° x 1°) mean anomalies, modelled using a bicubic spline approximation), coupled with a DEM, reduced the gravity signal significantly, before collocation was applied to this residual field. **C.C. Tscherning** (co-author : **D. Arabelos**) employed a similar approach in the *Computation of the Gravity Vector from Torsion Balance Data in Southern Ohio Using Collocation*. Surprisingly good results were obtained, considering the quality (= 10 EU) of the torsion balance data. This experience should prove useful in evaluating the gravity gradiometer data of the future.

Day four : Friday 26 September 1986

As mentioned earlier, the first hour of this day was spent discussing the Newtonian constant, G. A report on this discussion is given under session 5.

The remainder of Friday morning was given over to a discussion of the planned activities of the BGI and IGC over the next quadrennium. The DB has set the following priorities for the activities of the BGI :

(i) evaluation and validation of existing data,

(ii) response to requests for data (preferably within one month),

(iii) gravity data acquisition,

(iv) other tasks.

Tasks to be carried out by the IGC through its sub-commissions and working groups include : the updating of station descriptions (including those at harbours) ; the comparison of marine gravity and satellite altimetry results ; the further intercomparison of absolute gravity meters (possibly not at Sevres) ; the implementation of the IAGBN ; technical and moral assistance for the AGSN ; and the production of a one sheet world gravity map.

The meeting closed at 11h30 with a vote of thanks to the Director of the BGI and his staff for the excellent organisation of the meeting.

RESOLUTION N° 1

Considering
the earlier resolutions of the I.G.C. on the realization of the African Gravity Standardization Net, particularly at the I.G.C./G.C.A. meeting in Paris in May 1985.

The International Gravity Commission recommends
that the international scientific community assists the **Gravity Network Committee** of the **Commission for Geodesy in Africa** in realizing at least the **Gravity Training Workshops** and the 20 proposed absolute stations in the African gravity Standardization Net in the near future.

RESOLUTION N° 2

Recognizing
the ability of both superconducting and absolute gravimeters to monitor perturbations of the gravity field at the microgal level and

Considering
that modelling instrumental effects is the most crucial problem for interpretation and that an intercomparison of both types of instruments is highly desirable,

The International Gravity Commission recommends
that reapeated absolute measurements of gravity should be made at the sites where the superconducting gravity meters are operating.

RESOLUTION N° 3

Considering
the recent theoretical advances in the study of the Earth's response to tidal forces and the accuracy now required for tidal corrections to gravity measurements,

The International Gravity Commission asks
the Permanent Commission on Earth Tides to reconsider the definition of the standard model for tidal gravity corrections.

RESOLUTION N° 4

Recognizing that
there is a need for a global network of absolute gravity base stations of the highest possible accuracy,

The International Gravity Commission recommends
that the realization of the International Absolute Gravity Base Station Network (IAGBN), based on the report of I.A.G.-SSG-3.87, now proceed.

REPORT OF THE INTERNATIONAL GRAVITY COMMISSION

J. Tanner, President

During the past year the principal activity of the IGC concerned the organization and execution of its quadrennial meeting, held in Toulouse during September. Some 70 individuals were in attendance throughout the meeting, which followed a format similar to that of general assemblies - four one and a half hour sessions daily. Most of the sessions were devoted to scientific subjects - the liveliest probably being the two concerned with the Newtonian constant. The business sessions invoked good participation on the part of the attendees who provided valuable input to the policies and activities of the Commission.

The quadrennial meeting was preceded by a day long series of meetings of the Directing Board of the International Gravity Bureau (IGB) and its advisory working groups. At these meetings it became evident that the IGB was having difficulty in meeting the needs of the user community, which has led to a variety of problems relating to loss of confidence in the IGB and its ability to service the community. After a lengthy discussion the roots of the problem were identified as due principally to the departure of the programmer responsible for the software development within the IGB and the frequency of the meetings of the directing Council : the latter leaving the IGB without a sufficiently well defined set of priorities. The remedies will include annual meetings of the Directing Board beginning in 1987 and top priority to servicing requests for information and data within the IGB.

Considerable discussion in the business sessions was also devoted to the structure of the Commission and the effectiveness of the Sub-Commissions in realizing the goals of the Commission. The members agreed for the moment to retain the existing structure but requested the executive of the Commission to keep the question under review within the context of the Directing Board and to report as necessary. A good test of the effectiveness of the Sub-commissions will be the review of the status of IGSN 71.

The proposal to create a new commission for geoidal studies was presented to the meeting by Prof. Birardi. This proposal arose out of discussions at the meeting of his Special Study Group held in Florence in the spring of 1986. The reaction within the IGC to the proposal was mixed with the majority expressing reluctance to see any hasty action before a thorough discussion of the real need and the consequences in terms of the relationship of any such commission to the IGC and to the IGB. The questions raised during formal discussions and informal evening sessions centred on the need to examine specifically the impact on an IGB already having difficulties in meeting the needs of the IGC because of lack of staff and the dangers of duplication of effort in gathering global gravity data and the consequent confusion arising from lack of a co-ordinated effort within the geodetic community. Overall the reaction seemed to be one of proceeding cautiously, possibly by forming a sub-commission of the IGC to allow the working relationships to be developed in a rational manner. Once the working relationships had been tested in practice, the question of a separate commission could be examined anew with more confidence that any new commission would not create unnecessary problems.

REPORT ON ACTIVITY OF SUB-COMMISSION FOR NORTH PACIFIC REGION

I. Nakagawa

The efforts to organise the Sub-Commission for North Pacific Region have been devoted for several years. Some of member's countries sent me the national representatives in its early stages, but other countries have not nominated their national representatives up to the present time. In case of countries which have nominated the national representatives, I had exchanged some informations within the Sub-Commission with these countries through the national representatives. In case of countries without their national representatives, I had exchanged some informations with institutions and organizations participated in gravity researches.

Studies and researches in various fields of gravimetry were actively carried out for the period from April 1982 to March 1986.

As for international gravimetric connections, a gravimetric mission organized by the National Bureau of Surveying and Mapping of China performed an international gravimetric connection between China and Japan with six LaCoste & Romberg gravimeters (model G) in April 1984. A few sets of LaCoste & Romberg gravimeters (model G) from Japan joined to this mission for the gravimetric connection Japan. A Japanese gravimetric mission headed by I. Nakagawa performed another international gravimetric connection between Japan and China with four LaCoste & Romberg gravimeters (model G) from October to December in 1985, being obtained a cooperation from the State Seismological Bureau in China. Two LaCoste & Romberg gravimeters (model G) and one Worden gravimeter from china joined in this connection for some portions in China. Besides these two international gravimetric connections, the following researches were carried out during the period concerned ; the international gravimetric connection in the route of China - Hong Kong - Paris by the National Bureau of Surveying and Mapping of China, and gravity measurements in Indonesia, Peru and East African Rift Valleys by Japanese gravimetric missions.

As for national gravity nets, the People's Republic of China has established the China Basic Gravity Net 1985, which is a new gravity net of China, in 1985. The Republic of Korea is being carried out surveys for establishing a new gravity net. Japan is being carried out repeatedly not only gravity connections but also gravity surveys all over the Japan in order to maintain and reform the Japan Gravity Standardization Net 1975 which is the current gravity net in Japan.

The Japan Antarctic Research Expedition has carried out sea gravity measurements between Japan and Syowa Station in Antarctica, by using icebreakers on both ways to and from Antarctica, and gravity measurements in the Antarctic Continent. The Ocean Research Institute of Tokyo University and the National Institute of Polar Research published a map of free-air gravity anomaly in Antarctic region with contours of 20 mgals interval and a scale of 1/13,000,000.

The Hydrographic Department of Japan has conducted dense gravity surveys on the sea surface in the vicinity of the continental shelf around Japan. The results of the surveys have been published in free-air gravity anomaly maps on

a scale of 1/200.000 or that of 1/500.000. Gravity measurements at sea have also been carried out by "Hakuho-maru" belonging to the Ocean Research Institute of Tokyo University and "Hakurei-maru" belonging to the Geological Survey of Japan, and moreover, by a French research vessel "Jean Charcot" under the "KAIKO" project conducted by the cooperation between Japan and France. In the People's Republic of China, the State Seismological Bureau and the Chinese Academy of Sciences have performed gravity measurements by means of sea gravimeters made in China on East China Sea and South Pacific.

The progress in the field of absolute measurements of gravity was remarkable during the period concerned. In the People's Republic of China, the National Institute of Metrology developed firstly a transportable absolute gravimeter of the first generation several years ago and, in succession to it, developed a transportable absolute gravimeter of the second generation in 1984. The latter gravimeter joined in the Second International Absolute Gravimeter Campaign held in June 1985 at Sèvres. These absolute gravimeters were employed for the revision of the China Basic Gravity Net on one hand, and they were also contributed to the establishment of a calibration line for relative gravimeters on the other hand.

In Japan, the International Latitude Observatory of Mizusawa has carried out absolute gravity measurements using a transportable apparatus (Tsubokawa-type) at several stations in Tohoku district. The data obtained are available for detecting the gravity changes associated with seismic activities in Tohoku District. Another transportable apparatus (Sakuma-type) belonging to the Geographical Survey Institute is being employed for maintaining and improving the Japan Gravity Standardization Net 1975.

Continuous observations of the earth tides by means of gravimeters are being performed at many stations during the period concerned. There are two purposes for these observations. The first purpose is to determine accurately the values of tidal factor and phase lag at each station. It was carried out as a part of the transworld profile of tidal factors.

The second purpose is to detect gravity changes associated with seismic and volcanic activities or crustal deformations. It was carried out as a part of the project for realizing the earthquake prediction and volcanic eruption prediction. The International Centre for the Earth Tides cooperated with the former project. The People's Republic of China and Japan are, in particular, active in the latter project. In both projects, Askania, Geodynamics, LaCoste & Romberg and other gravimeters were employed. Some of these gravimeters were modified to a better advantage for continuous observations of gravity change. Some of institutions are being performed continuous observations using gravimeters developed by themselves.

The researches mentioned above are mainly of gravimetric works from international points of view performed by the members countries of the Sub-Commission for North Pacific Region during the period from April 1982 from March 1986. In the other fields of gravity, a lot of studies and researches have been made for various purposes. Their details are described on the Report to the 12th IGC meeting which has been compiled by C. Morelli and already distributed to all of the participants. Particularly, a Report on Gravimetry in Japan during the period has been published separately from the report compiled by C. Morelli. The list of references is attached to this Report.

Gravity researches in the Sub-Commission for North Pacific Region set the main aim on their dynamic studies ; studies for getting higher precision of

gravity net, for promoting gravity measurements in areas where there were no or few measurements, for detecting gravity changes with time, and for understanding the relation with other phenomena.

In conclusion, it only remains to be stated that I thank all persons concerned in every country that cooperated for making this Report.

REPORT ON ACTIVITY OF SUB-COMMISSION FOR AFRICA

R.O. Coker

The African Gravity Net

The pre-occupation of the African Sub-Commission has been the African Gravity Standardization net project of the Gravity Network Committee of the Commission for Geodesy in Africa. (CGA) the Chairperson of which is Professor D.E. Ajaikaiye.

The International Gravity Commission has lent support to the African Gravity Net Project. A joint meeting of the IGC and CGA was held in Cairo during the International Symposium on Recent Crustal Movement in Africa in November 1984. This paved the way for the Workshop on the project in Paris in May 1985 to discuss a plan of action and the sources of assistance that might be given for the implementation of the project. The 46 participants were from 13 African countries and 10 other countries from Europe, USA and Canada. The African Association of Cartography (A.A.C.) was also represented. They included representatives of National and International agencies who had expressed interest in the project.

The proposal was exhaustively discussed and the issues involved were critically and frankly discussed. The meeting however achieved very limited success as no sources of finance and assistance were identified at the workshop. It was however stated in the published report of the meeting that some countries had indicated support for the project.

The project was however referred back to the Gravity Network Committee of the C.G.A. to finalize the proposal and to present it in collaboration with the A.A.C. and the Nairobi centre to the O.A.U. and E.C.A. for adoption. It is hoped that those countries which were mentioned as indicating support for the project will re-affirm their support to the Gravity Network Committee of the C.G.A. In this respect it is worthy of note that the Sub-Commission of Western Europe through Dr. Ing. Gerd Boedecker has taken the initiative in contacting both the E.C.A. and the C.G.A. on the project.

The project also featured prominently at the 3rd Symposium on Geodesy in Africa of the C.G.A. and a programme for action was decided upon. This includes the listing of the project as an item to be discussed at the 6th United Nations Regional Cartographic Conference for Africa in November 1986 in Addis Abeba Ethiopia.

Prof. D.E. Ajaikaiye, the Chairperson of the Gravity Network Committee of C.G.A. will give a more comprehensive progress report on the project.

Other Programmes

The Special Study Group 3.87 of the International Association of Geodesy has completed a status report and network proposal for the International Absolute Gravity Base-Station Network I.A.G.B.N. with 4 stations site locations suggested on mainland Africa and on Madagascar.

The I.G.N. in France is also proposing to establish gravity stations in some African countries.

REPORT ON ACTIVITY OF SUB-COMMISSION FOR INDIA AND ARAB COUNTRIES

Col. M.G. Arur

1. Introduction

In accordance with the decision of the International Gravity Commission (IGC) during the 11th meeting of the International Association of Geodesy held at Hamburg in August, 1983 constant efforts were continued to collect information regarding activity and program in the field of gravity and related technology from the countries which fall under the sub-commission. Efforts were made to establish contacts with the following scientists/Executive heads of the concerned departments in their respective countries :

1) Algeria	Mr. M. Tefiani, Secretaire, Comité National de l'UGGI, Algérie.
2) India	Various Scientific Institutions.
3) Iran	Dr. E. Aghshahi, Director, Institute of Geophysics, Iran.
4) Iraq	Dr. M.J. Abbas, Director General, Geological Survey and Mineral Investigation, Iraq.
5) Jordan	Dr. Issam Khairy, General Secretary, Jordan Research Council, Jordan.
6) Kuwait	Mr. M.A. Alshamali, Director, Kuwait Institut of Scientific Research, Kuwait.
7) Lebanon	Dr. A. Zehil, Observatoire Ksara, Kearaper, Zahee, Lebanon.
8) Lybia	Mr. Milun Etgamudi, Survey Department of Lybia, Lybia.
9) Saudi Arabia	Dr. M.S. Joukhdar, Ministry of Petroleum and Mineral Resources, Riyal, Saudi Arabia.
10) Somalia	Ingeneer Igrahim Gaileh, Director, National Cartographic Directorate, Somalia.
11) Sudan	Mr. Abbas Elhag, Sudan Survey Department, Sudan.
12) Syria	Geog. Eng. A.M. Safi, Commandement General des Forces Armées, Director of Military Survey, Syria.
13) Turkey	Prof. A. Aksoy, TTU Insaat Fakultesi Jeodozi, Turkey.
14) Tunisia	Mr. M.M. Charfi, Office de la Topographie, Tunisia.
15) United Arab Republic	Dr. A. Ashour, Academy of Scientific Research & Technology, Egypt.

2. Status Report

This report is intended as a brief review of significant scientific investigation of the gravity field of the Earth, its relationship with the Earth's interior and its variations with time. Review of the results of such investigations made only during the period of 1983-86 have been included in this report.

2.1. India

Scientific investigations in gravity, particularly concerning to the Commission's programme have been given briefly in the ensuing paragraphs.

Detailed account of the Gravimetric work carried out in the country during the period 1.6.1982 to 31.5.1986 has been reflected in the National Report on the gravimetric work done in India by various organisations and institutions during the period 1982-86 being presented at the 12th meeting of the International Gravimetric Commission of International Association of Geodesy to be held at Toulouse in September 22-26, 1986.

2.2.1. Survey of India - Geodetic Research Branch

The charts of topography and compensation (T+C) corrections for Hayford Zones 18-1 both on Pratt-Hayford (D = 113.7 km) and Airy-Heiskanen (T = 30 km) hypothesis for India and adjacent countries and adjoining sea areas have been completed.

The map for the gravimetric geoid for India and adjoining countries and seas has been prepared with respect to GRS-1967 by using a combination of GEM 10B potential field model and surface data.

Post earthquake gravity variation studies of Cachar (Assam) earthquake of December, 84 were carried out where the microgravimetry has been utilised in studying the crustal deformation due to the earthquake. The conspicious feature being that the epicentre lies in the zone of transition from subsidence to elevation.

2.2. Algeria

Contacts are being persued.

2.3. Iran

Contacts are being persued.

2.4. Iraq

Iraq established its IUGG Committee in 1984. Dr. Abbas is appointed as the coordinator of IGC in Iraq. They are in the process of formulating their 5 years plan 1986-*90 for the IUGG Iraq Committee.

The report "Gravity Activities in Iraq till the end of year 1983" has been prepared. The abstract of this report is enclosed in the Annex I. The full report can be obtained from Dr. M.J. Abbas IGC coordinator for Iraq, Director General, Geological Survey and Mineral Investigations, P.O. Box 986, Alwiyia Baghdad - Iraq.

2.5. Jordan

Contacts are being persued.

2.6. Kuwait

Contacts are being persued.

2.7. Lebanon

Contacts are being persued.

2.8. Lybia

Contacts are being persued.

2.9. Saudi Arabia

Contacts are being persued.

2.10. Somalia

Contacts are being persued.

2.11. Sudan

Contacts are being persued.

2.12. Syria

It was informed that Syria has not yet received their LaCoste Romberg Gravitymeters therefore no gravity report could be made.

2.13. Turkey

Contacts are being persued.

2.14. Tunisia

From 1985 to 1986. There is no gravity work done in Tunisia. However some efforts have been made to publicate rapidly a gravimetric map of Tunisia (scale 1/500.000).

2.15. United Arab Republic

Contacts are being persued.

3. Future Programme

As would be seen from this report many individual countries of the sub-commission have yet to provide input for the report and further efforts in this direction are continuing. It is possible many of the member countries would provide this input in their National reports for the XIXth IUGG General Assembly due to be held at Vancouver (Canada) in August, 87 and it is hoped that exchange of the information will promote scientific investigation in this field.

4. Acknowledgements

The Co-ordinator of the sub-commission for India and Arabian Countries expresses his thanks to the scientists of various member countries who have sent their report including the executive heads of various Indian institutions for their kind co-operation in sending reports in time.

Annex I

Abstract

The gravity activities in Iraq are divided in two periods. The first period extended from 1939-1953, was performed mainly by foreign oil companies. The second very important period started in 1969 after the establishment of the State Organization for Minerals (SOM).

The paper presents a general review of all gravity field activities during these two periods and gives information on areas covered, network used and accuracy of the different regional gravity surveys concerning its instrumentation, trigonometric levelling, observed gravity values and data presentation. Besides that general information on the detailed research and future gravity activities in the country is also given. At the end of this paper lists of references for the most published and unpublished papers and known reports are attached, which are valuable to all gravity researcher.

COMPILATION OF A MARINE GRAVITY DATA BASE FOR THE EAST COAST OF CANADA

R.K. McConnell and J.M. Woodside

Some 2.3 million marine gravity observations acquired on 73 cruises carried out by the Atlantic Geoscience Centre, Dartmouth, Canada over the past 21 years have been edited using interactive graphics and adjusted by least squares to minimize crossover errors and ensure datum homogeneity. The adjusted data set, which has an estimated accuracy of ± 3 mgals, has been incorporated into the National Gravity Data Base.

THE NEWLY DEVELOPED CHZ SEAGRAVIMETER

Zhang Shanyan, Li Xiqi, Liang Chujian,
Liu Ruozeng, Pan Xianzhang, Zhang Xianlin

Institute of Geodesy and Geophysics,
Chinese Academy of Sciences
Xu dong Road, Wuhan, China

ABSTRACT

A new seagravimeter, CHZ meter, has been developed by Institute of Geodesy and Geophysics, Chinese Academy of Sciences. This is an axially symmetric seagravimeter with zero-length spring, force-balanced feedback, silicone oil damping, digital filter and data acquisition system. It is essentially unaffected by cross-coupling accelerations and can operate in high sea states with vertical accelerations up to 500gal and horizontal accelerations up to 200gal.

The principle of operation, design features and system structure are described. The results of testing in laboratory and at sea are presented. In laboratory it has been tested against vertical accelerations up to 250gal. The non-linear error is generally less than 1 mgal. A side by side instrumental comparison between a CHZ and a Bodenseewerk KSS-30 seagravimeter was made in August of 1985 at South China Sea. The RMS value of discrepancies between the two meters is 1.4 mgal

INSTRODUCTION

A new seagravimeter, CHZ meter, has been developed by Institute of Geodesy and Geophysics, Chinese Academy of Sciences. This is an entirely new designed meter. Developing a new instrument has many advantages over transforming or rebuilding an old one, because it offers many freedoms, such as choosing measuring principle, using state-of-the art technology and electronic components, adopting reasonable layout of system and so on. A straight line type measuring principle is adopted in CHZ meter to eliminate the cross-coupling effects which occur in rotatory type seagravimeter. Other features, for instance, zero-length spring suspension system, silicone oil damping, high precision capacitance transducer, digital filter and programmable data acquisition system also characterize the CHZ Seagravimeter.

The CHZ meter has been tested both in laboratory and at sea against accelerations vertically up to 250gal and horizontally up to 50gal, mounted in a gimbal or a gyro-stabilized platform using a sinusoidal lift or rocking machine and on board the research vessel of 1,000 tons. The results are satisfactory.

DESIGN FEATURES

Zero-length spring suspension system

The mass-spring system consists of a tube-shaped mass and a vertically suspended main spring. In order to eliminate the effect of horizontal accelerations, the mass is connected to the meter case with five or six ligaments and two tension springs which are so arranged and placed that the mass is translated only along the meter sensitive axis, accompanied with a slight rotation of it. Fig.1 shows a simplified version of suspension system with six ligaments used in CHZ meter. The ligaments and springs are arranged in such a way that all of them are symmetrical in both dimension and distribution of tension about the vertical axis A-A, i.e. the axis of zero-length and tube-shaped proof mass.

The reasons for using a zero-length spring consist in obtaining a high displacement sensitivity and ruling out the error caused by the deflected spring on which as horizontal accelerations act.

The major advantages of this kind of suspension system are as follows.

1. it is strictly axially-symmetric, and therefore free of the cross-coupling of horizontal and vertical accelerations.
2. it has almost no responseto horizontal accelerations and can operate properly against them up to 200gal.
3. it practically has no friction.

Silicone oil damping

Seagravimeter responds both gravity variation and vertical accelerations caused by sea motion. The latter could be 10,000 or 100,000 times as large as the former in magnitude. Fortunately, it has much higher frequency, thus can be minimized by heavy damping.

From the differential equation of motion of mass-spring system of CHZ meter it can be obtain that

$$P \doteq \frac{\omega_0^3}{2\lambda\omega_2}$$

where P = the ratio between sensitivity to noise and that to gravity variation.

ω_0 = the proper oscillation frequency of mass-spring system.

λ = the damping coefficient.

ω_2 = the frequency of disturbing accelerations.

For a given P, the λ is directly proportional to ω_0^3. In view of the very high frequency of mass-spring system in CHZ meter, a fluid damping whose damping coefficient could be very large is used and silicone oil is chosen to be the damping fluid because it has excellent property in isolation, viscosity

stability and so on. In addition, silicone oil damping has some other advantages:

1. it is easy and convenient to achieve a satisfactory noise suppression with different viscous silicone oil.
2. as a result of heavy damping in all directions non-linear errors and irregular cross-coupling effects are minimized.
3. the meter is less subject to performance degradation due to rough handling and less sensitive to vibration and shock.

High precision capacitance transducer and force-balanced feedback

The CHZ Seagravimeter is a non-astatic meter whose proof mass displacement caused by gravity change is very small. In order to achieve high accuracy of measurement, a highly precise and stable capacitance transducer is used to detect the deflection of the mass-spring system. Its sensitivity is about $10^{-4}\mu m$, less than 0.01mgal; Its maximal linear output is 10v, corresponding to ±50gal when P-I feedback is added. The transducer voltage is fed through proportional and integrating feedback circuit to two winding of a moving coil attached to the proof mass, the coil moving in the field of a permanent magnet. Whereby the mass displacement is reduced by the feedback amplification factor and driven to zero position by integrating feedback which also suppresses disturbing vertical accelerations with 10 sec. period by 10 times. Because it maintains the mass in a near-null position, thus is called force-balanced type gravimeter. The current generated in integrating coil is the measure of gravity variation, its maximal output is 10v, corresponding to 10,000 mgal, enough for global measurement.

Digital filter and programmable data acquisition system

Though there are silicone oil heavy damping in mass-spring system and 20db attenuation in integrating circuit, the output signal from integrating coil is undulatory. It must be heavily filtered to average the relatively short period (3-18 sec.) vertical components of ship accelerations. a low-pass digital filter is used to meet this requirement, because digital filter has many advantages over other kinds of filter. It has large suppression ratio up to 120db and small time constant, thus much less distortion of gravity variation. In addition, its output can easily be printed or recorded on a cassette tape for processing later on.

The data acquisition system consists of a digital filter, program control circuit, clock, printer, cassette recorder and chart recorder. There are three kinds of readout in the system. One is printed data whose printing interval can be selected from 1 to 100 minutes or manually. Another is cassette recorder on which the gravity value stored in a microprocessor is recorded every 10 minutes. The third is continuous analog record on a chart recorder.

Thermostats and temperature compensation

The CHZ meter has two thermostats to keep its inside temperature stabilizingat 50±0.01°C. There is also a temperature compensation advice to eliminate the effect of residual temperature on gravity measurement. The temperature sensing element is a Weatstone bridge with two wirewound resistor sensitive to temperature change controlling its diagonal voltage. A winding of the moving coil attached to mass-spring system is connected to two ends of this diagonal. It is so adjusted that no current goes through the winding when inner temperature of the meter is exactly at 50°C, and the electro-magnetic force generated in the winding by the bridge precisely compensates the force change occurred in mass-spring system when inner temperature changes to keep reading of the meter constant.

SYSTEM COMPOSITION AND PRINCIPLE OF OPERATION

The CHZ Seagravimeter comprises three units:

- -Gravity sensor
- -Electronic control unit
- -Data acquisition unit

The block diagram of system is shown in fig.2. The system principle of operation is as follows.

The sensing system is a force balanced type. The weight of proof mass is balanced by a pretension helical spring to maintain the mass in original position where the output of capacitive displacement transducer is zero. The gravity changes are detected by transducer and compensated by electro-magnetic force generated in moving coil by P-I feedback control circuit, and therefore the current of the integrating coil is the measure of gravity variations.

The capacitor of transducer consists of three metal plates parallel to each other. The middle one, moving plate, is a part of the proof mass. The displacement caused by gravity changes is detected and changed into electrical signal which goes into the preamplifier, major amplifier and phase sensitive detector. The output of capacitive transducer is fed back into the P-I coil to compensate gravity changes. There is a non-linear correction circuit between output of transducer and input of integrator to ensure that dynamic reading of the meter agrees with the static one.

The output of integrating circuit goes into A/D converter to be digitized and then is sent to low-pass digital filter to average the short period (3-18 sec.) vertical accelerations. Disturbing accelerations with period of 10 sec. can be attenuated 40db, 80db and 120db according to sea states. The output data of digital filter is printed at interval of 1 to 100

minutes or manually in terms of need, and recorded on a cassette tape. The printing format is as follows.

year months days
hours, minutes; gravity observations

In order to monitor visually the performance of the meter the output data of digital filter is also sent to a D/A converter and then recorded continuously on the chart recorder.

Data acquisition system includes three pieces of microprocessor which are controlled by digital clock and can be programmed to conduct desirable operation, such as determining the data printing interval, multiplying gravity observations by calibration factor of the meter and so on.

TESTING RESULTS

A number of testing in laboratory, in field and at sea have been made to check the performance of the CHZ meter.

Laboratory testing

To simulate shipborne measurement the CHZ meter was placed in a gimbal suspension on a sinusoidal lift which was able to produce vertical accelerations up to 500gal. The meter has been tested against up to 250gal. Fig.3 shows the recorded results for non-linear correction test in sinusoidal lift. The deviations at the starting from static states to moving states or opposite were caused by impulse which occured whenever the lift started or stoped. The results indicate that the non-linear errors are less than 1 mgal, even though the vertical acceleration is up to 250gal.

Another testing in laboratory was made on a rocking machine on which the CHZ meter along with stabilized platform was mounted. The rocking machine swung from side to side up to $\pm 20°$, horizontal accelerations being up to 50gal, but the reading of the CHZ meter was hardly affected.

Field testing

The CHZ meter with the P-I feedback control circuit operative was placed in a car and was drove to city or countryside for several hours and then home. This kind of testing was conducted three times. No tares occured.

Testing at sea

The first testing measurement was conducted at South China Sea in August of 1985 on board a research vessel "Experiment 2" which belongs to South China Sea Institute of Oceanology. A Bodenseewerk KSS-30 Seagravimeter was aboard. This was a geophysical survey mission which included gravity seismological and magnetic measurements.

Fig. 4 and 5 show the measurement results in two cruise lines respectively. A dotted line representes the gravity observationsof CHZ meter, and a solid one is the measurements of KSS-30. The RMS value of discrepancies between the two meters is 1.4 mgal.

ACKNOWLEDGEMENT

We thank the South China Institute of Technology for developing the gyro-stabilized platform for CHZ meter, the South China Sea Institute of Oceanology who provided the research vessel for the testing and other cooperations, and the Shanghai Geological Instrument Factory who assisted in constructing and assembling the CHZ meter. Thanks is also given to Zhou Dongmin, Ye Bin, Wang Danian, Jiang Feng, Xu Zhiyang, Ding Chaoxi, Chen Jiaou, Liu Shuliang, Zhong Jie, Tong Songbo, He Jiangang, Shen Jianhua and Wu Chenyong who took part in the developing of CHZ meter and made contribution.

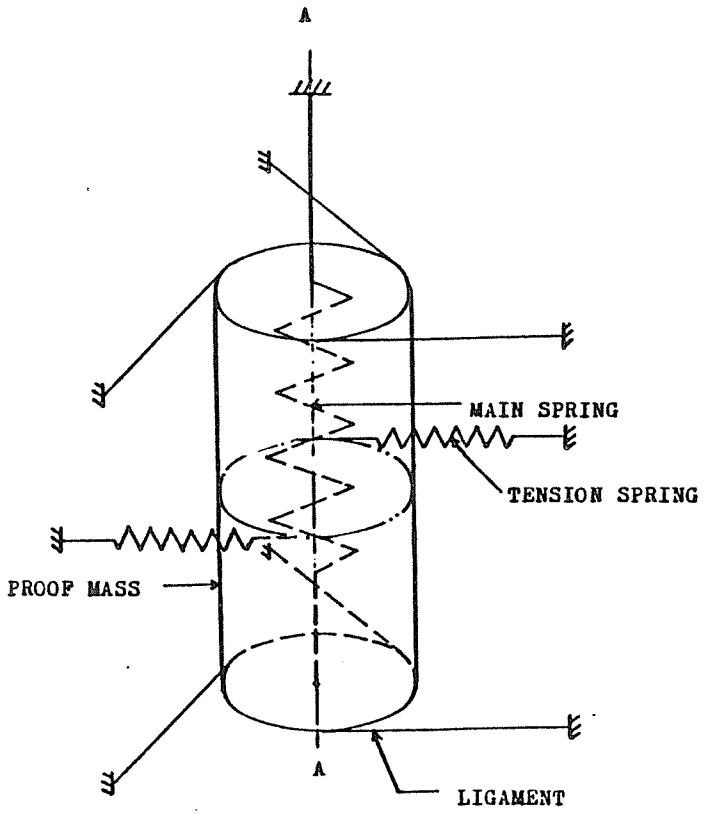


Fig.1 Simplified suspension system of CHZ meter with six lihaments

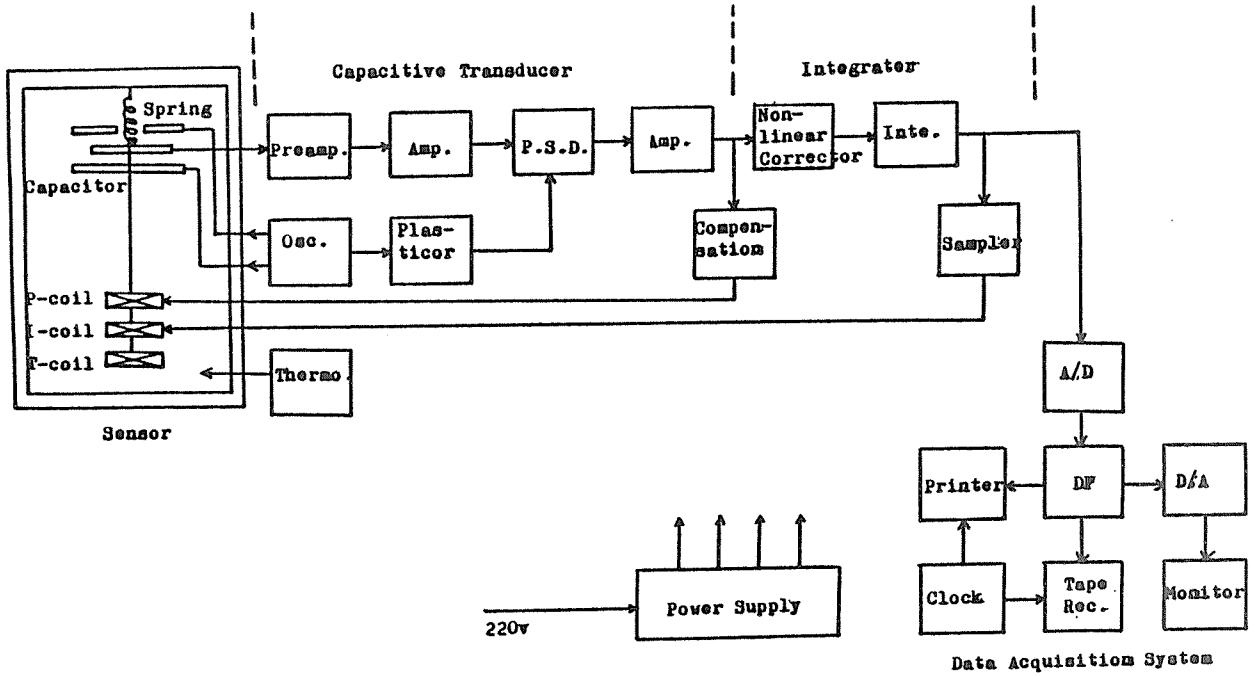
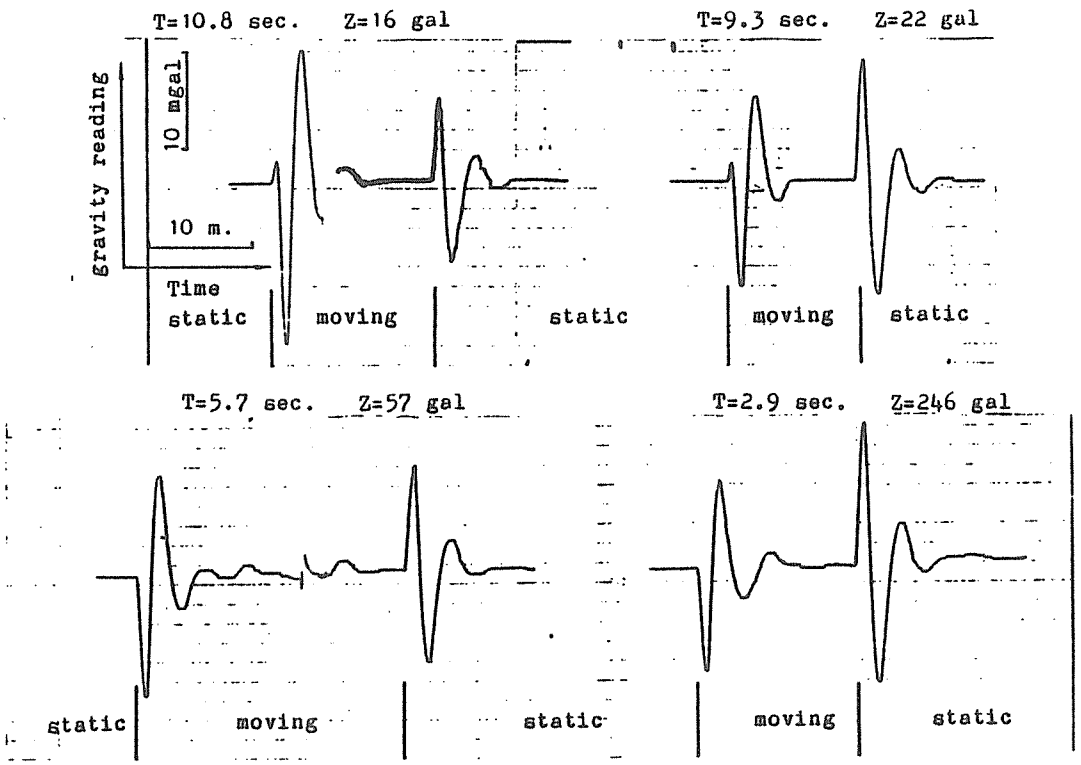


Fig. 2 CHZ Sea Gravity Meter Block Diagram



Z=amplitude of vertical accelerations. T=periods.

Fig.3 The results of non-linear correction test

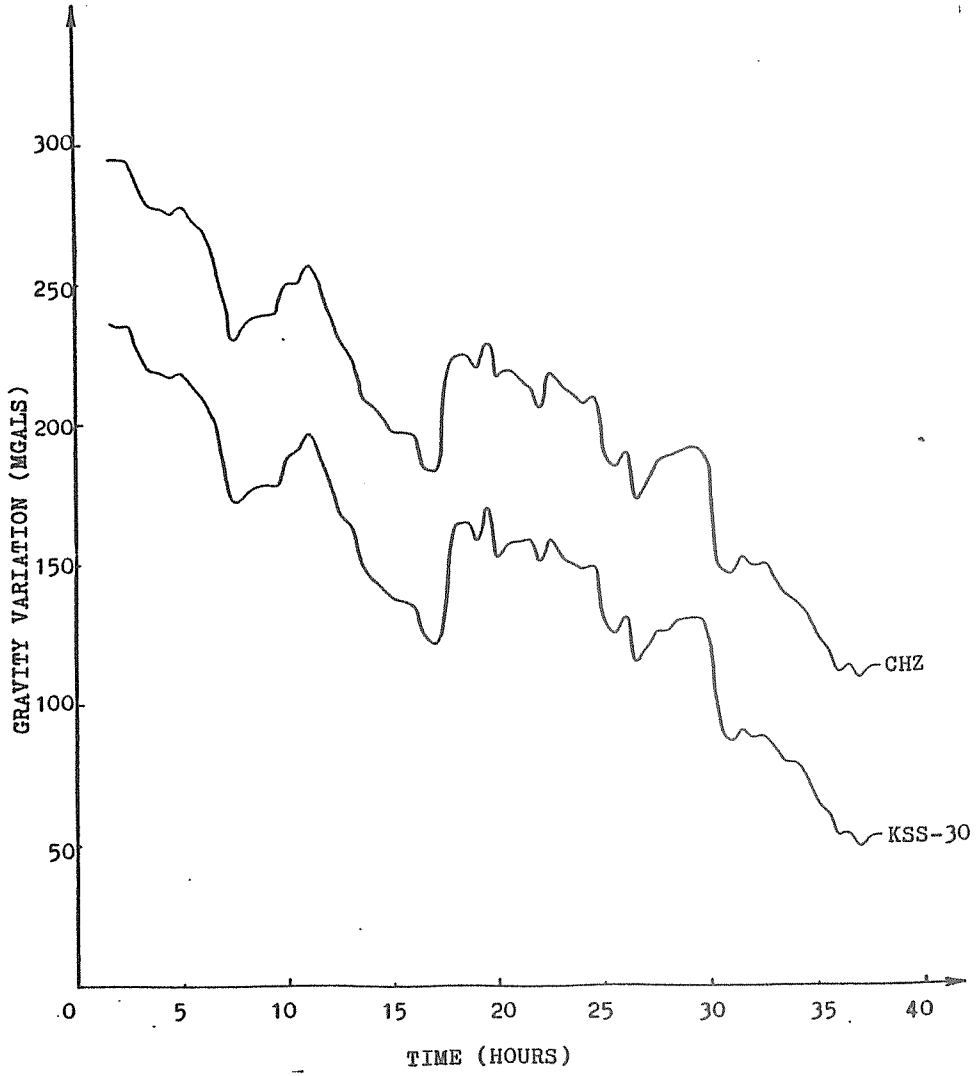


Fig.4 Gravity measurements of KSS-30 and CHZ meters on cruise line 1 at South China Sea

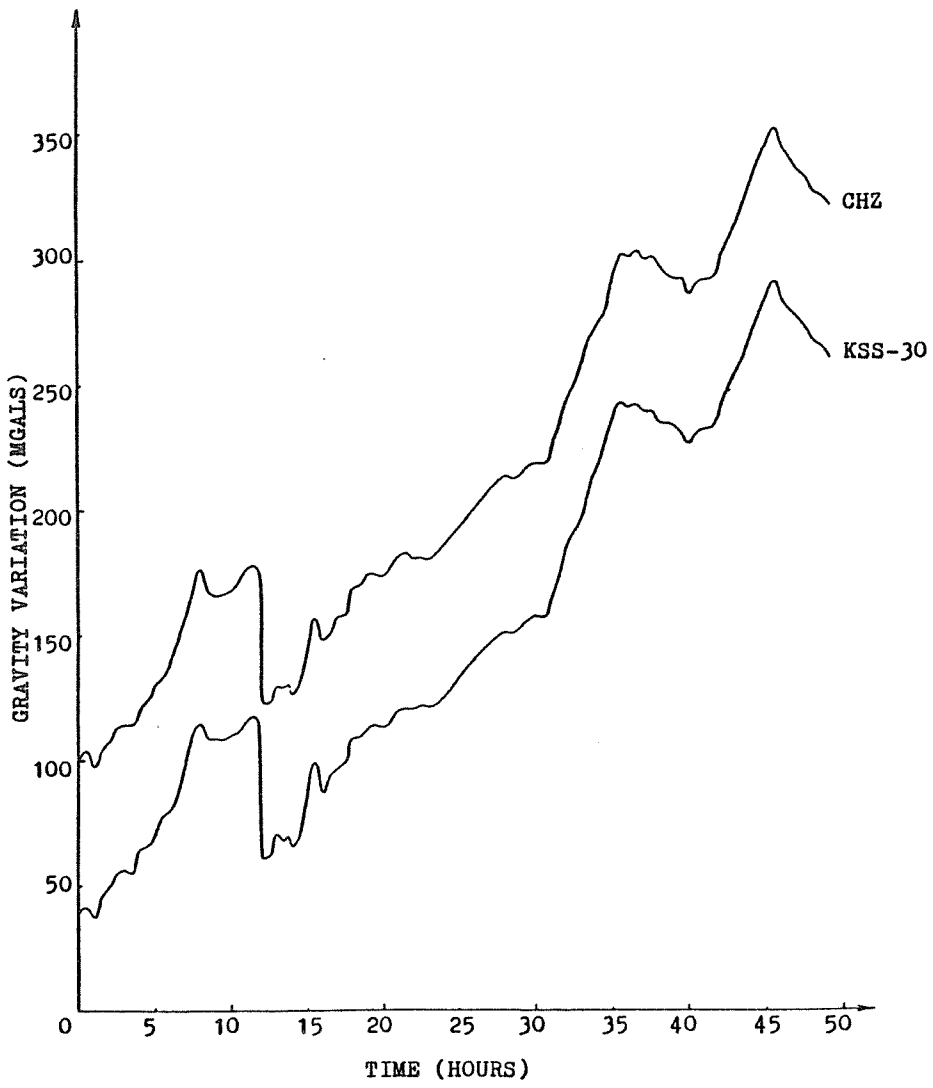


Fig.5 gravity measurements of KSS-30 and CHZ meters on cruise line 2 at South China Sea

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FOUR YEARS EXPERIENCE WITH THE KSS30 SEAGRAVIMETER

B.D. Loncarevic

Since July 1980 we have used KSS30 Seagravimeter on 12 cruises on 6 different ships. On ships of over 2000t displacement, with winds under 30 kts, the repeatability of readings is better than 2 mgal after applying a drift correction (usually less than 0.1 mgal/day) and compensating for a filter delay. Comparisons with other instruments showed that : i) an agreement of ± 0.05 mgal RMS can be reached between two KSS30s operating side-by-side ; ii) LaCoste & Romberg SL1 instrument had a slightly lower standard deviation on crossovers under high ship accelerations ; iii) KSS30 has the same or better accuracy as bottom gravimeter measurements ; and iv) latest improvements in the platform design (KT31) improve the standard deviation on crossovers by a factor of two.

Calibration Measurements with the Bodenseewerk Seagravity Meter Sensors KSS30 and KSS31

by
J. Fritsch (Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover)
and
K. H. Tödt (Institut für Geophysik, Universität Hamburg)

Abstract

Two sensors of the Bodenseewerk Seagravity meters - the KSS30 No. 15 and the KSS31 No. 22 - have been calibrated at the absolute gravity stations of the European Calibration Line (ECL). It was possible to determine the scale factors of the instruments with an accuracy of 1.E-4 over a gravity range of 2600 mGal. No evidence of a nonlinearity of the calibration function was found.

Introduction

For gravity measurements at sea we are seeking an accuracy of better than 1 mGal. In some coastal surveys an accuracy of 0.2 mGal has already been achieved. Well offshore, the present accuracy is typically 1 to 2 mGal and is limited by navigational errors at sea. When the GPS system is able to give a fullday coverage, the accuracy should increase to 0.1 mGal.
Sytematical errors in the gravimeter scale factor become important when the survey area is far from the starting point at which a harbour tie was measured. Measurements in the Antarctic are an extreme situation. Gravity measurements of RV POLARSTERN during the 1985/6 antarctic summer commenced at Punta Arenas, base for the Weddell Sea survey between latitudes 65 and 85 degrees south. The next harbour tie was measured in Cape Town at latitude 35 degrees south. The minimum gravity difference between these two harbours and the survey area is more than 1000 mGal. Therefore to achieve an accuracy of 0.1 mGal in the measured gravity values, the required scale factor accuracy is 1.E-4. Unfortunately the accuracy of the scale factor determined by the Bodenseewerk is only 50. E-4.
Our aim has been to improve this accuracy to 1.E-4 on the ECL using the absolute gravity values determined by Cannizzo, Cerutti and Marson (1978). The repetition accuracy of the sensors after clamping is approximately 0.2 mGal, so measurements must span a gravity difference of at least 1000 mGal. On the other hand the accuracy at the absolute stations is 10 times better than this, and thereby does not delimit the needed precision.
An map of the stations is given in fig. 1. For a few of these the remeasured values from Becker and Groten (1983) and Sigl et al (1981) were used.
Fritsch (BGR) carried out the first calibration of the KSS31 from Hannover to Hammerfest, and made additional measurements from Hannover to Munich passing through a gravity difference of 1500 mGal.
Tödt (IFG HH) made two trips with the KSS30 from Hamburg to Hammerfest and from Hamburg to Catania, passing through a gravity difference of 1300 mGal each time.
Calibration of the KSS31 on the southern part of the ECL will be carried out by Fritsch in October 1986.

Technical Details

The calibration was carried out [illegible] measurement. [illegible] transported in [illegible] heating of the gravit[illegible] with [illegible] mGal, [illegible]
The data were analogue recorded [illegible]
In the evenings, approximately [illegible] meter for recording. [illegible]

the room. Measurements were recorded during the entire night, after which the was taken down and boxed, an operation which took another 1.5 hours.
Operation of the gravity meter was controlled by observing the heating current and the surface temperature of the gravity meter. Athmospheric pressure was recorded with a microbarograph along some sections of the journey.

Evaluation of the Measurements

The readings were corrected for earth tides.
A simple drift curve was determined from the inconsistency of the up and down measurements.
A straight line was fitted to the readings which were plotted against absolute gravity (Ludwig, 1969). The gradient of this line is the scale factor.
Fig. 2 to 4 show the residuals which remain when the values from this line are subtracted from the readings.
Fig. 2 gives the residuals for the KSS31. The scale factor is

$$0.94558 \pm 0.4\ E\text{-}4.$$

The residuals are nearly all smaller than 0.1 mGal.
Fig. 3 shows the residuals for the KSS30 for the northern part of the calibration traverses and Fig. 4 for the southern part. The respective scale factors are

$$0.9116 \pm 0.6\ E\text{-}4$$

and

$$0.9116 \pm 1.0\ E\text{-}4$$

The residuals are about 0.1 mGal except for two cases of 0.2 mGal.

Conclusions

It has been possible to calibrate both gravity sensors with an accuracy of better than 1. E-4. No differences were found between the calibration factors determined on the northern and southern sections of the calibration line. The absence of a significant trend in the residuals indicates that the instruments have a linear calibration function in the investigated gravity range.

Acknowledgements

Tödt thanks the Deutsche Forschungsgemeinschaft for funding the calibration measurements of the KSS30 of the IFG Hamburg, and Prof. J. Makris who initiated the project and contributed many ideas.

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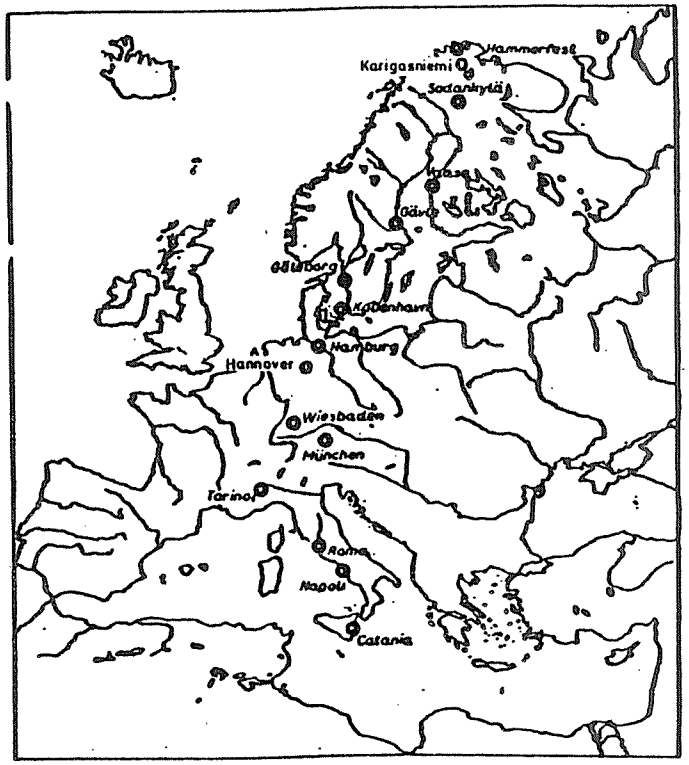
Figure Captions

Fig. 1 Map of the sites of the gravity stations

Fig. 2 Residual error of the readings of gravity sensor KSS31 No. 22 plotted against the gravity differences between Hannover and other stations using a scale factor of 0.94559 mGal/reading unit (Mu = Munich, Hn = Hannover, Co = Copenhagen, Gö = Göteborg, Gä = Gävle, Va = Vaasa, So = Sodankylä, Ka = Karigasniemi, Hm = Hammerfest).

Fig. 3 Residual error of the readings of gravity sensor KSS30 No. 15 plotted against gravity for the first part of the calibration measurements from Hamburg to Hammerfest (HH = Hamburg).

Fig. 4 Residual error of the readings of gravity sensor KSS30 No. 15 plotted against gravity for the second part of the calibration measurements from Hamburg to Catania (Wi = Wiesbaden, Tu = Turin, Ro = Roa, Ne = Naples, Ct = Catania).



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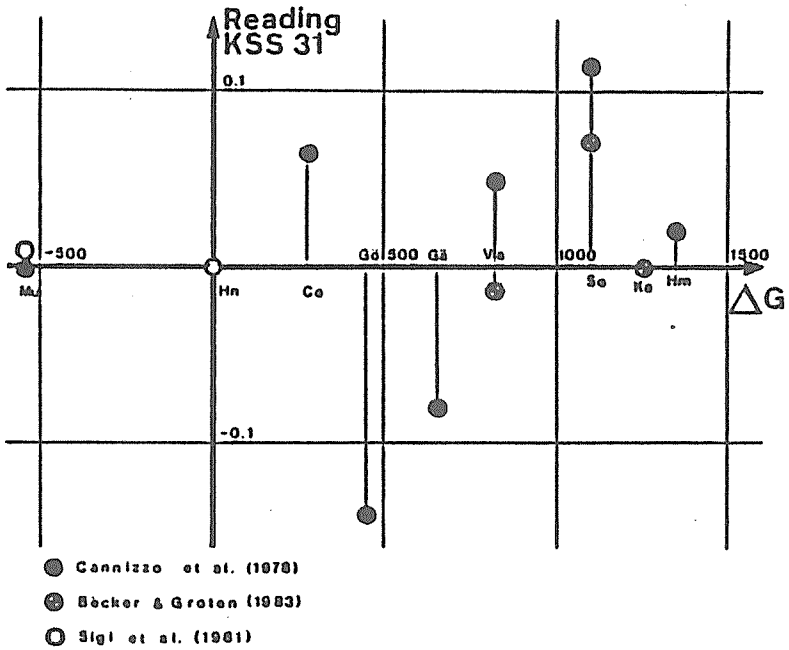

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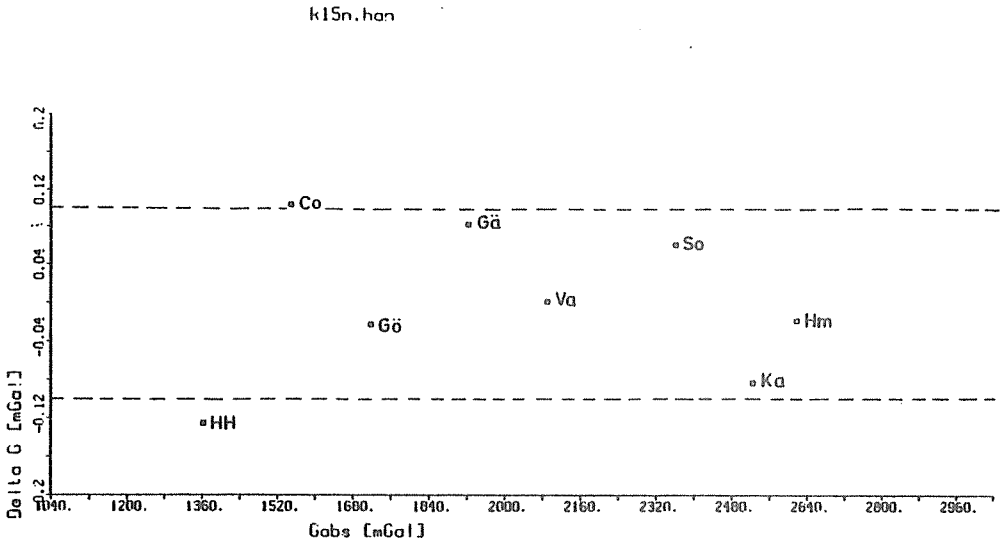

Fig. 3 Residual error of the readings of gravity sensor KSS30 No. 15 plotted against gravity for the first part of the calibration measurements from Hamburg to Hammerfest (HH = Hamburg).

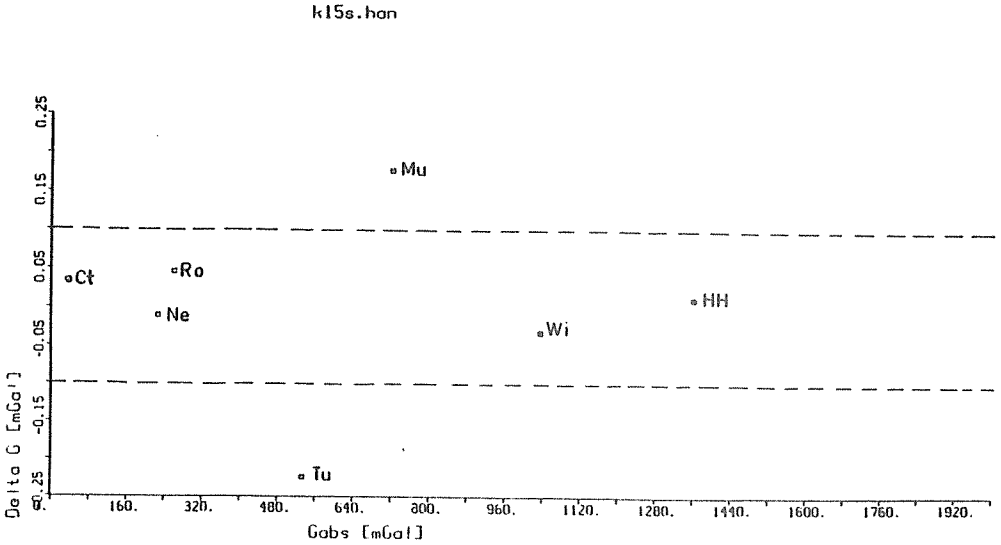

Fig. 4 Residual error of the readings of gravity sensor KSS30 No. 15 plotted against gravity for the second part of the calibration measurements from Hamburg to Catania (Wi = Wiesbaden, Tu = Turin, Ro = Rom, Ne = Naples, Ct = Catania).

*SATELLITE ALTIMETRY DERIVED GRAVITY ANOMALIES OVER THE OCEANS**

G. Balmino, B. Moynot, M. Sarrailh, N. Valès

We present here the result of the computation of 15' x15' free air gravity anomalies all over the oceans between latitudes 72° N and 60° S, using the inverse Stokes operator method combined with a high degree and order spherical harmonic model of the gravity field, and based on the most recent global mean sea surface derived from Seasat and Geos 3 (Marsh, 1985). It is a geodetic type work which should serve a variety of investigators in geophysics.

* EOS, January 1987 (in press)

STATUS OF THE GRAVITY GRADIOMETER SURVEY SYSTEM

DONALD H. ECKHARDT
Air Force Geophysics Laboratory
Earth Sciences Division
Hanscom Air Force Base, MA 01731-5000 USA

12th MEETING OF THE INTERNATIONAL GRAVITY COMMISSION
Toulouse, France

September 22-26, 1986

Under Defense Mapping Agency sponsorship, Bell Aerospace/Textron is building for the Air Force Geophysics Laboratory a moving base Gravity Gradiometer Survey System (GGSS). The GGSS is being installed in a motor van (Figure 1) that can be driven around to make ground level surveys or flown around, in a Lockheed Hercules (C-130) cargo airplane, to make airborne surveys. In its airborne mode, the GGSS will provide a rapid means for the detailed mapping of broad regions of the terrestrial gravity field.

The heart of the GGSS consists of three rotating fixtures, each of which holds four Bell Model VIIB accelerometers spaced every 90° about the rotation axis and with their input axes aligned with the direction of rotation (Figure 2). The three rotation axes are mutually orthogonal and they are mounted on a platform in an "umbrella configuration" so that each axis subtends the same angle from the local vertical. Just as the diurnally rotating Earth senses the gravity gradients of the Moon and Sun by responding with semi-diurnal M_2 and S_2 tides, the rotating accelerometer gravity gradiometer senses the local gravity gradients with a signal at twice the $\Omega = 0.25$Hz rotation rate of each fixture. The signal from each fixture is a linear combination (sums and differences) of the signals from its four accelerometers, bandpass filtered and demodulated at 2Ω into two outputs in quadrature (Figure 3). The six outputs from the three fixtures are adequate to determine the five independent elements of the local gravity gradient tensor. (Because the tensor is symmetric and its trace is zero, only five of its nine elements are independent.)

Figure 4 depicts the Bell Model VIIB accelerometer. Figure 5 is one of the rotating fixtures. Two of its four accelerometers are visible at the bottom; the electronics are at the top. The enclosed fixture is shown in Figure 6; three of these are mounted together on the GGSS platform as shown in Figure 7. In Figure 8, the platform is shown on test stand at the Bell facility in Niagara Falls, NY.

The actual real-time data processing scheme of the GGSS is very complex, involving the introduction of known frequency dithers along with feedback circuits to null the outputs due to the dithers; this allows one to minimize the sensitivity of the gradiometer to linear and angular accelerations and to balance the scale factors of the accelerometers. The GGSS sensitivity is ultimately determined by its principal noise source, the sensitivity to 1Ω linear accelerations, coming through the platform from the motor van and aircraft. This sensitivity can be improved by real-time and post survey data processing, and by changing the rotation rate; and the linear accelerations that are the original noise sources, are minimized by smooth rides or flights. While we are not yet certain what the rms noise of the GGSS in flight will be, we expect it to be in the range $\nu = 100E^2/Hz$ to $\nu = 600E^2/Hz$.

The GGSS is now being tested in the van and aircraft in the Phase I test area in the region of the Bell plant near Niagara Falls, New York. Soon the tests will move to the Phase II test area in Oklahoma and Texas.

Jekeli (1984) reviews considerations that go into the design of the most efficient survey flight path network for airborne surveys. In general, the GGSS aircraft will fly in an orthogonally gridded pattern. Trade-off

studies between the GGSS sensitivity and survey network geometry indicate that the inter-track spacing should be about 5 km. The survey altitude should be as low as safety permits; a survey altitude of about 600 m above ground level is appropriate. The Phase II airborne test will be flown over a 300 km x 300 square centered near Lawton, Oklahoma. With a north-south and east-west intertrack spacing of h = 5 km, the survey pattern is, in effect, a 60 x 60 square lattice. Integrating the appropriate elements of the gravity gradient tensor along each 5 km link gives the gravity vector difference between the connected nodes of the lattice.

Some of the techniques that have been devised for processing the airborne GGSS data are reviewed by Jekeli et al. (1985). Because a gravity gradiometer is inherently less sensitive to the longer wavelength components of the gravity field and is absolutely insensitive to the mean gravity vector in a survey region, GGSS data will have to be supplemented by long wavelength information to complete a survey. The favored technique is to have one or more tie points in the survey grid where the gravity disturbance and deflections of the vertical are measured at the ground and upward continued to the survey grid. Error analyses for the square test region indicate that the tie points are best chosen near the corners of the square.

There are several data processing steps that are required to map the gravity disturbance and deflections of the vertical using airborne GGSS measurements. The initial step is to process the raw GGSS signals to extract the elements of the gravity gradient tensor; next, ground truth measurements are upward continued to the network tie points; then the internodal adjustment is done; and finally the gravity vector is calculated along the tracks between the nodes and the field is interpolated and downward continued to the reference surface. The interpolation and the upward and downward continuations are done using the surveyed gravity gradients.

Error analyses for the square test region indicates that the tie points are best chosen near the corners of the square. Another consideration is that ground truth measurements should be made where the fine scale gravity gradients are fairly uniform -- away from tunnels or large structures.

Most techniques proposed for performing the internodal adjustment use least squares collocation (LSC). LSC techniques use the expected correlations of the gravity field and measurements to provide optimal solutions of GGSS networks. However, a priori covariances between different nodes of a network furnish very little information compared with multiple independent gradient measurements that are integrated and adjusted. In side-by-side comparisons of error analyses for several simple survey networks, calculations based on ordinary least squares and by a LSC template method, the results were identical for $\nu = 100\ E^2/Hz$ and they differed by no more than 4 per cent for $\nu = 600\ E^2/Hz$.

On the basis of my error analysis of the Phase II airborne survey (Eckhardt, 1986) and continuing studies along the same line, a simple rule of thumb for the (gravity disturbance or deflection of the vertical) variance, σ^2, at the center of a N x N square lattice with four tie points, one near each corner, has been derived:

$$\sigma^2 \approx \frac{1}{4}\sigma_o^2 + [\frac{1}{3}\ln N - 0.2]\nu v h$$

where σ^2 is the variance of each tie point, upward continued to a survey node and v is the aircraft velocity. The noise level, ν, should be in units of $(mGal/km)^2/Hz$ where $100E^2/Hz = 1(mGal/km)^2/Hz$. The

variances at other nodes away from the center are slightly larger than σ^2, except at the tie points where they are smaller, and at or near to the perimeter of the square where they are larger.

As examples in the use of this equation suppose that

$$\sigma_o = 0.3 \text{ mGal}$$

$$N = 60$$

$$\nu = 100E^2/\text{Hz} = (\text{mGal/km})^2/\text{Hz}$$

$$v = 400 \text{ km/hr} = 1/9 \text{ km/s}$$

and $h = 5$ km;

then $\sigma = 0.8$ mGal. Changing ν to 200 E^2/Hz, σ becomes 1.2 mGal; and changing it to 600 E^2/Hz, σ becomes 2.0 mGal. For deflections of the vertical, ν should be multiplied by $(206265/980000)^2 = 0.044$ where 206265 is the number of arc-seconds in one radian and 980000 mGal is, approximately, the acceleration of gravity. Suppose, then, that

$$\sigma = 0''.3$$

$$N = 60$$

$$\sigma = 100E^2/\text{Hz} = 0.27 \text{ (arc-s/km)}^2/\text{Hz}$$

$$v = 1/9 \text{ km/s}$$

and $h = 5$ km;

then $\sigma = 0.''23$. Changing ν to 200 E^2/Hz, σ becomes $0.''28$; and changing it to 600 E^2/Hz, σ becomes $0.''44$. We should have a much better idea of the value of ν and of the overall survey variance in a few months.

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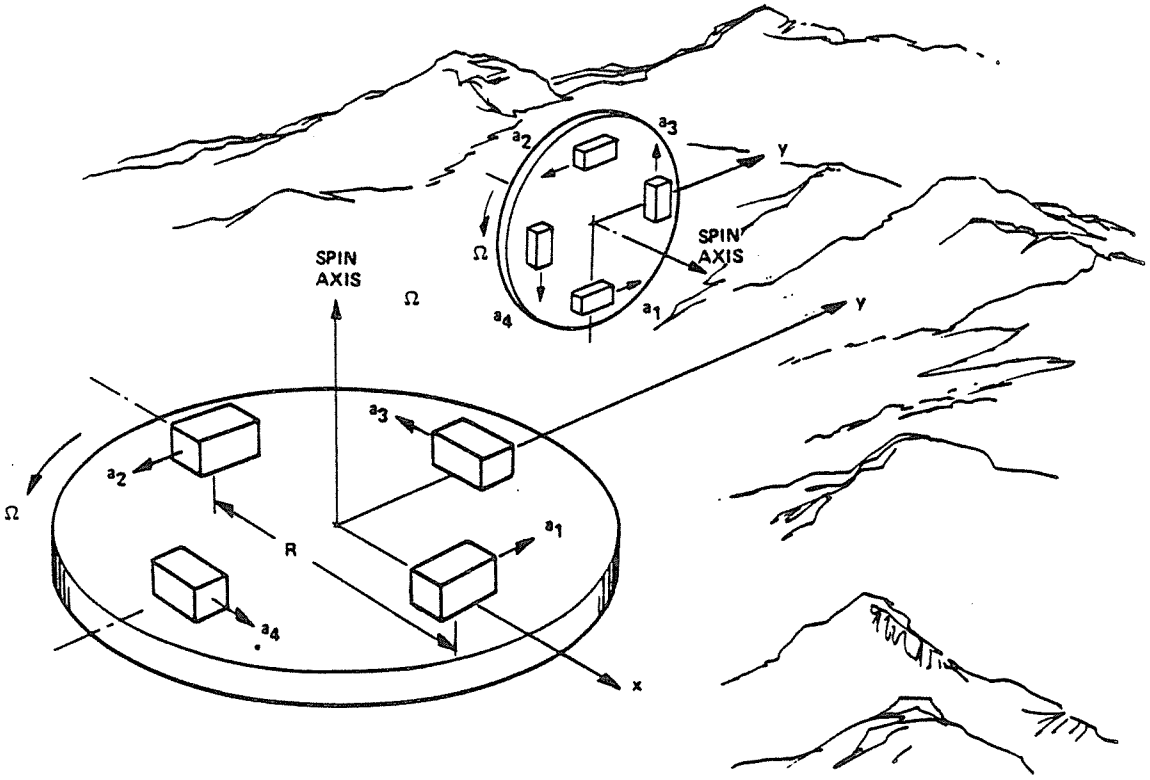
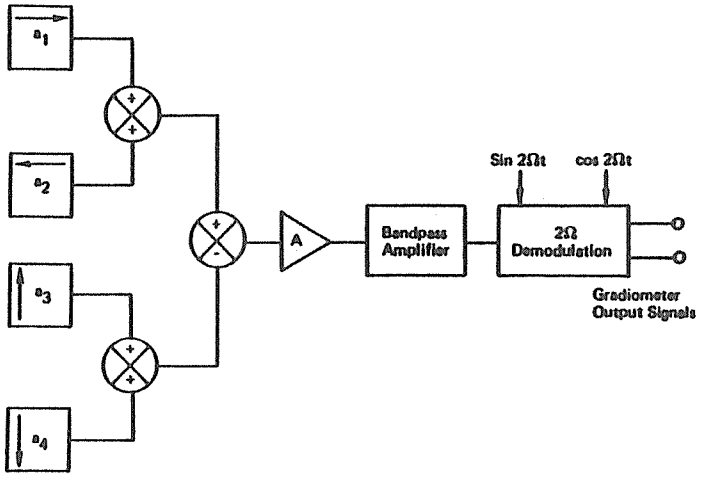
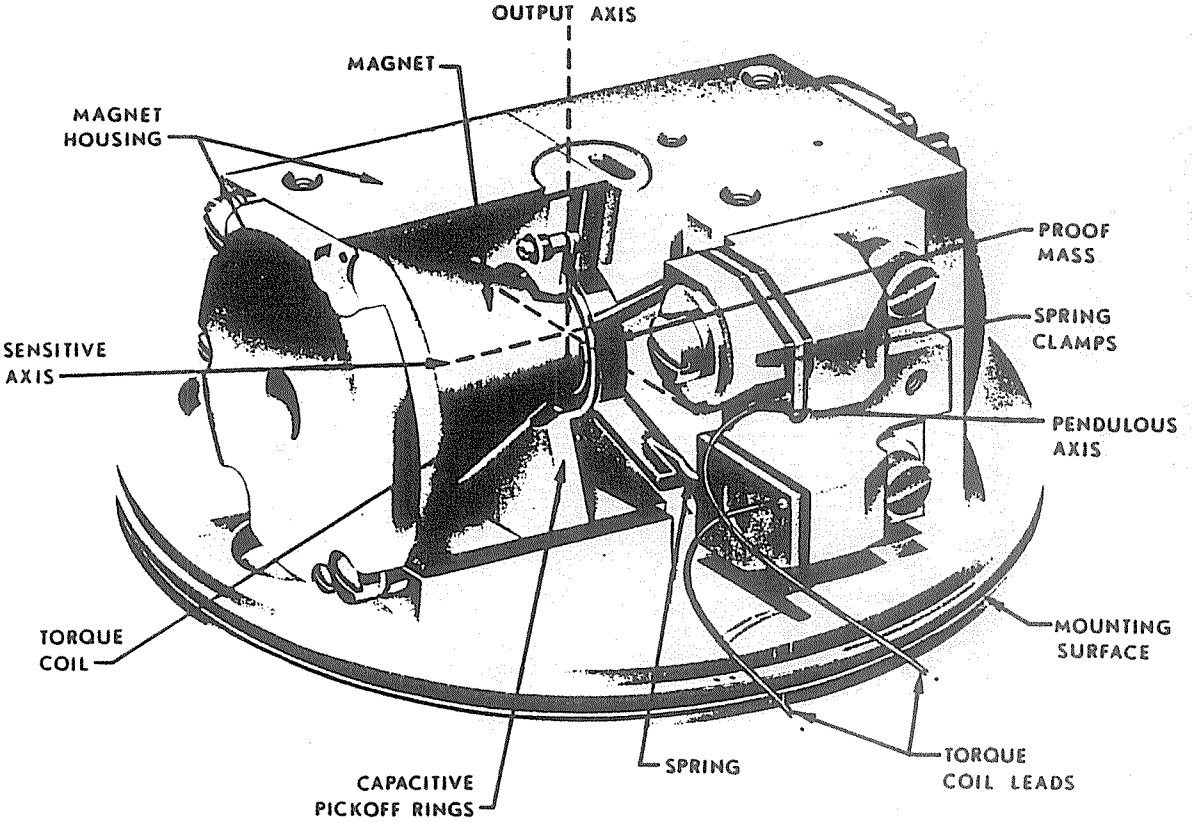


Schematic Illustration – Rotating Accelerometer Gravity Gradiometer

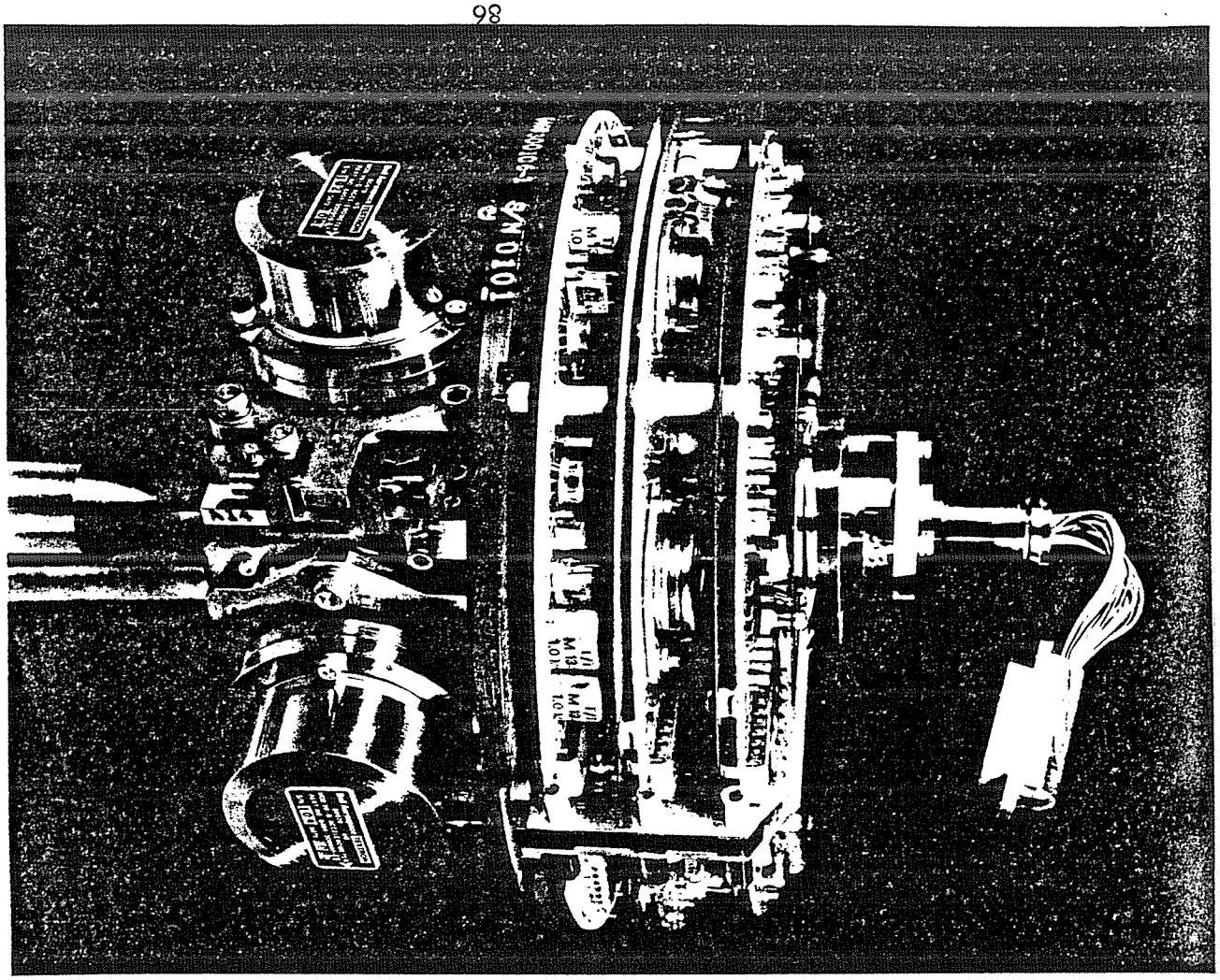


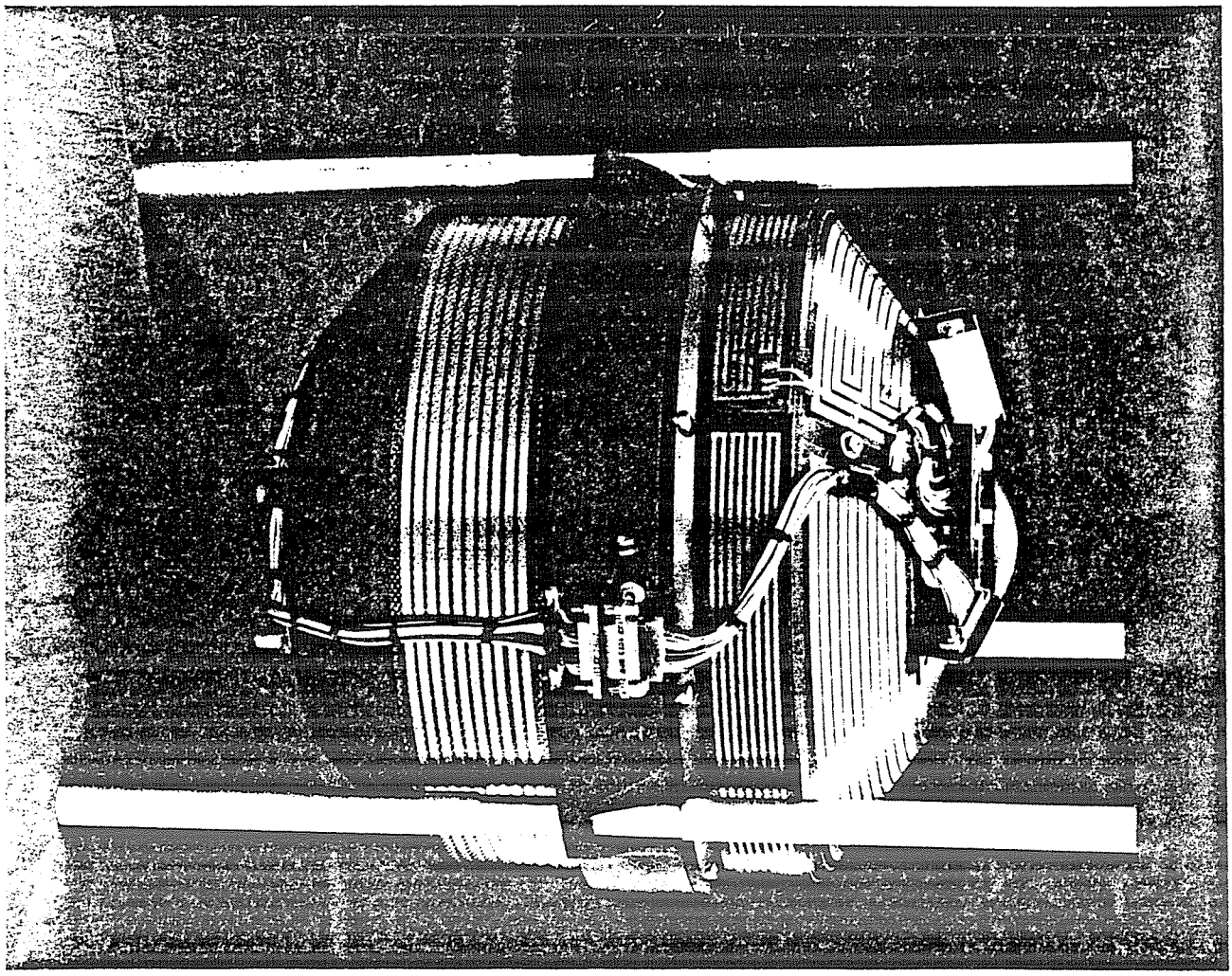
Simplified Block Diagram - Rotating Accelerometer Gradiometer

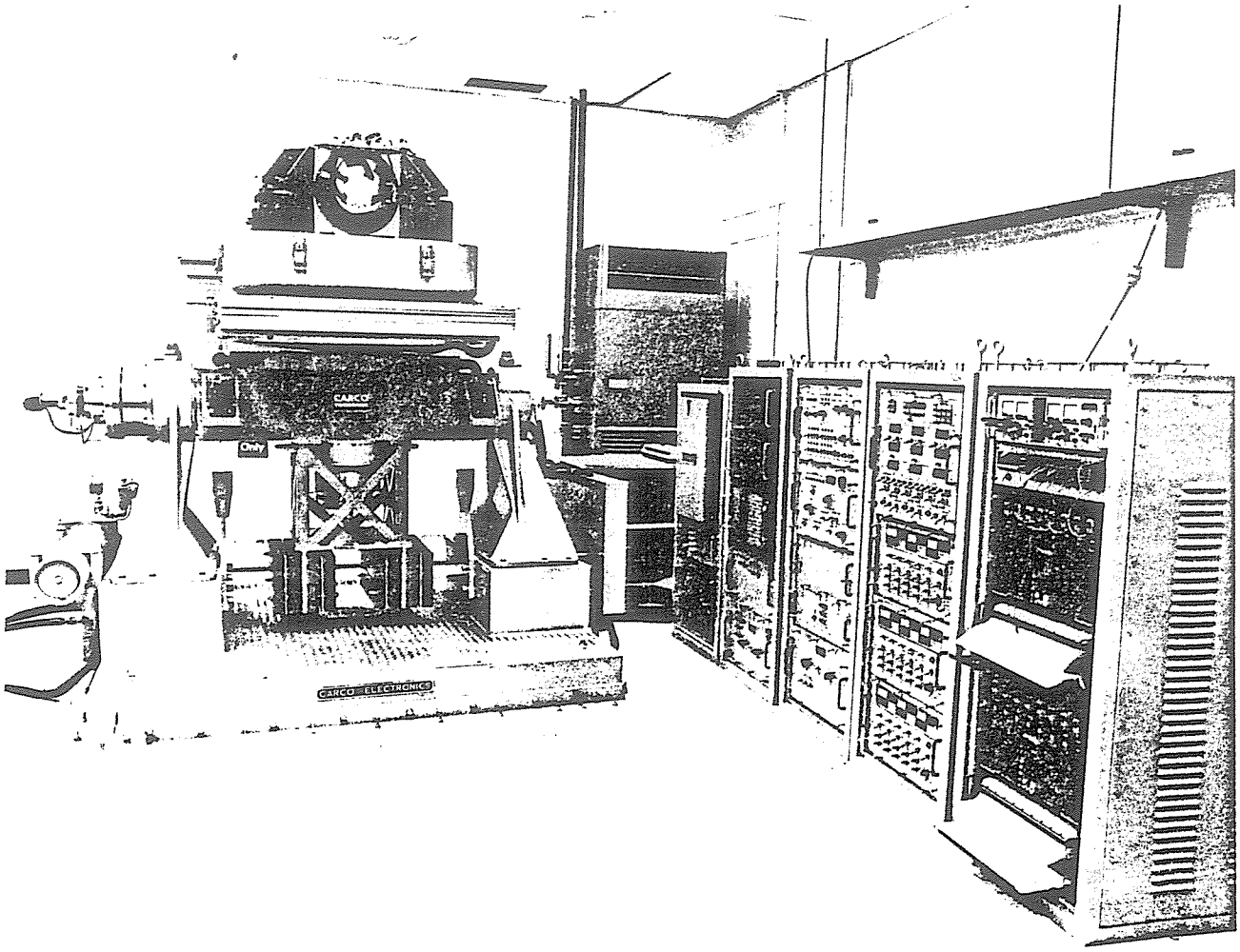


MODEL VIIB ACCELEROMETER

BELL AEROSYSTEMS · A textron COMPANY



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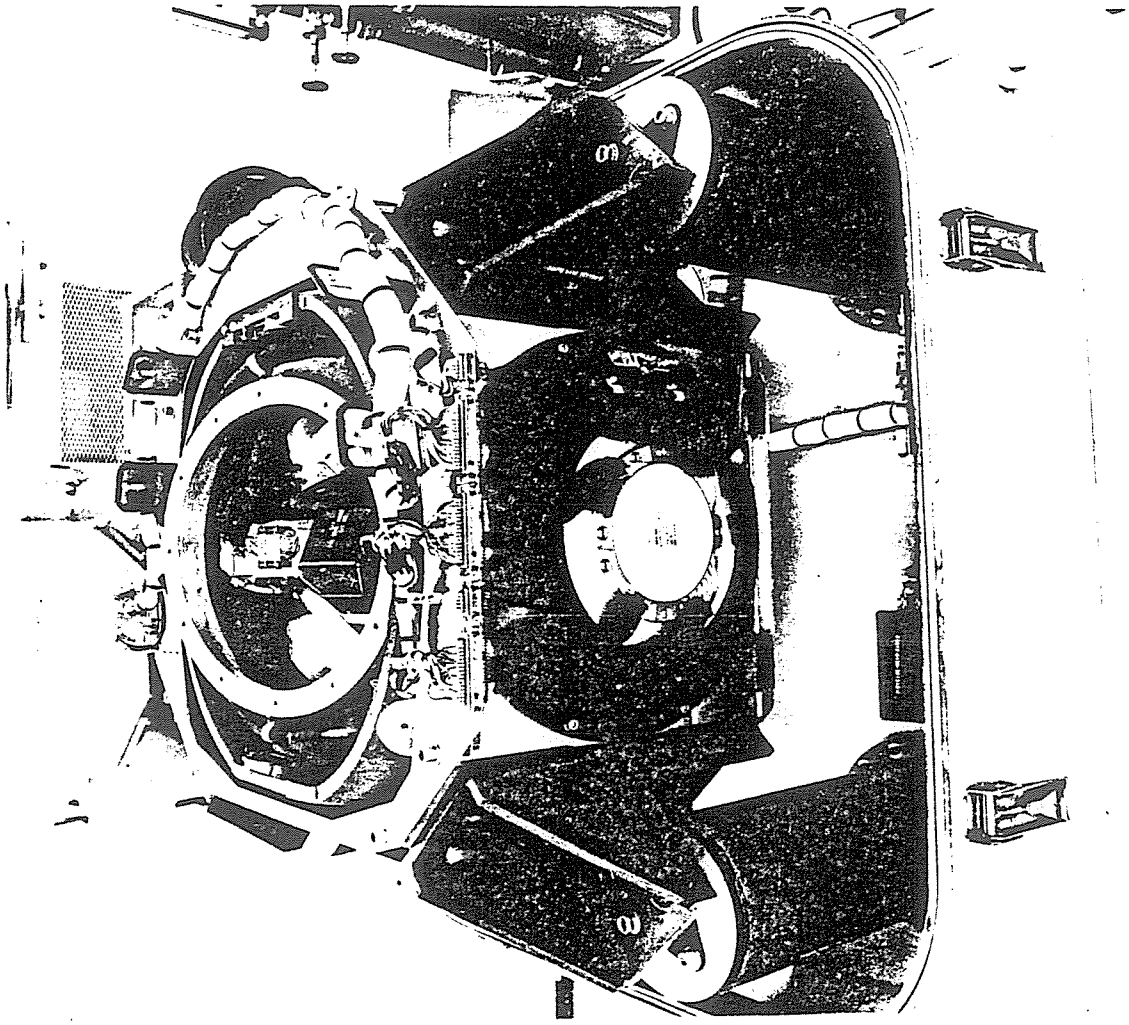

STATUS OF THE SATELLITE GRAVITY GRADIOMETER PROJECT GRADIO

G. Balmino, A. Bernard

Satellite gravity gradiometry is one of the most promising ways to map the Earth gravity field at medium and short wavelength. After recalling the basis principle of the method, we describe the concepts of a presently studied project. GRADIO, based on differential micro-accelerometry.

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RESULTS OF THE SECOND INTERNATIONAL COMPARISON OF ABSOLUTE GRAVIMETERS IN SEVRES 1985

Yu. Boulanger[1*)], J. Faller[2*)], E. Groten[3*)], G. Arnautow[4], M. Becker[3], H. Beetz[5], R. Beruff[6], L.Cannizzo[7], G. Cerutti[7], Feng-Youg-Yuan[8], Guo Yuguang[8], L.A. Haller[9], H. Hanada[10], W. Hollander[2], Huang Da-Lun[8], E. Kalish[4], I. Marson[11], T. Niebauer[2], C. Poitevin[12], B. Richter[5], R. Röder[13], A. Sakuma[14], R. Sands[15], G. Sasagawa[16], S. Schleglov[1], M. Schnüll[13], W. Spita[6], Yu. Stus[4], W. Tarasiuk[4], G. Wenzel[13], Zhang Guang-Yuan[8], Zhou Juing-Hua[8], Zhou Kungen[12], M. Zumberge[16]

1 Institute of Physics of the Earth, Academy of Sciences of the USSR, Moscow 123810, USSR (Absolute Gravimeter GABL)
2 Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, Colorado 80309-0440, USA (Absolute Gravimeter USA 1)
3 Institut für Physikalische Geodäsie, University of Darmstadt, Fed. Rep. of Germany (Gravimeters G258 and D38F)
4 Institute of Automatics and Electrometry, Siberian Branch of Academy of Sciences of the USSR, Novosibirsk 630090, USSR (Absolute Gravimeter GABL)
5 Institut für Angewandte Geodäsie, Frankfurt, Fed. Rep. of Germany (Gravimeters G563 and D21)
6 Defense Mapping Agency HTC, 20315 Washington D.C., USA (Gravimeters G131 and D79)
7 Instituto di Metrologia "G. Colonnetti", 10135 Torino, Italy (Italien Absolute Gravimeter)
8 National Institute of Metrology, Beijing, China (Chinese Absolute Gravimeter)
9 Land Survey of Sweden, S-801 12 Gävle, Sweden (Gravimeters G290 and G54)
10 International Latitude Service, Mizusawa, Japan (Gravimeter G305)
11 University of Triest, 34123 Trieste, Italy (Italien Absolute Gravimeter)
12 Observatoire Royal De Belgique, B-1200 Bruxelles, Belgique (Gravimeters G487F and D31F)
13 Institut für Erdmessung, University Hannover, Fed. Rep. of Germany, (Gravimeters G298F, G709F and D8F)
14 Bureau International des Poids et Mesures, Pavillon de Breteuil, Sevres, France (BIPM Absolute Gravimeter)
15 Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts 01731, USA
16 Scripps Institution of Oceanography, A-025, University of California, La Jolla, California 92093, USA (Absolute Gravimeter USA 2)

*) Editor

Following the recommendation of the International Association of Geodesy, the First Comparison of Absolute Gravimeters was carried out in 1981 (Sevres, 1981)/1,2/. One result that came out of that highly successful intercomparison was the confirmation of certain previously suspected systematic errors. At the General Assembly of IAG (Hamburg, 1983), with the hope of a somewhat greater participation and with a view to establishing a new first-order world gravimetric network, a resolution was adopted to organize in 1984 a Second International Comparison of Absolute Gravimeters. However, as several instruments were either not ready or unavailable for joint operations at the initially fixed date, the comparison was postponed to June-July 1985.

At the kind invitaion of the Bureau International des Poids et Mesures, the comparison was again conducted in Sevres at the main laboratory building of the BIPM. The preparation and the comparison procedure was entrusted to Prof. Yu. Boulanger, Chairman of SSG 3.86. (This special study group's charge is the evaluation of absolute gravity measurements.)

The instruments that were used came from five different countries: China, France (BIPM), Italy, USA (two instruments), and the USSR. All six of these instruments employ ballistic methods and utilize laser interferometry to measure position as a function of time. Two of them (BIPM and Italian) employ symmetrical rise-and-fall methods, while the others use direct free fall. Four (BIPM, Italian, Soviet, and the Jila-USA instrument) utilize some form of long-period isolation device to help reduce the drop-to-drop scatter. The IGPP-USA instrument uses a short (~1 sec) period isolation device, and the Chinese instrument does not (yet) utilize any form of mechanical isolation.

The intercomparison of all of the absolute instruments was made by transferring each of the individual measurements to a single benchmark set on the pillar at site A. To do this, a micro-gravity net (Fig. 1) of gravity differences was established using relative gravimeters. The vertical gravity

gradients were also measured at all of the sites on which absolute gravimeters were installed. The sites of absolute gravimeter installations were fitted precisely with the marks over which the absolute measurements were taken.

Prof. E. Groten, Chairman of SSG 3.85 (This study group is concerned with the comparison of high-precision gravimeter techniques), kindly agreed to organize and carry out the relative measurements and to process the results obtained. Table 1[3] shows vertical gradients W_{zz} assumed at the reduction to the pillar surface of g_o determined at the effective height H_o. Table 2 gives reductions to Site A and their errors.[3]

Altogether more than 1200 gravimeter readings were taken by 14 LaCoste Romberg gravimeters. The average accuracies as obtained in the least-squares adjustment are ± 0.8 μgal for the gradients and ± 0.7 μgal for the gravity differences. Questions of precision and accuracy of the relative gravimetry are discussed in Ref./3/ in more detail. With respect to the accuracy of the absolute apparatuses to be described below, the gravity differences of the combined adjustment of all instruments can be regarded as true reference values.

All absolute measurements were taken between June 28 and July 9, 1985, with a break from July 3 to 8, during which period the relative measurements were performed.

Table 3 gives the assigned errors for the absolute measurements. Column 1 lists the sources of these errors; the other columns give their values obtained on the engineering-physical basis. The similarity of errors for all instruments should be noted. The complete error for g,

$$M = \pm (M_o^2 + \Sigma m^2)^{1/2}$$

fell within the range of ± 5.6 μgal to ± 7.8 μgal. The Chinese instrument is an exception (± 13.8μgal); it has a large random error of ± 11.2 μgal (attributable to its present lack of a mechanical isolating system).

Table 4 presents a summary of all measurements taken by the absolute gravimeters. Appendices 1,2,3, 4 and 5 give more detailed data, i.e., results of measurements by individual falls and by series of falls. Results of measurements with the JILA instrument at Site A5 are represented by two histograms (Appendix 6). No detailed results of measurements performed by the Sakuma instrument were presented.

Corrections for tidal gravity variations were introduced into all of the absolute measurements; they were taken from the tables kindly supplied by Prof. Sakuma to all participants. This provided a uniform system of tidal corrections for all the instruments to use during this intercomparison. These corrections, incidently, were found to have a systematic discrepancy in amplitude of between 2 and 4 μgal on comparing them with the tidal corrections normally used with the various instruments.

The Honkasalo correction and the correction for polar motion were not introduced, whereas (common) corrections for the atmopheric mass attraction were introduced to all measurements.

Reduction to the pillar surface of g measured at an effective height, H_o, was calculated by the formula:

$$\Delta g_{W_{zz}} = W_{zz} H_o .$$

Gradients, W_{zz}, and their errors are shown in Table 1.

Table 5 gives results of all absolute determinations made during the calibration of gravimeters and adjusted to Site A at the pillar surface. The results of the intercomparison were rather surprising (Table 5). The results tend to fall into three groups. The maximum discrepancy between instruments reached 37.7 ± 9.4 μgal, an amount which cannot be explained simply by an accumulation of the individual quoted errors. Further, given the grouping, no simple correspondence with the particular method of measurement is evident.

One can only conclude from these data that in addition to the stated mean square errors of about ± 5 to ± 8 μgal for 5 of the 6 individual instruments, some or all have an as yet unrecognized systematic error source that could be as large, in the extreme case, as some tens of μgals. It should be noted that our analysis of the measurements does not single out for preference any one group of instruments. Therefore, without the benefit of additional studies and/or further intercomparisons, and noting the general similarity of instruments, the present accuracy of an absolute gravity determination by any one instrument could be in doubt (mean square error) by as much as ± 15 μgal.

This result poses an important question in regard to establishing a new first-order global gravity network. If a mean error of ± 10 μgal is required for this net (as has been stated many times) and absolute gravimeters are to be (necessarily) utilized, then the multiple instrument method of measurements would seem to be required. Under this approach, each site of this net would need to be occupied by no less than three different absolute gravimeters. The difficult question is: "Which three?"

There is, however, another possibility to be considered. One would expect the relative precision of measurement of an absolute gravimeter to exceed its absolute accuracy - at least over time periods during which major modifications and/or component changes have not occurred. And indeed, there is an excellent correlation of the Δg results between pillars A3 and A6 as measured by the GABL absolute gravimeter and the relative instruments. From absolute measurements, this difference was found to be 679.4 μgal; but from relative measurements it was 679.9 ± 0.8 μgal. This serves to corroborate this expectation: the measurement precision of an absolute instrument is higher than its measurement accuracy. When one is using absolute gravimeters to look for slow changes of the gravity field of the Earth with time, this fact can be expected to be helpful. Given the long time intervals (one year or longer) required to look for these changes, this increase in precision may not in practice be fully realizable unless one is conducting differential measurements. In using absolute gravimeters to establish a global gravity network, however, one would expect to be able to take advantage of this increase in precision. In that case, one is making (in part) differential measurements and the time intervals between absolute measurements at the various sites would be short.

The discrepancies between the gravity differences of the relative gravimeters to site A3 in the 1981 and the 1985 campaigns can be associated with the eccentric position of the gravity meters in the 1981 campaign. If a suitable correction is applied, the differences are reduced significantly, see Table 7.

The situation with the gradient on A3 is more complicated as can be seen in Table 8. Even if the measurements in 1981 were affected by the eccentric measurements, there has been a rather large increase in the gradient since 1980 or even since 1984 of more than 10 μgal/m.

It is interesting to compare the results of absolute determinations made in 1981 and 1985, Table 6.

On pillar A5 the difference between g (1981) and g (1985) was + 17.1 ± 12.6, whereas on pillar A6 it was − 0.4 ± 10.1 μgal. If we compare the correlation of g results on pillar A, it appears from the total of all measurements that gravity on pillar A during the intervening four years changed by 4.1 ± 5.9 μgal, a result completely consistent with no change at all having occurred. This result is in itself a bit surprising, for in this time frame a new laser laboratory was built at the BIPM immediately adjacent to the building in which pillar A is located. And though it is difficult to calculate exactly the effect of this new building's resulting "mass change" on the value of g at site A, a rough estimate would suggest that the value of g on pillar A - were nothing else to have changed in this four-year period - should be smaller by about 20 μgal, a number which is consistent with the (apparent) change that Sakuma has measured.

Conclusions

The second International Comparison of Absolute Gravimeters involving six instruments from five different countries was carried out in Sevres during June-July of 1985. All of the instruments appeared to work very well. The results of this intercomparison are, however, somewhat more discordant than one would have expected in view of the assigned 6-12 μgal error associated with the various instruments. Further, the apparent measurement discordance between the BIPM instrument of Sakuma and the other instruments is both surprising and unresolved. Transfer errors - even were the estimated error of the relative measurements to be increased by a factor of 3 to allow for some possible systematic error source affecting all of the instruments - cannot explain this discrepancy. The desireability of making measurements, however, with the same absolute apparatus at each of these sites is apparent. The intercomparison has served (again) to alert the various participants to the possibility that systematic errors may still be associated with their instruments. Accordingly, it has made clear the need for continued testing of the individual instruments in their home laboratories. Finally, it has pointed to the value of and the probable need for a Third International Comparison of Absolute Gravimeters in some 3-5 years.

Acknowledgements

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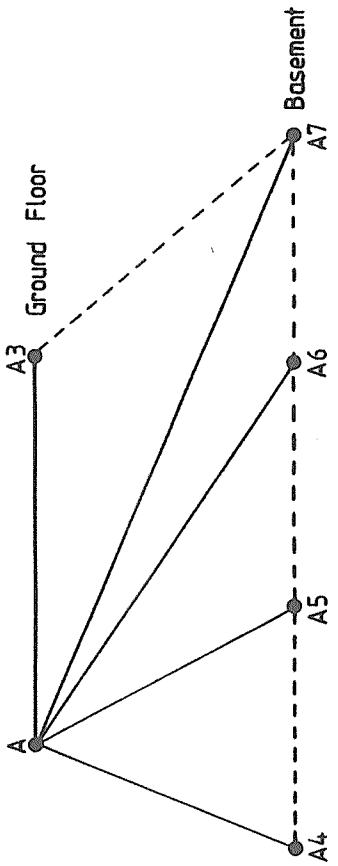


Fig.1 Micro gravity net, Sèvres 1985

Gradient-Measurements S è v r e s A

	Instr.	Instrumental height down	up	Difference m	Number of obs.	Gradient µgal/m
1	D8F	0.212	1.212	1	11	312.5±0.4
2	G298F	0.214	1.214	1	13	313.7±1.3
3	G709F	0.208	1.208	1	11	311.1±0.7
4	G563	0.406	1.406	1	8	313.7±0.9
5	D21	0.186	1.185	0.999	6	309.7±0.1
6	G54	0.217	1.031	0.814	6	314.3±0.9
7	G290	0.212	1.027	0.815	8	-
8	G305	-	-	1	6	308.2±4.6
9	G258	0.229	1.227	0.998	8	312.0±1.4
10	D38F	0.234	1.232	0.998	9	313.5±1.7
11	G131	0.206	1.206	1	7	303.3±1.3
12	D79	0.208	1.208	1	8	311.4±4.6
	Mean					311.4±0.7

Table 1.1

Gradients S è v r e s A 3

	Instr.	Instrumental height down	up	Difference m	Number of obs.	Gradient µgal/m
1	D8F	0.212	1.212	1	15	296.0±0.5
					13	296.4±1.2
2	G298F	0.214	1.214	1	11	290.0±0.7
					11	291.3±1.0
3	G709F	0.208	1.208	1	13	296.8±1.6
					11	297.0±0.7
4	G563	0.406	1.406	1	8	292.1±0.9
5	D21	0.192	1.191	0.999	6	291.5±0.5
6	G54	0.216	1.035	0.819	6	295.7±1.3
7	G290	0.212	1.032	0.820	8	303.9±0.5
8	G305	-	-	1	6	300.4±1.3
9	G258	0.229	1.229	1	8	299.4±3.3
10	D38F	0.234	1.234	1	9	302.3±1.0
11	G131	0.206	1.206	1	7	290.1±1.0
12	D79	0.208	1.208	1	7	298.7±2.1
	Mean					295.2±1.1

Table 1.2

Gradients — S è v r e s A 4

	Instr.	Instrumental height down	Instrumental height up	Difference m	Number of obs.	Gradient µgal/m
1	D8F	0.212	1.212	1	12	257.4±1.1
					11	254.4±1.5
2	G298F	0.214	1.214	1	11	255.0±1.2
3	G709F	0.208	1.208	1	13	252.0±1.4
					11	255.0±0.7
4	G563	0.406	1.406	0.999	6	253.9±1.2
5	D21	0.190	1.190	1	6	254.7±0.1
6	G54	0.219	1.036	0.817	6	261.1±0.6
7	G290	0.214	1.031	0.817	8	261.8±0.7
8	G305	-	-	1	6	246.5±0.8
9	G258	0.229	1.229	1	8	256.7±2.5
10	D38F	0.234	1.234	1	8	259.9±1.5
11	G131	0.206	1.206	1	7	262.3±0.7
12	D79	0.208	1.208	1	7	258.2±4.5
	Mean					255.9±1.0

Table 1.3

Gradients — S è v r e s A 5

	Instr.	Instrumental height down	Instrumental height up	Difference m	Number of obs.	Gradient µgal/m
1	D8F	0.212	1.212	1	13	251.8±0.5
2	G298F	0.214	1.214	1	11	256.4±0.8
					11	253.5±0.9
3	G709F	0.208	1.208	1	11	251.3±0.5
4	G563	0.406	1.406	1	6	252.5±1.0
5	D21	0.191	1.190	0.999	6	251.4±0.3
6	G54	0.218	1.035	0.817	6	253.4±0.3
7	G290	0.213	1.031	0.818	9	254.3±1.0
8	G305	-	-	1	6	245.5±1.0
9	G258	0.229	1.229	1	8	255.8±1.5
10	D38F	0.234	1.234	1	8	250.1±1.7
11	G131	0.206	1.206	1	7	255.4±0.9
12	D79	0.208	1.208	1	7	256.8±4.2
	Mean					252.5±0.7

Table 1.4

Gradients — S è v r e s A 6

	Instr.	Instrumental height down	Instrumental height up	Difference m	Number of obs.	Gradient µgal/m
1	D8F	0.212	1.212	1	14	259.6±1.0
					11	257.4±1.0
2	G298F	0.214	1.214	1	11	257.3±1.0
3	G709F	0.208	1.208	1	11	257.4±0.5
4	G563	0.190	1.189	0.999	6	256.6±1.4
5	D21	0.190	1.189	0.999	6	257.9±0.4
6	G54	0.217	1.036	0.819	8	261.3±1.4
7	G290	0.213	1.033	0.820	8	260.1±0.9
8	G305	-	-	1	6	253.2±0.7
9	G258	0.229	1.229	1	8	267.4±1.3
10	D38F	0.234	1.234	1	8	264.0±1.0
11	G131	0.206	1.206	1	7	262.5±1.4
12	D79	0.208	1.208	1	6	259.9±0.9
	Mean					259.0±0.8

Table 1.5

Gradients — S è v r e s A 7

	Instr.	Instrumental height down	Instrumental height up	Difference m	Number of obs.	Gradient µgal/m
1	D8F	0.212	1.212	1	11	257.8±0.7
					11	260.2±0.7
2	G298F	0.214	1.214	1	11	256.2±0.9
3	G709F	0.208	1.208	1	11	258.8±0.8
					10	258.0±1.1
4	G563	0.407	1.406	0.999	6	254.7±0.7
5	D21	0.192	1.191	0.999	6	258.7±0.3
6	G54	0.218	1.036	0.818	6	263.8±1.5
7	G290	0.214	1.032	0.818	8	261.2±0.8
8	G305	-	-	1	6	260.4±0.7
9	G258	0.229	1.229	1	10	262.0±2.0
10	D38F	0.234	1.234	1	10	260.5±1.0
					8	259.7±0.6
11	G131	0.206	1.206	1	7	262.5±0.5
12	D79	0.208	1.208	1	6	256.8±3.3
	Mean					259.1±0.5

Table 1.6

Table 2a. G-values of free-net single and combined adjustments with relative gravimeters only (μgal).

Instr.	1		3		4		5		6		7		
	g	mg	g	mg	g	mg	g	mg	g	mg	g	mg	mg
D8F	+0.05	1.32	-67.85	1.15	+583.75	1.93	+577.85	0.91	+608.85	1.34	+657.85	1.12	1.3
G298F	-0.72	1.0	-72.02	1.10	+584.18	1.37	+579.88	1.02	+609.48	1.22	+659.68	1.13	1.1
G709F	-0.45	0.62	-67.65	0.61	+582.85	0.50	+577.45	0.48	+610.05	0.58	+658.25	0.57	0.6
G563	+4.28	1.26	-67.52	1.32	+581.78	1.54	+575.98	1.36	+606.88	1.32	+659.08	1.24	1.3
D21	-1.45	0.25	-69.45	0.33	+583.55	0.34	+579.35	0.26	+609.75	0.35	+661.65	0.32	0.3
G54	-0.65	1.09	-70.05	1.08	+582.05	1.36	+576.95	1.11	+610.75	1.13	+661.45	1.17	1.2
G290	-1.45	1.24	-74.55	1.24	+584.25	1.59	+579.25	1.25	+610.05	1.24	+662.95	1.36	1.3
G305	+4.22	2.86	-64.38	3.19	+578.62	4.90	+580.12	2.73	+607.42	2.86	+654.52	2.67	3.3
G258	-3.88	1.58	-75.88	1.42	+589.82	2.73	+579.52	1.75	+607.82	2.07	+663.12	1.55	1.9
D38F	-1.32	1.89	-77.52	1.62	+587.48	1.52	+580.18	1.71	+612.68	1.62	+658.98	1.62	1.7
G131	-2.55	0.80	-71.05	0.78	+584.95	0.86	+579.45	0.72	+610.45	0.75	+659.25	0.80	0.8
D79	-0.57	2.14	-70.77	1.98	+582.83	2.22	+580.83	2.26	+607.73	1.89	+660.43	2.30	2.1
D31F	+0.47	2.92	-74.53	3.01	+588.37	2.96	+580.77	2.58	+607.87	4.95	+657.57	2.60	3.2
G487F	+0.12	1.02	-73.58	1.10	+585.32	1.09	+581.62	1.04	+611.42	1.21	+655.62	1.00	1.1
comb.	0.0	0.4	-70.7	0.4	583.2	0.5	578.7	0.4	609.2	0.4	660.1	0.4	0.4

Table 2b. Review of relative measurements

Instrument	Date	Number of station occupations						
		A	A3	A4	A5	A6	A7	S
D8F	03.07.85	2	7	-	8	2	12	31
	04.07.85	2	3	1	2	2	1	11
	05.07.85	2	-	-	2	4	-	8
	06.07.85	7	10	5	11	3	2	38
G298F	03.07.85	9	8	-	8	4	5	34
	05.07.85	3	2	2	2	2	2	13
	06.07.85	6	6	7	9	2	5	35
G709F	03.07.85	8	9	-	6	5	11	39
	04.07.85	3	2	3	2	2	3	15
	06.07.85	6	6	12	12	5	4	45
G563	04.07.85	6	4	-	6	6	4	26
	05.07.85	2	2	2	2	2	3	13
	06.07.85	4	4	2	2	3	4	19
D21	03.07.85	3	3	-	2	2	2	12
	04.07.85	3	2	-	2	2	2	11
	06.07.85	3	-	6	3	-	-	12
G54	03.07.85	2	2	-	2	3	2	11
	04.07.85	2	2	2	3	2	2	13
	06.07.85	3	3	2	2	2	2	14
G290	03.07.85	2	2	-	2	3	2	11
	05.07.85	2	2	2	3	2	2	13
	06.07.85	3	3	2	2	2	2	13
G305	03.07.85	2	2	-	2	2	3	11
	04.07.85	2	2	3	2	2	2	13
G258	03.07.85	2	2	-	2	2	2	10
	04.07.85	2	2	3	2	2	2	13
	06.07.85	2	3	2	2	2	3	14
D38F	04.07.85	2	2	3	2	2	2	13
	05.07.85	2	2	3	2	2	2	13
G131	03.07.85	2	4	-	2	2	2	12
	05.07.85	2	4	2	2	2	2	14
	06.07.85	2	2	2	3	4	2	15
D79	03.07.85	3	2	-	2	1	2	10
	05.07.85	2	3	2	2	4	2	15
	06.07.85	3	3	3	2	2	2	15
D31F	03.07.85	-	-	-	1	2	1	4
	06.07.85	2	3	2	2	-	2	11
	07.07.85	2	2	2	2	-	2	10
G487F	04.07.85	4	3	-	2	1	2	12
	05.07.85	2	2	2	2	2	3	13
	06.07.85	2	2	2	3	1	2	12

tie	1981	1981 corrected	1985	Diff
A -A3	-79.6	- 69.6	-70.7	- 1.0
A3-A4	657.4	647.4	653.9	+ 6.5
A3-A5	659.2	649.2	649.4	+ 0.2
A3-A6	686.4	676.4	679.9	+ 3.5
A4-A5	1.8	-	-4.5	- 6.3
A4-A6	29.0	-	26.0	- 3.0
A5-A6	27.2	-	30.5	- 3.3

Table 7

Source	Sakuma	Becker, Groten	B.R.G.M. (Ogier)	Becker	B.R.G.M. (Ogier)
year	1980	1981	1984	1985	1985
W_{zz}	273	283.6±1.6	274.8	295.2±1.1	296.9±4.6

Table 8

Table 3

Errors of Measurements

Source of errors	France A	Italy A3	USSR A3	China A4	USA A5	USSR A6	USA A7
	m c g a l						
Error of one drop	-	± 13	± 130	± 283	-	± 144	± 175
Number of drops	300	112	900	292	3950	1651	2571
Accidental errors	± 5.6	± 2.2	± 3.2	± 11.2	± 2.0	± 4.0	± 3.6
Laser wavelength	-	2	2	4	2	2	2
Magnetic forces effect	-	-	1	3	1	1	1
Electrostatic effect	-	-	-	-	1	-	1
Pressure effect	-	3	3	6	5	3	2
Optical effects	-	-	2	-	1	2	3
Time interval determination	-	1	1	-	1	-	1
Deviation from vertical	-	2	-	-	-	-	2
Body rotation	-	2	-	-	-	-	1
Frequency non-stability	-	-	1	-	-	1	1
Temperature effect	-	-	-	-	1	-	2
Response effect	-	-	-	-	5	-	1
Translation	-	-	-	2	-	-	1
Reduction to pillar surface	0.7	1.1	1.1	1.0	0.7	0.8	0.5
Total errors M	± 5.6	± 5.3	± 5.6	±13.8	± 7.8	± 6.0	± 6.7

Table 4

Results of absolute gravity measurements

Country	Points	H_o	W_{zz}	g $(H - H_o)$	Δg_H	g $(H = 0)$	M
		mm	mcgal	mcgal	mcgal	mcgal	mcgal
1. BIPM	A	1120	311.4	980 925 627.5	348.8	980 925 976.3	± 5.6
2. Italy	A3	851	295.2	673.4	251.2	924.7	5.3
3. USSR	A3	980	295.2	642.5	289.3	931.8	5.6
4. China	A4	1120	255.9	926 313	286.6	926 599.6	13.8
5. USA	A5	830	252.5	368.5	209.6	578.1	7.8
6. USSR	A6	971	259.0	359.7	251.5	611.2	6.0
7. USA	A7	1090	259.1	391.1	282.4	673.5	6.7

Table 5

Results of comparison absolute gravimeters

Country	Points	g		Reductions		g(A)		$\bar{g}$(A)
		mcgal		mcgal		mcgal		mcgal
BIPM	A	980 925 976.3	± 5.6	-		980 925 976.3	± 5.6	980 925 976.3 ± 5.6
Italy	A3	925 924.7	5.3	+ 70.7	± 0.4	925 995.4	5.3	980 925 999.8 ± 3.1
USA 1	A5	926 578.1	7.6	- 578.7	0.4	925 999.4	7.6	
USSR	A3	925 931.8	5.6	+ 70.7	0.4	926 002.5	5.6	
USSR	A6	926 611.2	6.0	- 609.2	0.4	926 002.0	6.0	
USA 2	A7	926 673.5	6.7	- 660.1	0.4	926 013.4	6.7	980 926 014.8 ± 7.6
China	A4	926 599.4	13.8	- 583.2	0.5	926 016.2	13.8	

Average simple of all results: $\bar{g}$ = 980 926 000.7

m = ± 13.2

M = ± 5.0

Average weighed of all results: $\bar{g}$ = 980 925 997.7

M = ± 4.4

Table 6

Changes of gravity field

Year	g	W_{zz}	Δg	g(A)
	mcgal	mcgal	mcgal	mcgal
Point A5 (USA, J.Faller)				
1981	980 926 562 ± 10	250.0 ± 1.1	- 579.6 ± 1.2	980 925 982.4 ± 10.1
1985	578.1 7.8	252.5 ± 0.7	- 578.7 ± 0.4	939.4 7.8
Diff.	+ 16.1 ± 12.7	+ 2.5 ± 1.3	+ 0.9 ± 1.3	+ 17.0 ± 12.8
Point A6 (USSR, G.Arnautov)				
1981	980 926 609 ± 8	251.8 ± 1.2	- 606.8 ± 1.4	980 926 002.2 ± 8.1
1985	611.2 ± 6.0	259.0 ± 0.8	- 609.2 ± 0.4	002.0 ± 6.0
Diff.	+ 2.2 ± 10.0	+ 7.2 ± 1.4	- 2.4 ± 1.5	- 0.2 ± 10.1
Point A3 (All measurements)				
1981	980 925 914 ± 3.7	(283.6±1.6)	+ 79.6 ± 1.5	980 925 993.6 ± 4.0
1985	928.2 ± 4.4	(295.2±1.1)	+ 70.7 ± 0.4	998.9 ± 4.4
Diff.	+ 14.2 ± 5.7	(+11.6±1.9)	- 8.9 ± 1.6	+ 5.3 ± 5.9

Appendix 1

Results of measurements at point A3, Sevres, 1985

Observers: L.Cannizzo, G.Cerutti, I.Marson; Instituto di Metrologia "G.Colonnetti", Italy

W_{zz} = 295.5 mcgal/m

No	Time (UT)	H_o	Measured g	g	P_a	C_{p_a}	g
		mm	mcgal	mcgal	mbar	mcgal	mcgal
			Serie n 1	June 30			
1	13^h35^m	856.9	980 925 620.0	57.4	1009.7	- 1.4	980 925 929.2
2	13 40	865.8	604.6	53.6	9.7	- 1.4	912.6
3	13 51	863.1	602.2	45.2	9.6	- 1.5	900.9
4	13 56	862.0	613.0	41.4	9.6	- 1.5	907.6
5	14 03	854.5	637.6	36.1	9.5	- 1.5	924.7
6	14 08	854.6	641.1	32.3	9.5	- 1.5	924.4
7	14 14	860.3	642.7	27.7	9.4	- 1.5	923.1
8	14 18	861.2	663.2	24.6	9.4	- 1.5	940.8
9	14 23	860.2	657.9	20.6	9.4	- 1.5	931.1
10	14 28	853.3	679.6	16.9	9.3	- 1.6	947.1
11	14 34	860.3	663.5	12.4	9.3	- 1.6	923.5
12	15 16	851.4	694.0	-18.0	9.1	- 1.7	925.9
13	15 21	861.9	683.3	-21.5	9.1	- 1.7	914.8
14	15 26	860.3	692.4	-25.0	9.0	- 1.7	919.9
15	15 31	851.4	701.3	-28.4	9.0	- 1.7	922.4
16	15 36	858.4	720.5	-31.5	9.0	- 1.7	941.0
17	15 41	857.7	712.3	-34.7	8.9	- 1.8	939.3
18	15 50	851.3	712.1	-40.2	8.9	- 1.8	921.7
19	15 55	858.9	730.9	-43.4	8.8	- 1.8	939.5
20	16 00	858.0	724.7	-46.5	8.8	- 1.8	929.9
21	16 05	856.6	726.9	-49.1	8.8	- 1.8	929.1
22	16 10	856.6	734.4	-51.8	8.7	- 1.8	933.9
23	16 16	855.7	740.5	-54.9	8.7	- 1.8	936.7
24	16 22	848.0	737.5	-58.1	8.7	- 1.8	928.2
25	16 27	848.3	725.0	-60.7	8.6	- 1.9	913.1
26	16 33	849.0	741.9	-63.1	8.6	- 1.9	927.8
27	16 38	856.1	742.1	-65.9	8.6	- 1.9	927.3
28	16 44	847.0	750.2	-68.2	8.5	- 1.9	930.4
29	16 49	847.2	751.8	-70.3	8.5	- 1.9	929.9
30	16 54	854.8	756.1	-72.5	8.4	- 2.0	934.2

Continuation

		mm	mcgal	mcgal	mbar	mcgal	mcgal
31	16^h59^m	848.3	980 925 749.8	-74.6	1008.4	- 2.0	980 925 923.9
32	17 04	854.6	746.9	-76.3	8.2	- 2.1	921.0
33	17 09	854.1	756.4	-77.8	8.2	- 2.1	928.9
34	17 16	854.3	753.0	-79.7	8.2	- 2.1	923.6
35	17 20	854.0	764.1	-81.3	8.2	- 2.1	933.1
36	17 25	854.7	772.8	-82.8	8.2	- 2.1	940.5

k = 36; $\overline{H}_o$ = 855.6 mm

$\overline{g}$ = 980 925 927.1
m = ± 9.6 mcgal
M_o = ± 1.6 mcgal

Serie n.2 July 01

1	08 30	846.6	980 925 584.4	91.0	1008.5	- 1.9	980 925 923.7
2	08 36	846.1	586.5	95.1	8.5	- 1.9	929.7
3	08 42	846.7	578.0	99.1	8.5	- 1.9	925.4
4	08 46	845.1	586.4	101.8	8.5	- 1.9	936.0
5	08 49	845.1	592.1	103.9	8.5	- 1.9	943.8
6	08 53	852.6	543.8	106.6	8.5	- 1.9	900.4
7	08 56	852.6	599.5	108.6	8.5	- 1.9	958.1
8	09 00	846.0	559.6	111.3	8.5	- 1.9	919.0
9	09 03	853.0	554.8	113.0	8.5	- 1.9	918.0
10	09 07	854.8	570.0	115.3	8.5	- 1.9	936.0
11	09 11	845.3	573.2	117.6	8.5	- 1.9	938.7
12	09 15	844.6	567.8	119.9	8.5	- 1.9	935.4
13	09 20	851.9	525.9	122.8	8.5	- 1.9	898.5
14	09 25	845.4	558.6	125.1	8.6	- 1.9	931.6
15	09 32	851.0	577.7	129.4	8.6	- 1.9	956.7
16	09 36	843.6	551.3	131.2	8.6	- 1.9	929.9
17	09 40	851.1	541.2	132.9	8.6	- 1.9	923.7
18	09 44	843.1	545.3	134.7	8.6	- 1.9	927.2
19	09 47	851.0	525.0	136.0	8.6	- 1.9	910.6
20	09 50	843.6	547.6	137.4	8.6	- 1.9	932.4
21	09 53	851.0	531.2	138.7	8.6	- 1.9	919.5
22	09 59	850.3	519.0	141.4	8.6	- 1.9	909.8
23	10 02	842.9	549.7	142.4	8.6	- 1.9	939.3
24	10 06	842.9	532.7	143.5	8.6	- 1.9	923.4
25	11 09	850.4	547.2	144.4	8.6	- 1.9	941.0

Continuation

		mm	mcgal	mcgal	mbar	mcgal	mcgal
26	10^h12^m	851.3	980 925 517.4	145.3	1008.6	- 1.9	980 925 912.4
27	10 16	842.6	523.9	146.4	8.6	- 1.9	917.4
28	10 19	850.1	510.8	147.3	8.6	- 1.9	907.4
29	10 22	842.9	538.3	148.2	8.6	- 1.9	933.7
30	10 26	850.7	526.7	149.3	8.6	- 1.9	925.5
31	10 29	851.5	552.1	150.2	8.6	- 1.9	951.7
32	10 33	851.5	522.5	150.9	8.6	- 1.9	923.1
33	10 36	842.4	519.2	151.3	8.6	- 1.9	917.5
34	10 39	842.3	527.8	151.6	8.6	- 1.9	926.4
35	10 43	843.9	523.1	152.0	8.6	- 1.9	922.6
36	10 46	850.4	549.6	152.5	8.7	- 1.8	951.6
37	10 49	850.3	532.5	152.9	8.7	- 1.8	934.9
38	10 52	850.0	509.8	153.3	8.7	- 1.8	912.5
39	10 56	850.3	510.6	153.8	8.7	- 1.8	913.9
40	11 00	851.3	536.7	154.3	8.7	- 1.8	940.8
41	11 03	842.4	517.5	154.2	8.7	- 1.8	918.8
42	11 06	842.3	530.8	154.0	8.7	- 1.8	931.9
43	11 10	843.9	510.6	153.9	8.7	- 1.8	912.1

k = 43; $\overline{H}_o$ = 847.6 mm

$\overline{g}$ = 980 925 927.0
m = ± 14.0 mcgal
M_o = ± 2.2 mcgal

Serie n.3 July 01

1	13 19	845.7	980 925 566.1	108.0	1008.8	- 1.8	980 925 922.2
2	13 22	853.9	558.8	106.1	8.9	- 1.8	915.4
3	13 30	845.6	563.3	101.7	8.9	- 1.8	913.1
4	13 55	843.4	619.2	83.0	8.9	- 1.8	949.6
5	13 58	845.8	601.6	80.8	8.9	- 1.8	930.5
6	14 02	852.5	623.7	77.8	8.9	- 1.8	951.6
7	14 06	853.7	588.0	74.7	8.9	- 1.8	913.2
8	15 41	848.4	683.4	- 0.4	9.1	- 1.7	932.0
9	15 46	848.4	691.6	- 3.8	9.1	- 1.7	936.8
10	15 50	856.0	704.9	- 6.5	9.1	- 1.7	949.6
11	15 54	854.9	671.4	-10.3	9.1	- 1.7	912.0
12	15 57	849.0	683.6	-12.5	9.1	- 1.7	920.3
13	16 00	856.2	696.1	-14.8	9.1	- 1.7	932.6
14	16 04	856.7	664.2	-17.6	9.1	- 1.7	898.1

Continuation

		mm	mcgal	mcgal	mbar	mcgal	mcgal
15	16 08	848.3	980 925 684.7	-20.3	1009.1	- 1.7	980 925 912.4
16	16 22	851.1	685.3	-30.1	9.1	- 1.7	905.0
17	16 26	857.7	720.0	-32.1	9.1	- 1.7	939.7
18	16 29	856.7	686.3	-34.9	9.1	- 1.7	902.9
19	16 32	856.5	725.9	-36.8	9.1	- 1.7	940.5
20	16 35	855.9	701.0	-38.6	9.1	- 1.7	913.6
21	16 39	856.4	710.4	-40.4	9.1	- 1.7	921.4
22	16 42	855.1	711.4	-42.8	9.1	- 1.7	919.6
23	16 45	848.2	715.4	-44.6	9.1	- 1.7	919.7
24	16 48	847.2	702.6	-46.5	9.1	- 1.7	904.7
25	16 54	855.5	723.5	-50.1	9.2	- 1.6	924.6
26	16 58	847.7	717.9	-52.5	9.2	- 1.6	914.3
27	17 01	846.7	721.6	-54.2	9.2	- 1.6	916.0
28	17 04	847.1	702.6	-55.7	9.2	- 1.6	895.6
29	17 07	847.8	703.7	-58.5	9.2	- 1.6	894.1
30	17 13	845.7	717.1	-60.2	9.2	- 1.6	905.2
31	17 17	845.6	732.2	-62.1	9.2	- 1.6	918.4
32	17 21	846.8	743.8	-63.6	9.2	- 1.6	928.8
33	17 24	853.0	742.1	-65.6	9.2	- 1.6	927.0

$k = 33$ $\bar{H}_o = 850.9$

$\bar{g} = 980\ 925\ 920.7$
$m = \pm 15.2$ mcgal
$M_o = \pm 2.7$ mcgal

Serie n.1	g = 980 925 927.1	m = ± 9.6	M_o = ± 1.6
Serie n.2	927.0	14.0	2.1
Serie n.3	920.7	15.2	2.7
Average:	g = 980 925 924.9	m = ± 13.2	M_o = ± 2.2

Appendix 2

Results of measurements at point A3, Sevres, 1985

Observer: G.Arnautov (USSR) $H_o = 0.980$ m $w_{zz} = 295.5$ mcgal/m

Set No	Date	Time (UT)	Measured g Value mcgal	k	m	P_a mbar	Corrections Δg_p mcgal	Δg_{p_a} mcgal	g mcgal
1	July 08	$21^h59^m-22^h16^m$	980 925 731	90	± 16	1013	14	-70	0 980 925 941
2	08	22 35 22 50	726	90	13	1013	14	-73	0 933
3	08	23 00 23 18	716	90	14	1013	14	-73	0 923
4	July 09	1 19 1 33	710	90	12	1013	16	-51	0 941
5	09	1 43 1 58	711	90	14	1013	16	-45	0 948
6	09	2 06 2 23	677	90	14	1013	18	-39	0 922
7	09	2 33 2 47	681	90	13	1013	16	-32	0 931
8	09	3 09 3 24	677	90	14	1013	16	-23	0 936
9	09	3 30 3 48	651	90	15	1013	16	-18	0 915
10	09	3 56 4 13	661	90	13	1013	17	-13	0 931

$\sum k = 900$ $\bar{g} = 980\ 925\ 932.1$
$m = \pm 131$ mcgal $m = \pm 10.0$ mcgal
$\bar{m}_o = \pm 13.8$ mcgal $M_o = \pm 3.2$ mcgal

Constant corrections:
$\Delta g_c = -24$ mcgal
$\Delta g_{H_o} = 299.6$ mcgal

Appendix 3

Results of measurements at point A4, Sevres, 1985

Observers: Guo You-Gang, Huang Da-Lun, Feng Youg-Yuan, Zhang Guang-Yuan, Zhou Juing-Hua, National Institute of Metrology, China.

H_o = 1120 mm $\qquad$ W_{zz} = 255.4 mcgal/m

Set	Date	Time (UT)	k	Measured g	m	g_{H_o}	g
				mcgal	mcgal	mcgal	
1	06 28	11^h-12^h	21	980 926 352	± 234	286	980 926 638
2	28	14 -16	20	392	210	286	678
3	06 29	8 - 9	20	282	189	286	568
4	29	12 -14	20	357	336	286	643
5	29	14 -16	25	316	274	286	602
6	06 30	8 -10	20	319	320	286	605
7	30	13 -15	20	317	264	286	603
8	30	15 -17	20	301	298	286	587
9	07 01	7 - 9	24	233	233	286	519
10	01	11 -13	21	347	264	286	633
11	01	17 -18	20	284	355	286	570
12	07 08	12 -13	20	323	398	286	609
13	08	14 -16	20	303	298	286	589
14	09	7 - 8	21	255	288	286	541

Σk = 292 $\qquad$ $\bar{m}$ = 283 $\qquad$ $\bar{g}$ = 980 926 599

$\bar{m}$ = ± 41.9

M_o = ± 11.2

Appendix 4

Results of measurements at point A6, Sevres, 1985

Observer: G.Arnautov (USSR) $\qquad$ H_o = 0.971 m $\qquad$ W_{zz} = 259.0 mcgal/m

Set No	Date	Time (UT)	Measured g Value	k	m	p_a	Corrections Δg_p	Δg_r	Δg_{p_a}	g
			mcgal		mcgal	mbar	mcgal	mcgal	mcgal	mcgal
1	July 01	15^h28^m - 15^h47^m	980 925 371	120	± 12	1013	+ 16	+ 2	0	980 926 616
2	01	15 55 16 14	387	120	12	1013	17	- 18	0	613
3	01	17 00 17 19	431	120	11	1013	20	- 58	0	620
4	01	17 50 18 10	453	120	11	1013	20	- 80	0	620
5	01	20 20 20 40	440	120	17	1013	15	- 91	0	591
6	01	20 50 21 10	428	120	17	1013	15	- 88	0	582
7	01	21 40 22 00	432	120	15	1013	14	- 81	0	592
8	01	22 10 22 30	447	120	16	1013	14	- 77	0	611
9	01	22 40 23 00	438	120	14	1013	14	- 75	0	604
10	01	23 45 24 05	469	120	11	1013	14	- 75	0	635
11	July 02	0 20 0 40	468	120	10	1013	14	- 78	0	631
12	02	0 50 1 10	462	120	13	1013	14	- 82	0	621
13	02	1 50 2 10	162	120	13	1013	14	- 90	0	613
14	02	2 20 2 35	461	91	12	1013	14	- 94	0	608

Σk = 1651 $\qquad$ $\bar{g}$ = 980 926 611.2

Constant corrections:

Δg_c = - 24 mcgal $\qquad$ m = ± 144 mcgal $\qquad$ m = ± 15 mcgal

Δg_{H_o} = +251 mcgal $\qquad$ $\bar{m}_o$ = ± 13.1 mcgal $\qquad$ M_o = ± 4.0 mcgal

Results of measurements at point A7, Sevres, 1985

Observers: M. Zumberge, G. Sasagawa, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093, USA

H_o = 1090 m W_{zz} = 259.0 mcgal/m

No		Time (UT)	Measured g Value	m	k	Corrections: Finite c	Corrections: Laser	Corrections: Tide	g (H = H_o)
			mcgal			mcgal	mcgal	mcgal	mcgal
1	06 25	09^h32^m	980 926 439	± 181	99	- 10	- 3	- 25	980 926 401
2	25	11 48	427	173	100	- 10	- 3	- 27	387
3	25	12 12	437	157	99	- 10	- 3	- 25	399
4	25	12 48	411	208	100	- 10	- 3	- 20	378
5	25	13 12	421	195	99	- 10	- 3	- 16	392
6	25	13 49	421	224	100	- 10	- 3	- 8	400
7	25	14 22	399	161	99	- 10	- 3	- 2	384
8	25	14 52	398	189	99	- 10	- 3	+ 4	389
9	25	15 15	413	195	98	- 10	- 3	8	408
10	25	15 38	375	162	99	- 10	- 3	11	373
11	25	16 02	392	187	99	- 10	- 3	14	393
12	25	16 26	379	128	100	- 10	- 3	16	382
13	25	16 53	378	155	100	- 10	- 3	16	381
14	25	17 22	412	140	97	- 10	- 3	15	414
15	06 26	8 21	430	170	98	- 10	- 5	18	433
16	26	9 33	387	181	99	- 10	- 5	5	377
17	26	9 57	384	187	99	- 10	- 5	0	369

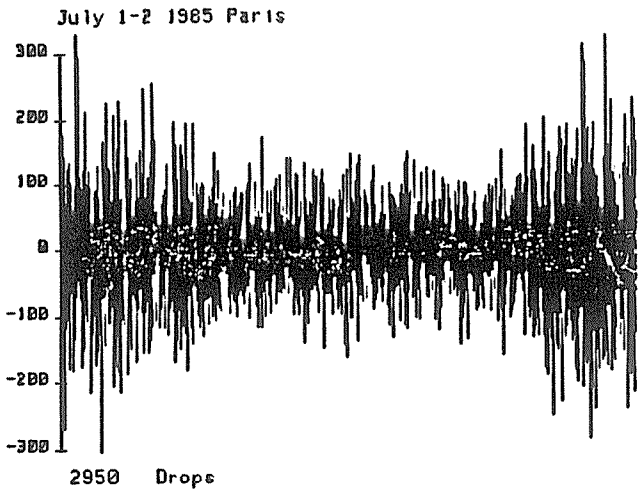
Continuation

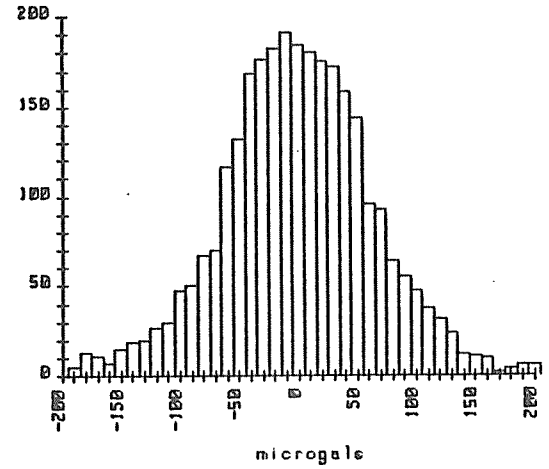
18	06 26	10^h19^m	980 926 441	± 177	98	- 10	- 5	- 5	980 926 421
19	26	10 52	426	171	98	- 10	- 5	- 13	398
20	26	16 18	414	142	99	- 10	- 5	- 21	378
21	26	16 54	414	169	98	- 10	- 5	- 18	381
22	06 28	10 41	339	167	100	- 10	- 3	+ 69	395
23	28	11 14	398	175	99	- 10	- 3	55	440
24	28	12 18	404	191	97	- 10	- 3	21	412
25	28	12 41	401	190	98	- 10	- 3	9	397
26	28	13 03	387	186	100	- 10	- 3	- 3	371

n = 26 $\sum k$ = 2571 $\bar{g}$ = 980 926 394.3

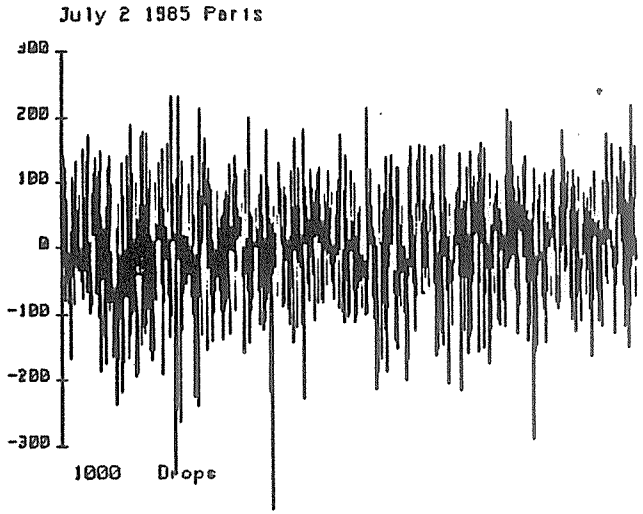
$\bar{m}$ = ± 175 mcgal m = ± 18.1 mcgal

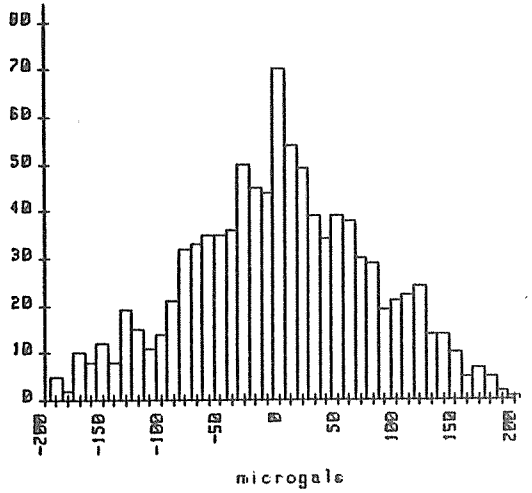
M_o = ± 3.6 mcgal





Appendix 6





Appendix 6

FIRST RESULTS WITH THE ABSOLUTE GRAVITY METER JILAG-3

W. Torge, R.H. Roder, H.G. Wenzel, J.E. Faller

A transportable absolute gravity meter has been built at the Joint Institute for Laboratory Astrophysics (JILA) in cooperation with the Institut für Erdmessung (IFE). Since January 1986, laboratory investigations of the instrument and absolute gravity determinations on 9 stations in the Federal Republic of Germany, and at BIPM, France, have been performed.

PAST AND FUTURE COMPARISONS : SOME THOUGHTS

J.E. Faller and T.M. Niebauer

A discussion will be given regarding possible site-dependent systematic errors that could affect the comparison of absolute instruments. Ways of eliminating these problems will be mentioned. Finally, methodology improvements for future absolute comparisons will be suggested.

*BRIEF ACCOUNT OF AFGL'S GRAVITY ERROR BUDGET**

R.W. Sands

During 1984 and 1985, the Air Force Geophysics Laboratory made a comprehensive re-evaluation of the data collected during the 1981 Absolute Gravity Symposium at the BIPM, Sèvres, France as well as those collected during the preceeding measurement period. As a result of this study, a faulty component which led to an error in the vacuum readout portion of the AFGL absolute gravity system was identified and corrected. We have, accordingly, re-evaluated the gravity data taken during the 1981 field trips in the United States and those taken in Paris, France. Based on careful study of our laboratory notebooks, we were able to determine that this component failure occurred at a time such that the 1981 calibration line data were not affected. The data collected at the AFGL Haskell Observatory, after the calibration line field trip, and those obtained at the BIPM were affected. The cause of the problem was excessive outgassing in the immediate area of the ionization tube gauge's sensing grid. This condition resulted in a higher than actual pressure reading. Since the correction for air drag vs pressure is logarithmic in the region of concern[1], the value of the operating pressure becomes an increasingly critical measurement as the pressure rises. This apparent pressure increase necessitated a correction (to allow for the poorer vacuum level that the gauge was indicating) to the measured value of g of 65 ± 10 μgal. A recalculation of the gravity data taken during the time periods in question, taking this pressure gauge error into account, put our Haskell value in agreement with previous measurements made there. The correction also puts our 1981 Paris value at site A4, when transferred to the common A site, within 3 μgal of the value obtained by Professor Sakuma at this point.

An in-depth report of error sources in the AFGL absolute gravity system has been reported[2]. At the Air Force Geophysics Laboratory, we are pleased to have solved this discrepancy and to report these findings which emphasize the importance of frequent system monitoring and attention to system detail.

References

1) Iliff, R.L., and Sands, R.W., "The AFGL Absolute Gravity Measuring System -A Final Report and Operating/Maintenance Manual", AFGL-TR-83-0297, 28 Oct. 1983.AD-A147853.

2) Iliff, R.L., and Sands, R.W., "The AFGL Absolute Gravity System's Error Budget Revisited", AFGL-TR-85-0102, 8 May 1985.

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* Paper not presented during the IGC meeting, but contribution is important with regards to some points discussed at the end of Session 2.

PROPOSAL FOR THE

ESTABLISHMENT OF AN

AFRICAN GRAVITY STANDARDIZATION NETWORK

Prepared by:
Gravity Network Committee
Commission for Geodesy in Africa

December, 1983
Rev. July, 1984
Rev. Nov., 1984
Rev. Jan., 1985
Rev. Aug., 1985

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1.0 SUMMARY

Project Title:	African Gravity Standardization Net
Purpose:	To provide a basis for unifying all present and future gravity measurements in Africa and to train African geoscientists in gravity surveying methodology.
Estimated Cost:	$1,610.000 U.S.
Duration:	2 years
Requesting Organization:	Commission for Geodesy in Africa.
Contact:	Prof. D. E. Ajakaiye Chairperson, Gravity Network Committee Faculty of Natural Sciences University of Jos, P.M.B. 2084, JOS - NIGERIA. Telex 81136, Unijos Ng.
Supporting Organizations:	1. The International Gravity Commission 2. African Cartography Association (ACA) 3. ECA Regional Centre for Specialised Services in Surveying, Mapping and Remote Sensing, Nairobi, Kenya 4. National Surveying agencies in various African countries.

1.1 List of Abbreviations

AGNP	African Gravity Network Project
AGSN	African Gravity Standardization Net
CGA	Commission for Geodesy in Africa (of the IAG)
ECA	Economic Commission for Africa
EEC	European Economic Commission
GNC	Gravity Network Committee (of the CGA)
IAG	International Association of Geodesy
IAGBN	International Absolute Gravity Base Network
IGB	International Gravity Bureau (of the IGC)
IGC	International Gravity Commission (of the IAG)
IGSN71	International Gravity Standardization Net 1971
LAGSN77	Latin American Gravity Standardization Net 1977
OAU	Organization of African Unity
SSG 3.87	Special Study Group 3.87 (of the IAG)
UNESCO	United Nations Educational and Scientific Organization
WG2	Working Group 2 on World Gravity Standards (of the IGB)

2.0 INTRODUCTION

A detailed knowledge of the earth's gravity field is essential in the development of geodetic reference systems, in large scale geophysical investigations of the earth's composition and structure and in detailed exploration of the earth's crust for economic mineral deposits. In recent years, gravity measurements have played a key role in investigating the dynamic processes within the earth as for example in the detection of notions of the earth's associated with natural hazards such as earthquakes and landslides.

Systematic mapping of the earth's gravity field is done using relative gravimeters i.e. instruments which measure gravity differences with respect to a reference station where the absolute value gravity is known. The use of gravity data for geoscience studies on a national, continental or global scale requires that local systems of reference stations be connected to national and international networks to ensure consistency of the gravity datum within and between countries.

The International Gravity Standardization Net 1971 (IGSN71) provided the first world wide gravity reference system on an absolute datum and thus in principle a basis for unifying all existing national gravity networks and local surveys for mineral exploration purposes. The unification has been done in North and South America, Europe, Australia and much of Asia.

In Africa, the unification of existing data and the development of national gravity networks has been hampered by the poor areal distribution of IGSN71 stations and the fact that in some cities all IGSN71 stations have been destroyed. The problem of unifying gravity surveys in Africa is further complicated by the large number of countries involved and the disparity of expertise in gravity surveying among these countries.

In recognition of the inadequacies of the gravity reference system in Africa to meet current accuracy and coverage requirements for geophysical, geological and geodetic applications, the Commission for Geodesy in Africa (CGA) of the International Association of Geodesy (IAG) studied the requirement for improved gravity reference standards in Africa and developed the plan presented here for the establishment of a new continental reference network. A key aspect of the plan involves the development of African expertise in gravimetry as a means of encouraging the application of this basic geophysical tool both to problems in geodesy and in the search for economic minerals.

3.0 EVOLUTION OF THE PROJECT

At the March, 1977 meeting of the CGA held in Lagos, Nigeria, a subcommittee was formed which identified the requirements for absolute gravity measurements in Africa and prepared a plan for the establishment of an absolute net. Although there was scientific support for this project, both inside and outside Africa, the limited practical benefits of a net consisting of only 20 absolute stations coupled with the tightening world economic situation led to difficulty in securing adequate financial support.

The membership of the Gravity Network Committee formed in Lagos was reviewed during the IAG General Assembly in Canberra, Australia in December 1979 at which time Dr. D.E. Ajakaiye became chairperson.

At the November, 1981, meeting of the CGA in Nairobi the GNC held two working sessions at which the concept of a first order African Gravity net and an implementation plan were developed. The plan was endorsed by the CGA through Resolution 17 (Appendix I) of the Nairobi meeting which formally launched the African Gravity Network Project (AGNP). Based on comments received from African agencies and consultations of the GNC Chairman with staff at the Earth Physics Branch, Canada and Prof. U. Uotila, Chairman of the International

Gravity Bureau (IGB) Working Group 2 (WG2) on World Gravity Standards, a new set of criteria (Appendix II) was developed which provided wider station coverage. The network design (Fig.1) based on these criteria was discussed at the Hamburg meetings of the CGA and International Gravity Bureau Working Group 2 in August, 1983, and endorsed by both groups. Early in 1984 the first draft of the proposal for the establishment of the African Gravity Standardization Net (AGSN) was circulated to various African agencies for comment. This proposal was discussed at a meeting in late November, 1984 in Cairo, Egypt by representatives of the IGC, its regional sub-commissions for Africa, the CGA and its Gravity Network Committee in line with resolution 10 of the IAG (Appendix III). A t that time the decision was made to hold a detailed planning meeting in Paris on May 23 - 25, 1985 to which representatives of various African and foreign agencies would be invited.

The Paris meeting was held on May 22 - 24, 1985 and it was attended by 46 participants from 13 African countries and 10 European/American/Canadian, countries representing international agencies and institutions.

The proposal was critically discussed, and modifications and implementation plan suggested. (A copy of the resolution adopted at the meeting is attached as Appendix IV).

4.0 OBJECTIVES

There are three main objectives:

(i) To provide a homogeneous continental reference standard for national gravity programmes and regional crustal movement studies in Africa.

(ii) To promote the use of gravimetry as an effective tool in the search for and location of economic minerals in Africa by training African geoscientists in the observation and

processing of gravity data with a view to facilitating the eventual exploitation of these economic minerals.

(iii) To collaborate in the work of IAG Special Study Group (SSG) 3.87 in the development of the International Absolute Gravity Base Network (IAGBN).

5.0 FUNDING

The total cost of the project is estimated to be $1,600,000 U.S. A breakdwon of the costs is given in Appendix V.

Since this is a major international project involving most countries in Africa and in view of its implications for mineral resource development, earthquake and other natural disasters prediction research, agencies such as UNESCO OAU, EEC, ECA, etc. have been approached to provide funding support. The ECA Executive Secretary, it was decided in Paris, was to be requested through a letter from the Secretary of CGA to solicit funds from aid providing bodies and explore bilateral and multilateral assistance from relevant international bodies and ister countries e.g. EEC, CIDA, SIDA, AID etc.

Individual African countries will be asked to support the project by making available high quality personnel for observer training, by providing local transporation and logistic support for observing crews, by selecting and preparing permanent sites for the stations in their respective countries and by providing funds where possible.

6.0 WORK PLAN

6.1 General organzation

At the Paris meeting held on May 22-24, 1985 (Sec 3.0) sponsored by the IGC/CGA and subsequent meetings it was generally agreed that:

(a) The AGSN-project should be carried out as initiated under the general coordination of the Gravity Network Committee (GNC) of the CGA with the cooperation of the AAC.

An African project manager (Sec 7.0) familiar with field logistics in various parts of Africa would organise and supervise field operations. Contributions to the project from outside Africa would be welcome by this management structure in close liaison with the IGC.

(b) The GNC should solicit for funds from ECA, UNESCO etc to organize a bilingual gravity training course for young African young scientists at a centre in Africa with translation facilities. The training programme would precede the field operations/measurements phase of the AGSN.

(c) The GNC should revise the proposal in line with the descussions at the Paris meeting. The revised proposal should, in conjunction with the AAC, be presented for funding to the ECA in February 1986 and the OAU in April 1986 with the active support of the Executive Secretary of ECA.

(d) GNC should jointly with AAC make contacts with international agencies such as ECA, UNESCO, etc. for financial support for the project.

The work will require a minimum of two years and is divided into training, field operations, data processing and publication phases. An outline of the activities and issues relevant to each phase of the work follows. An estimate of the time required for each phase of the work is given in Appendix (VI).

6.2 Training

To maximize the long term benefits of the project to African nations, considerable emphasis has been placed on training a pool of African geoscientists who can perform not only the data acquisition, processing and analysis tasks but also the many local follow-up projects which will be required to connect old stations to the new net and to perform on-going network maintenance. It is proposed to accomplish the training through two four-week workshops at which up to thirty Africans would be trained in gravimetry by experts from various agencies. One or two out of four applicants from each country would be

selected, through screening process, for the training. Travel expenses of the trainees would in general be borne by the trainees home country, or from a general fund where necessary. The most promising of the trainees would be invited to form the primary and back-up observing teams for the AGSN gravimeter observation campaign contingent upon their receiving a leave of absence from their home organizations.

The workshop would be held at one or more African locations and hosted by an organization willing to provide suitable facilities. Sites to be considered are Yamoussoukro, Ife and Algiers. At the Paris meeting, it was directed that the first workshop be held at the ECA Regional Centre for Training in Aerial Surveys and Mapping at Ifẹ, Nigeria in 1986. Training staff would be invited from one or more African and non-African agencies with recognized expertise in gravimetry and instruction would be available in both English and French. Major equipment for the workshop (gravimeters and altimeters) should be borrowed from African and, if necessary, overseas agencies. ECA Regional Centre for Services in Surveying, Mapping and Remote Sensing, Nairobi, Kenya and the Ahmadu Bello University, Zaria, Nigeria have offered to lend 2 gravimeters each for the project. The gravity and geodynamic division of the Earth Physics branch, Energy Mines and Resources, Ottawa, Canada has offered to provide software for gravity data reduction, network adjustment and simulation for the workshops, while the International Centre for Earth Tides, in Belgium has offered data and software for earth tides and atmospheric reduction. Other supplies including hand calculators and cameras would be purchased for later use in the AGSN observation campaign.

A tentative training programme for the workshop is given in Appendix VII. Funding for the workshops in the first instance would come from ECA, AA C* and the Nairobi Centre. ECA on behalf of the GNC would explore bilateral and multilateral assistance from donor countries and organisations such as the

* AAC African Association of Cartography.

International Centre for Theoretical Physics in Trieste, Italy; United Kingdom, Carl-Duisberg Gesellsch (Germany) etc.

6.3 Field Operations

6.3.1 Preparations

The main tasks are:

(i) distribute station selection criteria to national agencies with request to select tentative sites (primary station and at least 3 excentre stations) for each AGSN city in their respective countries. Reconnaissance visits will be made by the project Manager where necessary.

(ii) Contact foreign agencies who will carry out absolute measurements and appropriate African agencies to develop overall plan and schedule.

(iii) arrange contract for jet aircraft charter, consult with contractor concerning proposed itinerary, fuel availability, maps, travel documents etc. and work out flight itineraries to optimize movement of field parties.

(iv) finalize schedule for field work and advise national agencies of expected arrival dates of field crews in their respective countries.

6.3.2 Relative Gravimeter Measurements

6.3.2.1 Instrumentation

Four LaCoste and Romberg G type gravimeters would be borrowed from African or overseas agencies. These instruments would be sent to the manufacturer for complete check-out and dial calibration prior to commencement of AGSN field operations. Each leg of the net show in

Fig.1 would be observed in A-B-A sequence. In addition three or more excentre stations would be observed in each city and interconnected to ensure that the excentres have a relative accuracy (within one city) of ± 10 uGal. Excentres should be established prior to the campaign. Existing IGSN 71 stations, the African Doppler Observation Survey (ADOS) stations and the AGSN stations would be collated or connected where possible.

Cameras and programmable hand calculators previously acquired for the training workshop would be used for the gravimeter observation program and would become the property of the observer's home agency at the end of the survey.

It is proposed to rent SSB radiotelephones for installation in the survey vehicles and project co-ordinators office to facilitate regular communication between the survey crew and headquarters.

6.3.2.2 Phases of the Observation Program

Due to the size of the project and the length of time required to carry out the gravimeter measurements, the work may be divided into several phases. For logistic reasons it would be appropriate to observe the net in regional blocks. Thus, the phases of the observation program could be:

Phase 1 - Absolute measurements

Phase 2 - West African block

Phase 3 - East African block

Phase 4 - South African block

Gravimeter ties linking the absolute sites would be observe concurrently with Phase 1. Phases 2, 3 and 4 could be carried out in any sequence.

6.3.3. Absolute Measurements

No absolute gravimeter capability presently exists in Africa. Since this type of instrumentation has high capital cost, requires extensive training and is still to some degree in the experimental stage of development no provision has been made for the acquisition of these instruments for the project.

The criteria used for site selection will be, to every extent practicable, consistent with those proposed for the IAGBN (Appendix VIII). In addition, AGSN and IAGBN absolute stations will be collocated wherever possible. It was approved in Paris that absolute measurements should be made at 20 sites uniformly distributed in Africa. The choice of the sites should be such as would provide one N-S and an E-W calibration lines within Africa (Fig. 1).

A number of agencies that could be invited to carry out the absolute measurements, in 1987 include:

Instituto di Metrologia	Torino, Italy
U.S.S.R. Academy of Sciences	Moscow, U.S.S.R.
University of Colorado	Boulder, U.S.A.
Earth Physics Branch	Ottawa, Canada
Bureau International de Poids et Mesures	Paris, France
Geodetic Institute	Hannover, FRG
Geodetic Institute	Helsinki, Finland

To guard against the possibility of systematic error or instrument malfunction at least two different absolute instruments of (symmetrical fall and simple fall types) should observe each absolute station. In addition it is expected that the instruments used would be intercompared over a large gravity interval prior to deployment in Africa.

Transportation of these instruments to Africa should be by ship and within Africa by ship, train or car.

6.4 Data Processing

6.4.1. Data Reduction and Network Adjustment

Preliminary reduction and editing of the gravimeter observations would be done by the observers in the field using programmable hand calculators and procedures learned during the training workshop. In this way instrument malfunctions can be detected and remedied and apparently erroneous observations repeated. Data would be transferred daily to coding forms and mailed periodically to an established gravity computing centre for verification and final processing.

Final data reduction and editing and the least squares network adjustment would be performed at a computing centre in Africa. The work would be carried out by the project co-ordinator and observers guided by consultants in gravity network adjustments obtained from various agencies through the auspices of the IGC. The consulting organisation would be requested to install gravity data reduction and network adjustment software at the African computing centre chosen for the final adjustment computations.

6.4.2. Station Descriptions

Station descriptions will include photos, sketches and verbal description of station locations and will be compiled in an internationally accepted format similar to that of the IGSN 71 or Latin American Gravity Standardization Net (LAGSN 77).

6.5 Publication

The final project report would consists of a description of the measurements, data reduction and adjustment procedures, an analysis of errors and a complete set of station descriptions. The report would be compiled by a number of collaborators including the Project Manager and data processing personnel and will be issued under the auspices of the CGA. Other research reports may be published on specific aspects of the work during the course of the project.

7.0 PROJECT MANAGEMENT

In order to coordinate and manage the various activities described in the work plan and to ensure quality control on data acquisition, it is necessary to have full time Project Manager for a period of two years. The duties of the Project Manager under the general supervision of the GNC would include to,

(a) assess the field capabilities of the trainees at the training workshop.

(b) identify groups and organizations who have the necessary expertise to carry out continental adjustments and a willingness to commit resources in the form of training personnel and software.

(c) liaise with national agencies throughout Africa to arrange site selection and local agency support for observing crews.

(d) ensure that observing and flight crew have proper documentation to enter and operate in the fifty countries involved.

(e) establish a mechanism for developing a well documented microcomputer based system for reduction of anomaly data and reduction and adjustment of network data suitable for use in training programs associated with AGSN.

(f) Provide coordination, with the AGSN project committee and training groups, of software development documentation and installation at the training sites and later at the adjustment centre(s) in Africa.

(g) supervise the gravimeter observation programme, exercise quality control on data acquisition and solve logistic problems as they arise, and ensure documentation of station description.

(h) liaise with consultants as necessary to obtain scientific or technical advice.

(i) coordinate the absolute gravity measuring programme.

(j) coordinate the final data reduction and adjustment and the preparation of the final report, publication and distribution of the final report after approval by AGSN Project Committee.

(k) make provision for maintenance of the AGSN through coordination with local groups and the distribution of revision information.

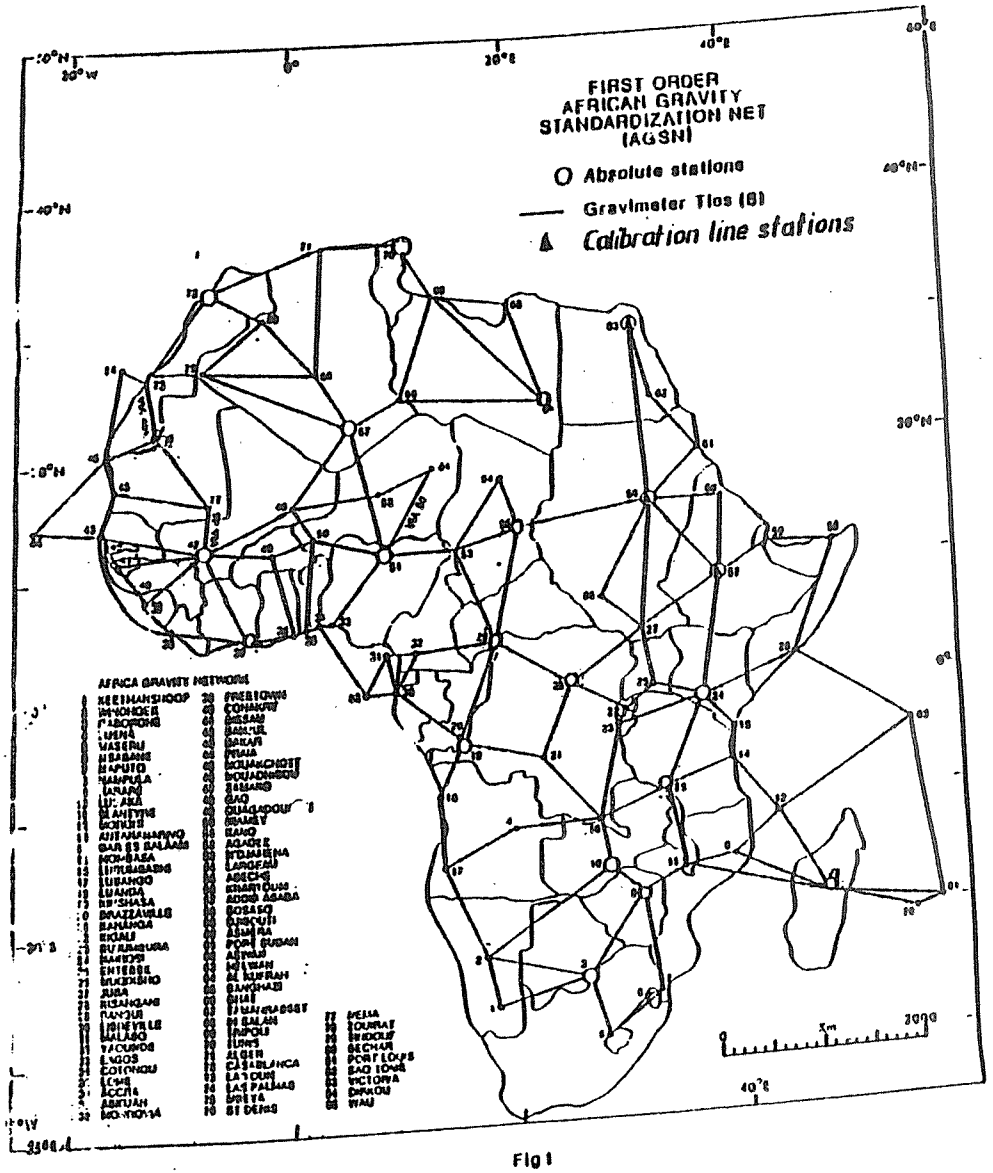

Fig 1

Appendix I

Resolution No. 17

from
Commission for Geodesy in Africa
2nd Symposium on Geodesy in Africa
Nairobi, November, 1981

AFRICAN GRAVITY NETWORK PROJECT(AGNP)

Noting that many resolutions have been passed at previous meetings in Khartoum, Lagos and Nairobi concerning the promotion of gravity survey in Africa, in view of its economic role.

Inaugurates the African Gravity Network Project (AGNP)

Calls on all African Governments to provide human and material resources for the execution of the Project.

Welcomes any assistance from international organizations and agencies outside Africa

Urges organizations and others who have any gravity data from Africa to co-operate with the chairpersons of both the Gravity National Committee and the Data Bank Committee of the Commission for Geodesy in Africa in releasing gravity data to the Commission for Geodesy in Africa in order to ensure an orderly implementation of the African Gravity Network Project.

Appendix II

AFRICAN GRAVITY STANDARDIZATION NET

DESIGN CRITERIA

- Datum Determined by Absolute Measurements
- 20-50 Microgal Accuracy
- 4 Lacoste Romberg Gravimeters (A-B-A Sequence)
- Minimum 1 Station (plus excentres) per country
- 500-700 km station spacing
- Stations near major airports for ease of access

APPENDIX III

RESOLUTION N° 10 (1984)

The International Association of Geodesy, recognising that techniques of repeated relative gravity measurement have achieved increased accuracy and have been applied:

1. as a fast and efficient tool to detect and investigate gravity changes associated with recent crustal movements.
2. in combination with other techniques such as levelling and VLBI to give a deeper insight into the underlying dynamic processes.
3. as an element in earthquake prediction research, and noting the success of recent campaigns in various parts of the world, recommends that high priority be given to this research.

APPENDIX 4

RESOLUTIONS ADOPTED AT THE PARIS IGC/CGA AFRICAN GRAVITY WORKSHOP.

RESOLUTION I*

Recognizing the scientific and economic importance of the establishment of an A frican Gravity Standardization Net.

Considering the need for active participation of African national geodetic and geophysical organizations as well as the active participation of other specialized African organizations for the success of this continental scale project. The Paris IGC/CGA African Gravity Workshop recommends

1. the establishment of national commissions for gravimetry, including all official bodies involved in gravimetric activities, in order to better coordinate activities at the national level and ensure the successful establishment of the continental network.
2. that the African Gravity Network Committee finalizes, as soon as possible, and jointly with A.A.C. and the Nairobi Centre, the project proposal for the African Gravity Standardization (A.G.S.N.), taking into account the suggestions and recommendations expressed at the Paris meeting.
3. that the finalized project be presented by O.A.U. and E.C.A. for the adoption of appropriate resolutions for the immediate establishment of the A.G.S.N. This presentation must be made jointly by A.A.C., the Nairobi Centre and the A frican Gravity Network Committee as soon as possible.
4. that a common approach, initiated by the African Gravity Network Committee, be made by African agencies to international organization and financing agencies and any other pertinent body capable of helping in the immediate establishment of the continental net.
5. that the African Gravity Network Committee continue to coordinate the continental project in close collaboration with A.A.C. and the Nairobi Centre, and that A frican centres take over the data processing, as was done for the geodetic network.

*This resolution was presented by the participants from African countries.

APPENDIX 4 (cont.)

RESOLUTION II

Recognizing the importance of training programs for the dissemination of expertise in gravimetry and considering the wide spectrum of benefits of such training for a future African Gravity Standardization Net and for national gravity mapping programs to meet economic and research needs. The Paris IGC/CGA African Gravity Workshop.

Recommends that training seminars on the acquisition, reduction, evaluation and use of gravity data be held in Africa at the earliest possible opportunity.

RESOLUTION III

Recognizing the benefits of absolute gravity measurements both for a future African Gravity Standardization Network and for the International Absolute Gravity Network. The Paris IGC/CGA African Gravity Workshop.

Recommends that these observations be carried out in cooperation between the individual African countries and groups owning absolute gravimeters, within the framework for the African Gravity Standardization Network project under the coordination of the Gravity Network Committee of the CGA.

RESOLUTION IV

Recognizing the value of gravity data for geophysical and geodetic investigation, and for mining and resource exploration, and considering that gravity measurements exist in both the BGI file and in A frican data bases. The Paris IGC/CGA A frican Gravity Workshop.

Recommends that BGI, in cooperation with A frican agencies, undertake a new compilation of these data with a view of updating our understanding of the gravity field in Africa, and make it accessible to all African countries.

APPENDIX V

AFRICAN GRAVITY STANDARDIZATION NETWORK

Estimated Cost

TRAINING		
Travel - 3 consultant/lecturers + 60 students + project Coordinator	52,700	
Per diems - 34 pers. x 24 days x $70 x 2	54,600	
Supplies and services	18,500	
Equipment/Fieldwork expenses	1,800	
		127,600
FIELD OPERATIONS		
Preparation		
Per diem - Project Manager 125 days x $100	12,500	
Gravimeter reconditioning and dial calibration (4 meters)	16,000	
Aircraft Charter		
Ties between absolute stations	225,000	
Ties between first order stations	600,000	
Airfares		
Reconnaissance	15,000	
Gravity Ties	15,000	
Crew Changes	10,000	
Local Transportation for field crew	25,000	
Per diems		
Aircrew - 2 pers. x 365 days x $100	73,000	
Gravimeter Crew 2 pers. x 365 days x $100	73,000	
Absolute Gravity Observers - 2 pers. x 160 days x $100	32,000	
Project Manager - 1 pers. x 290 days x $100	29,000	
Consulting		
Travel and per diem for Consultants	50,000	
Communications		
Telephone, telex, SSB Radiotelephone rental	20,000	
		1,195,500

DATA PROCESSING		
Computing and associated costs	15,000	
Travel		
Project Manager + 2 Observers	6,000	
Per diems		
Project Manager - 70 days x $100	7,000	
Observers - 2 pers. x 60 days x $100	12,000	
Consulting		
Travel and per diem for Consultants	20,000	
Communications		
Telephone, telex etc	1,000	
		61,000
PUBLICATION		
Station descriptions		
Compilation	8,000	
Printing	6,000	
Final Report		
Printing 500 copies x $50	25,000	
Per diem		
Project Manager 45 days x $100	4,500	
		43,500
SALARIES		
Project Manager - 2 years x $40,000	80,000	
Observers - 2 pers. x 15 mos. x $2,000	60,000	
		140,000
GRAND TOTAL		1,608,100

* Assuming salaries for trainees, instructors, some consultants and also salaries for absolute gravity observers are paid by agencies supplying these services.

APPENDIX VI

AFRICAN GRAVITY STANDARDIZATION NETWORK

Elapsed Time Estimates

ACTIVITY	DAYS
Detailed planning, preparation, reconnaissance, site selection and liaison with national agencies	125
Gravimeter measurements	
Long Range - 250 legs x 1.2 per day	208
Excentres - 74 cities x 1 per day	74
Absolute measurements (20 weeks concurrent with gravimeter measurements)	0
Data Processing/Description Compilation	70
Report Preparation	45
Days of Rest	208
=	730
	2 years

APPENDIX VII

AFRICAN GRAVITY STANDARDIZATION NEXT (AGSN): PROGRAMME FOR THE TRAINING WORKSHOP

Duration: 4 Weeks

1. Gravity as a Fundamental Tool for Economic and Scientific Research

- Reports on status of gravity mapping in participating countries.
- Problems and plans for unifying existing gravity data on AGSN datum.
- Economic and Scientific applications of gravity data
  - .mineral prospecting
  - .crustal deformations - earthquakes, volcanic eruptions, subsidence and flooding, faults.
  - .Scientific work - earth gravity field model: its determination and applications in science (o.g notrology), military, navigation and space research, oceanic geoid and structures of the sea floor.
- The elements of a national gravity mapping programme.
- Role of Absolute gravity data and concept of the African Gravity Standardization Net.
- Review of Theory and Principles of Gravimetry
  - .summary of fundamental principles
  - .gravity data observations and reductions and processing including spectral analysis of potential field data
  - .relative gravity data instrumentation
  - .absolute gravity data, principles and instrumentation
  - .Gravity network adjustment procedures
    - semi rigorous adjustments
    - least squares adjustments
    - error diagnosis and analysis
  - .computational and Field Exercises.

..../over

2. Gravity Standards

- Design of national gravity networks from the base net down to field observations.
- Selecting and describing sites
- Observing procedures
- Planning and costing field work
- Computer modelling as a means of reducing data
- Encoding data
- Diagnosis of errors
- Gravimeter maintenance and calibration.

3.. Mapping the Gravity Field

- Survey design
- Vertical and horizontal control: techniques and Accuracy requirements
- Elements of barometric surveying
- Field mapping of a test area
- Diagnosis of errors
- Data reduction and editing in the field
  - (a) for the test network
  - (b) for the anomaly mapping test area

4. Data Processing

- Final data reduction and processing; calibration, instrumental errors, environmental effects
- Least squares adjustment of the test network
- Network errors: numerical and statistical Analysis

APPENDIX VIII

International Absolute Gravity Basestation Network (IAGBN)

PURPOSE

The absolute sites will be used to provide stable locations for the continued testing of absolute gravity devices, to monitor possible changes in gravity as a function of time, etc. and to form a strong network of absolute stations for definition of the International Gravity Standardization Datum.

SITE SELECTION CRITERIA

1. General Location

1.1 Geology:

Site to be located on stable crystalline rock, preferably Precambrian or Paleozoic in age. The preferred location of maximum stability in the continental shield area of Precambrian rocks. The next preferred locations are on discordant plutons such as batholiths. The stations shall be at least 50 kilometers from active fault systems.

1.2 Seismic Hazard:

Sites shall not be located near high seismic risk area. They shall be located in areas comparable to zones 0 to 2 of the seismic risk map of the U.S.A.

1.3 Tidal Reduction:

Site location shall admit the determination of the tidal gravity reduction including all side effects as ocean loading etc. to an a ccuracy level of ± 2u Gal.

1.4 Local Gravity variations with Time:

It has to be assumed that gravity changes through possible mass changes from lake water table variations, groundwater table variations, large construction works are either to be monitored or are reliably below 2u Gal.

2. Other General Specifics

2.1 Irregular Noise:

Irregular noise level should be low, preferably no greater than five (5) microgal when measured by a gravity meter at peak periods.

2.2 Electromagnetic Interference:

The site shall not be located near devices that generate electro-magnetic interference with absolute or relative gravity measuring instruments.

2.3 Access to Site:

Access to the site should be relatively easy, without excessive cost and available to international measuring teams with their absolute gravity measuring devices.

2.4 Excentres:

Excentres shall be established at acceptable sites in the vicinity of the absolute station. When the absolute station is not located on bedrock, excentres should be established preferably on bedrock and the height difference of excentre stations with respect to the absolute site be determined by high precision levelling.

2.5 Linkage to Regional Networks:

In order to serve as zero order stations to subordinate networks and to make possible gravity variations monitoring representative for a region, the stations have to be tied into national and regional networks.

2.6 Geometric Position Monitoring:

Consideration should be given to location of as many sites as possible in the vicinity of stations where high accuracy geocentric positidns can be determined.

2.7 Levelling:

Sites should be tied to national levelling nets and relevelling to current mean sea level should be enabled wherever possible.

3. Additional Local Specifics

3.1 Building Stability:

A stable, permanent building will be chosen for the measurements. The building should be over ten years old preferably, in order to ensure that settling has already occured. The building should be far enough away from disturbances caused by railroad or vehicular traffic.

3.2 Room Selection:

The room chosen will be in the lowest level of the building to ensure maximum stability. It should not be near heavy machinery, power transformers or other equipment that would cause vibrations or an electromagnetic field. The room should have at least 2 x 3 meters of space to accommodate the equipment. There should be additional rooms to allow easy access by the personnel conducting the measurements and to allow dissipation of heat generated by the equipment.

3.2.1 Measuring Surface:

The surface on which the absolute apparatus sits shall be bare concrete, terrazo, marble, or other similar hard floor covering.

3.2.2 Temperature:

The room chosen for the measurements should not have external temperature or temperature vairation that would adversely affect instrument performance.

A climatically controlled room is preferred.

The ideal temperature for the room is 18 to 24 degrees of Celsius with only a two (2) degrees of Celsius variation during measurements. In order to avoid air currents, ventilation outlets and air ducts must not be located adjacent to the appartus or must be blocked off.

Furnace rooms should not be used because of excessive heat.

Attention must be paid to the year round temperature of the room, not just the temperature during one season.

3.2.3 Lighting:

The room must have provision for maintaining semidarkness during absolute observations to accommodate absolute instruments with external laser sources.

3.2.4 Electric Power Requirement:

Two kilowatts of power are generally required. This normally requires two separate circuits to supply the necessary power. Two 20-ampere circuit breakers will be adequate. A thorough analysis must be made of the electrical panel of the selected building as one or two separate circuits may have to be added.

INTERNATIONAL GRAVIMETRIC CONNECTION BETWEEN JAPAN AND CHINA

by

Ichiro NAKAGAWA[1], Ryūichi SHICHI[2], Sinzi NAKAI[3], Kajuro NAKAMURA[4], Toshihiro HIGASHI[1], Ruihao LI[5], Yihui CHEN[6] and Dongchu WANG[6]

Abstract

For improving the measured accuracy of gravity measurements by means of LaCoste & Romberg gravimeter, cooperative gravity measurements by utilizing domestic gravity calibration lines and international gravimetric connections at mainly the IGSN 71 stations around the Circum-Pacific zone were successfully carried out in 1979 - 1982.

As an extension of such investigations, an international gravimetric connection between Japan and China as well as domestic ones in both countries were executed in October - December 1985 and February 1986.

The following points were clarified through the present investigations.

(1) Gravity values in Japan determined are consistent with those obtained by both the international gravimetric connections along the Circum-Pacific zone and the domestic one.

(2) Periodic errors are highly important for a high precision gravimetry, because their effects are neither negligibly small nor random.

(3) The optimal offset angle of LaCoste & Romberg gravimeter depends on a gravity value at the measured point.

(4) Measured errors accompanied by mis-setting along the long-level of the gravimeters employed were limited to a few μgals.

1 Geophysical Institute, Kyoto University, Kyoto 606, JAPAN

2 Inuyama Crustal Movement Observatory, Nagoya University, Inuyama 484, JAPAN

3 International Latitude Observatory of Mizusawa, Mizusawa 023, JAPAN

4 Regional Center for Earthquake Prediction, Kyoto University, Takatsuki 569, JAPAN

5 Institute of Seismology, State Seismological Bureau, Wuhan, CHINA

6 Institute of Geology, State Seismological Bureau, Beijing, CHINA

1. Introduction

For the purposes of

(1) determining better scale values of each gravimeter by using gravity values in absolute systems and wider gravity ranges, and

(2) establishing an up-to-date gravity net useful for detecting possible gravity changes in the future,

international gravimetric connections were carried out with several LaCoste & Romberg gravimeters (model G) at selected cities mainly along the Circum-Pacific zone from 1979 to 1982 (NAKAGAWA *et al.*, [1983]).

Based on the data obtained, scale values of the gravimeters employed have accurately been calibrated and gravity values at the measured stations were determined using the revised scale values. The following conclusions were then derived through the investigations.

(1) Correction factors determined for the scale values of the LaCoste & Romberg gravimeter were estimated to be of an order of 10^{-4} over the whole measured range, and the scale values of the gravimeter given by the manufacturer were systematically small without exception.

(2) An accuracy of the derived gravity values was estimated to be better than ± 0.01 mgal for local gravity measurements within a city and ± 0.03 mgal for international gravimetric connections.

(3) The sensitivity of the gravimeter depends on a gravity value at the measured point, if the bubble position of the gravimeter is fixed.

As an extension of such investigations, an international gravimetric connection between Japan and China as well as domestic ones in both countries were executed during the period from October to December 1985 and February 1986.

2. Outline of the Investigations

The purposes of the present investigation were

(1) to offer new data valuable for the maintenance and improvement of the International Gravity Standardization Net 1971 (IGSN 71) through the international gravimetric connection between Japan and China,

(2) to establish a precise gravity net in the standard baseline field of gravity surveys in Lushan mountains of Jianxi Province, and to accurately determine gravity values at gravity stations in the net, and

(3) to make a direct calibration of the gravimeters and a sensitivity calibration at the time of every gravity measurement.

The investigation was executed during the period from October 4 to December 10, 1985 along the following route.

Tokyo - Mizusawa - Tokyo - Tsukuba - Tokyo - Beijing - Guangzhou - Beijing - Guangzhou - Beijing - Wuhan - Beijing - Wuhan - Guangzhou - Wuhan - Guangzhou - Wuhan - Lushan - Wuhan - Beijing - Tokyo - Nagoya - Kyoto - Nagoya - Tokyo - Mizusawa - Tokyo

Three sectors in China; that is, between Beijing and Wuhan, between Wuhan and Guangzhou, and between Beijing and Guangzhou, as well as a sector between Tokyo and Mizusawa were occupied by twice of round trip gravimetric connection, and the other sectors were occupied by a single of round trip one. Fig. 1 shows the investigation route.

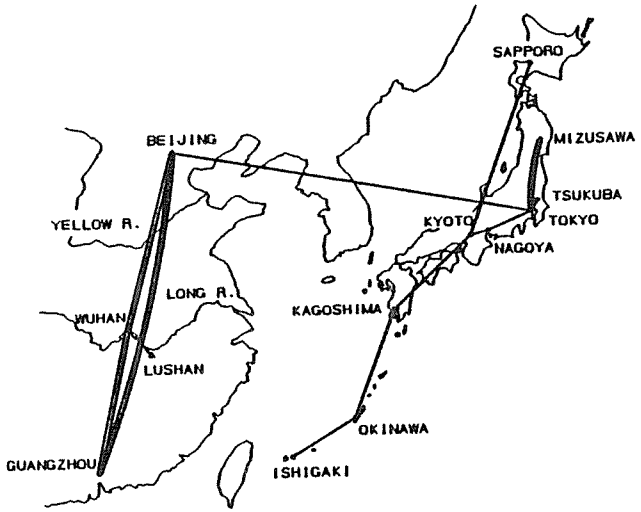

Fig. 1. Routes and regions occupied by the present investigations. A line connecting two regions shows an inter-regions sector where gravimetric connections by a set of going and returning trip were carried out. The gravimeters were transported by aircraft for all the inter-regions sectors, except by train for the sectors of Tokyo - Tsukuba and Mizusawa - Tokyo - Nagoya - Kyoto and also by ship for the sector of Wuhan - Lushan.

Four LaCoste & Romberg gravimeters G-196, G-305, G-484 and G-605 were employed in the whole investigation from the Japanese side, and three LaCoste & Romberg gravimeters G-793, G-808 and G-818 were participated to gravity measurements in China from the Chinese side.

After the completion of the investigation, a domestic gravimetric connection traversed along the Japan was subsequently and additionally carried out along the following route by employing the same four gravimeters as those in the international gravimetric connection between Japan and China in February 10 - 26, 1986.

Kyoto - Kagoshima - Okinawa - Ishigaki - Okinawa - Kagoshima - Kyoto - Sapporo - Kyoto

All sectors were occupied by a single of round trip gravimetric connection. The investigation route is also shown in Fig. 1.

Besides the gravimetric connections, a precise calibration for examining and checking the sensitivity characteristics of the gravimeters was made in each investigation region.

3. Data Processing

After deriving the correction functions for the scale values of all gravimeters by using the data of inter-regions gravimetric connections, unique gravity values at all the measured stations were precisely and simultaneously determined with all the available data of the gravimeters concerned. The method adopted for the present data analysis was almost the same as that for the international gravimetric connections along the Circum-Pacific zone (NAKAGAWA *et al.*, [1983]).

A correction function for the gravimeter was assumed to be a polynomial of its counter values and was estimated by comparing the differences of absolute gravity values or the IGSN 71 gravity values for sectors of inter-regions gravimetric connections with the measured gravity differences for the corresponding sectors. However, the numbers of both the absolute gravity stations and the sectors of inter-regions gravimetric connections were too few to independently derive the correction functions only by the present investigations, so that not only the data of the present investigations but also those of

(1) international gravimetric connections along the Circum-Pacific zone performed in 1979 - 1982 (NAKAGAWA *et al.*, [1983]),

(2) a domestic gravimetric connection in Japan by means of eight LaCoste & Romberg gravimeters (model G) covering a gravity range of about 1.6 gals performed in 1976 (NAKAGAWA *et al.*, [1977]), and

(3) an international gravimetric connection between China and Japan with six LaCoste & Romberg gravimeters (model G) by a gravimetric mission composed of several Chinese institutions as well as a domestic one in

Japan with four LaCoste & Romberg gravimeters (model G) by a cooperated team from Japanese institutions carried out in 1984 (LU, [1986]), were used for deriving the correction functions. Thus, correction functions for 22 LaCoste & Romberg gravimeters and offsets in gravity values for 49 investigation regions were simultaneously solved.

For the gravimeters employed in the international gravimetric connections along the Circum-Pacific zone, the adopted order of a polynomial for the correction functions was put to be the same as that in those calculations, so that almost the same revised scale values for the entire dial range (counter values) have been obtained. For the other gravimeters, the correction functions depending on the counter values have been derived for the first time, although the optimal order of a polynomial for the functions was proved to be 1 or 2 because the dial range used was rather narrower for the present gravimetric connections other than the Circum-Pacific ones. A well-known fact that the scale values of LaCoste & Romberg gravimeter given by the manufacturer are too small by an order of 10^{-4} has been confirmed for the whole dial range of all the gravimeters concerned through the present analysis. An example of the feature of scale values derived for the gravimeter G-196 is shown in Fig. 2. The optimal order of a polynomial was 4 for this case.

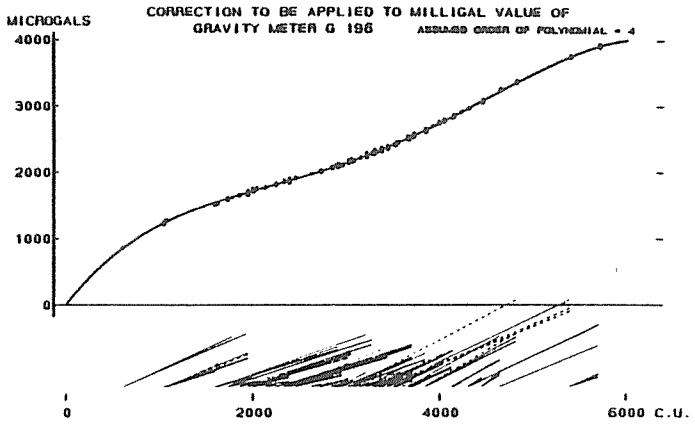

Fig. 2. An example of the determination of correction functions derived for the gravimeter G-196.

Gravity values at all the measured stations have been estimated by the least squares method under the assumptions of

(1) the drift of each gravimeter was linear with the lapse of time within a day, but might change day by day,

(2) no drift occurred during a day while a single inter-regions connection was made,

(3) sudden jumps of the gravimeter's drift might occasionally occur in the manner of a step function leaving no aftereffects, and

(4) parameters for the periodic errors were simultaneously estimated from the data themselves for all the gravimeters, except for the gravimeter G-484 whose parameters were independently derived from another set of data surveyed in Japan (SHICHI *et al.*, [1987]), and were applied for corrections in the process of deriving the gravity value at each gravity measurement.

Gravity values at the gravity stations in Japan thus obtained show a good agreement with those obtained by the three sets of the above-mentioned investigations within 10 μgals. Small discrepancies in both the correction functions and the gravity values of the present analysis from those of the Circum-Pacific ones might mainly be arisen from the fact whether periodic errors were taken into account or not.

An example of periodic error for the gravimeter G-605 is shown in Fig. 3

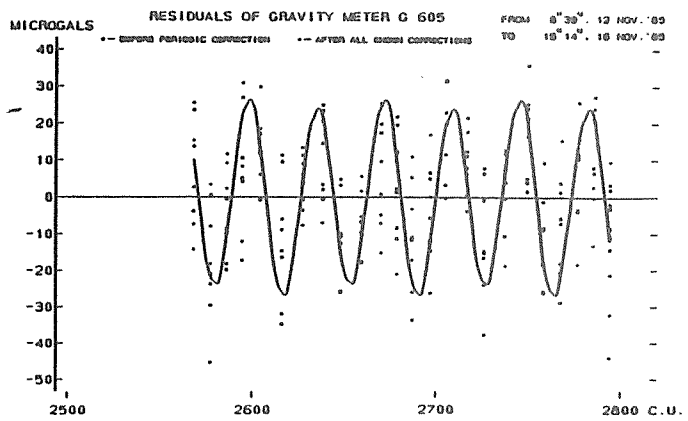

Fig. 3. Distribution of residuals for the gravimeter G-605 before and after the corrections for periodic errors, only for the data obtained in Lushan mountains.

Table 1. Gravity values at all the measured stations, other than in Lushan mountains, occupied by the present investigations with those already published if they are available. All gravity values are estimated referring to Kyoto C by assuming the gravity value of 979 707.732 mgals obtained from the international gravimetric connections along the Circum-Pacific zone.

A : Present investigations (1985-1986)
B : International gravimetric connections along the Circum-Pacific zone (1979-1982)
C : Domestic gravimetric connection in Japan (1976)

Station		A	B	C
Tokyo	B	979 788.763	979 788.783	979 788.700
Tokyo	B'	788.765	788.788	
Tokyo	C	763.177	763.210	763.180
Tokyo	C'	763.189	763.221	
Tokyo	N	758.080	758.103	758.081
Tokyo	11025	762.473	762.499	
Tokyo	NARTA	857.326	857.332	
Tokyo	HONGO	785.740		
Mizusawa	A	980 147.917	980 147.925	980 147.903
Mizusawa	B	146.351	146.376	
Mizusawa	C	146.443	146.466	
Mizusawa	ESSABS	121.762		
Mizusawa	ESSENT	121.712		
Kyoto	A	979 707.225	979 707.228	979 707.221
Kyoto	B	709.326		
Kyoto	C	707.732	707.732	707.732
Kyoto	J7900	708.136	708.143	
Kyoto	OSAAPT	702.937		
Tsukuba	FGS	979 951.063		
Tsukuba	ABS	951.257		
Nagoya	FGS	979 732.553		
Nagoya	EFRONT	732.402		
Nagoya	STN	731.517		
Sapporo	FGS	980 477.598		980 477.556
Sapporo	APTO	426.532		426.499
Sapporo	APTN	426.515		
Kagoshima	APTI	979 418.165		
Kagoshima	APTO	418.378		
Kagoshima	FGS	472.216		979 472.177
Kagoshima	WS-BH	472.459		
Kagoshima	KNY	443.668		
Okinawa	APT	979 107.510		
Okinawa	FGS	099.496		979 099.419
Okinawa	TS	104.340		
Okinawa	KDN-R89	111.126		
Ishigaki	APT	979 002.231		
Ishigaki	FGS	006.106		
Beijing	APT	980 131.719		
Beijing	YYT	119.651		
Beijing	KSO	129.443		
Beijing	GEOL	132.412		
Wuhan	APTS	979 346.286		
Wuhan	APT	347.594		
Wuhan	ABS	348.894		
Wuhan	ETS	349.521		
Wuhan	SEIS	351.047		
Guangzhou	APT	978 824.566		
Guangzhou	ABS	815.683		
Guangzhou	SEIS	817.514		
Guangzhou	CALI-1	817.457		
Guangzhou	CALI-2	791.246		
Guangzhou	CALI-3	769.091		

for the dial range covering the gravity values in Lushan mountains. A distinct periodic error amounting to the amplitude of 25.3 μgals with the period of 36.667 dial turns has been found for this case. The amplitude and phase for this period obtained by the present investigations showed a good agreement with those previously obtained. In any case, the periodic errors become highly important for a high precision gravimetry, because their effects cannot be reduced by increasing the number of gravity measurements.

Table 2. Gravity values at the gravity stations in Lushan mountains.

Station	Height (m)	Gravity value (mgal)
LUS BASE 01	36.42	979 268.907
LUS BASE 02	69.33	259.780
LUS BASE 03	107.14	251.061
LUS BASE 04	144.01	241.543
LUS BASE 05	189.48	232.136
LUS BASE 06	230.53	222.902
LUS BASE 07	284.95	210.762
LUS BASE 08	333.63	198.954
LUS BASE 09	388.21	189.288
LUS BASE 10	441.56	177.409
LUS BASE 11	481.04	168.830
LUS BASE 12	523.01	158.733
LUS BASE 13	562.34	150.112
LUS BASE 14	598.00	141.260
LUS BASE 15	651.21	130.381
LUS BASE 16	706.08	118.830
LUS BASE 17	752.15	108.700
LUS BASE 18	791.57	097.568
LUS BASE 19	865.09	086.039
LUS BASE 20	903.17	073.818
LUS BASE 21	958.87	063.879
LUS BASE 22	997.41	055.211
LUS BASE 23	1045.17	046.162
LUS BASE 24	1091.97	036.648

The gravity values at all the measured stations occupied by the present investigations are shown in Table 1 together with gravity values at some gravity stations of both the international gravimetric connections along the Circum-Pacific zone and the domestic one in Japan, if they are available. For the gravity stations in the standard baseline field of gravity surveys in Lushan mountains, gravity values determined are given in Table 2 with the station heights. The relationship between the gravity values and the station heights is shown in Fig. 4. However, there are some problems on a gravity calibration line established in mountains area, because the effects of atmospheric pressure as well as ambient temperature are generally different in mountains

area with large height differences. The gravity calibration line should be established in a level area as much as possible.

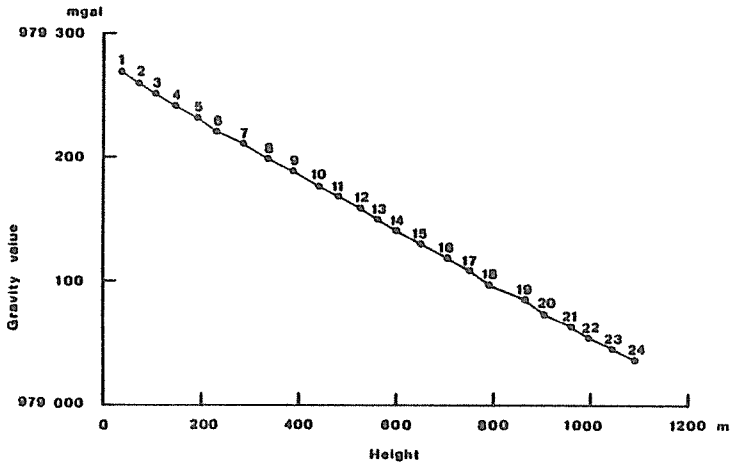

Fig. 4. Relationship between gravity values and station heights in Lushan mountains.

4. Sensitivity Characteristics and Measured Accuracy of the Gravimeters

During the whole course of the present investigations, a direct calibration of all the gravimeters employed was carried out as frequently as possible together with a sensitivity calibration at the time of every gravity measurement. These calibrations were planned and executed with purposes

(1) to assure the static characteristics of LaCoste & Romberg gravimeter clarified through the international gravimetric connections along the Circum-Pacific zone performed during the period from 1979 to 1982, and

(2) to attain a high accuracy of gravity measurements by evaluating the setting accuracy of the gravimeter at each gravity measurement.

Portable level triers made up very simple and compact in design and very light in weight were prepared for a direct calibration of the gravimeters, by which it was executed not only along the long-level but also along the cross-level with a resolution of 1 second of arc and with a repetition accuracy of a few seconds of arc. Only a brief summary of the calibration results will hereafter be described for the gravimeter G-484.

Gravity measurements by means of LaCoste & Romberg gravimeter are made by either an optical method or a readout method. As for the former, the dial value of the gravimeter is read when the cross-hair is adjusted to a designated reading line in eye-piece, whereas, as for the latter, gravity measurements can be made with a high resolution by adjusting the dial of the gravimeter so as to indicate the zero of its output reading. According to the theory, the setting error of the gravimeter along the long-level is expressed by a difference between the offset angle at a setting position and that at the optimal position for the optical method. For the readout method, however, the offset angle at the optimal position is essentially different in its characteristics from that for the optical method. The offset angle at the optimal position for the optical method depends only on gravity value at each measured point, while that for the readout method has a time-dependent character, because it has a time change by following the zero-drift of a readout amplifier and a low-pass filter.

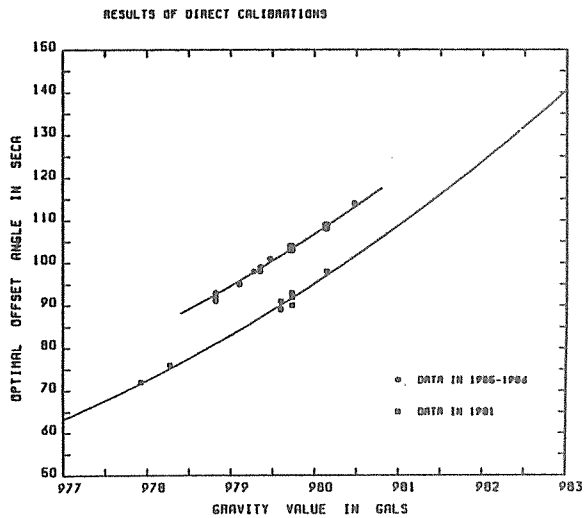

Fig. 5. Results of direct calibrations for the optimal offset angle on the gravimeter G-484.

Fig. 5 shows all of the calibration results on the optimal offset angle for the gravimeter G-484. The solid circles show data for the present investigations, while the solid squares show those for the international gravimetric connection along the Circum-Pacific zone performed in 1981. The lower curve

shows the optimal angle for the designated reading line 2.40 of the gravimeter G-484 determined from the sensitivity calibrations. The reason why the optimal angle for the present investigations was changed, is that the position of cross-hair image on the scale of the gravimeter's eye-piece was shifted by the exchange of a lamp of the optical system. The optimal angle for the present investigations was determined by fitting the second order polynomial to the calibration results under the assumption that the coefficients of the polynomial were kept unchanged except for the constant term. It is ascertained for all the gravimeters employed that the optimal offset angle depends on gravity value at the measured point.

Setting errors at every gravity measurement estimated from sensitivities for cross-hair movement are shown in Fig. 6.

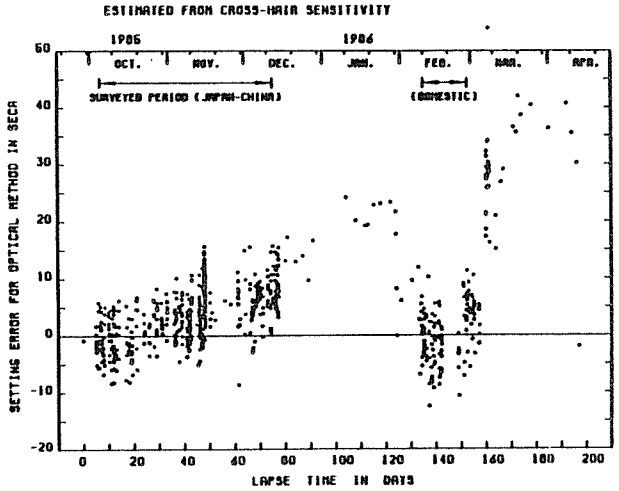

Fig. 6. Setting errors estimated by the optical method for the gravimeter G-484.

Fig. 7 shows measured errors along the long-level of the gravimeter G-484 for the optical method, in which results obtained from sensitivities for cross-hair movement are plotted. The measured errors accompanied by the setting errors of the gravimeter are shown in Fig. 7. A similar pattern is recognized for the other gravimeters. Therefore, it is concluded that the measured errors of the gravimeters employed during the whole period of the

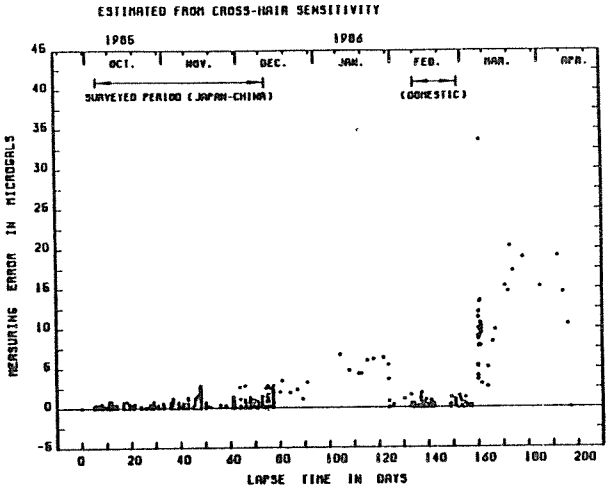

Fig. 7. Measured errors estimated by the optical method for the gravimeter G-484.

present investigations were limited to 3 μgals at maximum and 1 to 2 μgals for almost all cases.

The detailed consideration and discussion about the results of the present investigations will be made in their final report (NAKAGAWA *et al.*, [1987]).

5. Acknowledgements

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The numerical calculations were carried out with computer systems at the International Latitude Observatory of Mizusawa and Nagoya University Computation Center.

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ON THE ADJUSTMENT OF NATIONAL GRAVITY FUNDAMENTAL NETWORK IN CHINA

Song Xingli* Hsu Houtze* Hou Zhangwei*

Abstract

In China a new national gravity fundamental network had been set up in 1983-1985 by using several sets of LCR-G meters and two sets (Chinese made and Italian made) of absolute meters. In addition, we connected our network with the gravity stations in Paris, Hong Kong and Japan.

The network-adjustment problems, including mathematic model, the check of absolute gravity values and the weight-ratio between relative-absolute observations, etc. are discussed. We consider that,

1. For LCR-G meters, the use of mathematic model with period errors can greatly decrease the discrepancy of various meters, and improve the relative observation accuracy.

2. The accuracy of absolute measurements in some stations seems not enough and the inconsistent values have to be rejected during the final adjustment.

3. The weight-radio between relative-absolute observations is better in proportion of 1: 2 in our case.

I. The national gravity fundamental network in China[4]

The network consists of 8 datum gravity points, 46 fundamental gravity points. It covers about two thirds area of China. The gravity difference of the whole network attains 2852 mgal. Datum points have been measured by using the absolute gravimeters of Chinese Academy of Metrology & Torino Institute of Metrology, Italy respectively. Relative measurements among the datum points and fundamental points have been carried out by means of 9 sets of LCR-G model gravimeters. To improve and check up the realiablity and accuracy of network, we connected our network with the gravity points in Paris, Hong Kong and Japan too.

*Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, China
**Survey Department, Tongji University, Shanghai, China

II. Mathematic model

As well known, the scale of LCR-G gravimeter is possessed of non-linearity and periodicity. If in two points the gravimeter-counter readings are Z_1 and Z_2 respectively, the gravity difference will be

$$G_{T_1}-G_{T_2}=\sum_{i=1}^{n} D_i(Z_1^i-Z_2^i)+\sum_{j=1}^{K}\left[A_j\cos\left(\frac{2\pi Z_1}{T_j}+\theta_j\right)-A_j\cos\left(\frac{2\pi Z_2}{T_j}+\theta_j\right)\right] \quad (1)$$

where D_i - polynomial coefficient, i - polynomial order, A_j - amplitude of periodic error, T_j - period. (to take counter reading-scale as unit). θ_j - phase of periodic term, j - periodic term number.

let $D_1=D_0+\Delta D_1$ in equation (1), and within the limits of $n=2$, the following equation is obtained

$$G_{T_1}-G_{T_2}=(Z_1-Z_2)D_0+\Delta D_1(Z_1-Z_2)+D_2(Z_1^2-Z_2^2)+\sum_{j=1}^{K}\left[X_j\left(\cos\frac{Z_1 2\pi}{T_j}-\cos\frac{Z_2 2\pi}{T_j}\right)+y_j\left(\sin\frac{Z_1 2\pi}{T_j}-\sin\frac{Z_2 2\pi}{T_j}\right)\right] \quad (2)$$

where

$$X_j=A_j\cos\theta_j,\quad y_j=A_j\sin\theta_j \qquad \text{thus} \qquad A_j=\left|\sqrt{X_j^2+y_j^2}\right| \quad \theta_j=\mathrm{Arc}\,tg\frac{y_j}{X_j}$$

In equation (2), D_0 is segment scale taken from manufactory Table, all the 1st and 2nd order polynomials and periodic terms are correction to the manufactory scale-Table. corresponding observation equation is as follows:

$$\Delta g_{1.2}+V_{1.2}=G_{T_1}-G_{T_2}-\Delta D_1(Z_1-Z_2)-D_2(Z_1^2-Z_2^2)-\sum_{j=1}^{K}\left[X_j\left(\cos\frac{2\pi Z_1}{T_j}-\cos\frac{2\pi Z_2}{T_j}\right)+y_j\left(\sin\frac{2\pi Z_1}{T_j}-\sin\frac{2\pi Z_2}{T_j}\right)\right] \quad (3)$$

In addition, absolute gravity observation equation is

$$g_i+V_i=G_{T_i} \qquad i=1,2\cdots n \quad (4)$$

where $\Delta g_{1.2}$ and g_i are observation values of relative and absolute gravity respectively, G_{T_i} is gravity adjustment value. According to the indirect observation adjustment method the joint adjustment is made for equations (3) and (4) so that the representing gravimeter parameters $\Delta D_1, D_2, X_j, y_j$ (or A_j, θ_j) and gravity value G_{T_i} of measurement point can be found. It is noticed that, in equation (3) the footnote-numbers 1 and 2 stand for 2 terminal points numbers of arbitrary measurement side.

How do we choose the number k of periodic terms? It mainly depends upon distribution of gravity value in various measurement points. Because the gravity difference among various points in network of China is very large, apparently, only some larger period terms can be found out, through

the adjustment, the coefficients of 1st and 2nd order non-linear terms and the amplitudes of period terms for each meter are obtained as shown in Table 1. From Table 1, it can be seen that, the 2nd-order term coefficient and period amplitude of the instrument No-85 are larger than that of the newly produced instruments, this is due to the long use-duration and wear-tear in mechanical transmission system. For some instruments, we could not evaluate correctly its 2nd-order term coefficient and period term because of the lack of observation data. However, for instrument No 589 the case is different, the observation point value distribution is dense enough, but its 2nd-order term calculated is very small and can be neglected. Besides, from Table 2, we know that, after considering the periodicity of meter scale, the discrepancy of various meters can be greatly decreased so that observation accuracy of gravity network is improved.

III. The choice of absolute gravity observations

The absolute gravity values in some points of our network have been measured by Chinese-Italian cooperation and Chinese Academy of Metrology alone early or late. But, we discovered that there is very large discrepancy of the observation result in the some points for these 2 sets of absolute gravimeters, the maximum can be reached to more than 100 mgal, in other words, a greater error exists in some absolute gravity values. And we have to check and reject. It means, to choose the correct absolute values for controlling the national gravity fundamental network and calibrating the scale of relative gravimeters, it is the most important thing in our adjustment, for this purpose.As the first-step, we have made adjustment by only using relative connection data among Chinese absolute points & international connection data in order to check reality of absolute values. We choose Sévres in Paris, Chikunami in Japan, all IGSN-71 network points and Beijing point as the fixed points, other absolute points in China are supposed as unknown. In this way, the Chinese absolute gravity system can be unitedly compared with the international system. In Table 3 the discrepancy between first-step adjustment gravity values and original absolute observation values is listed. Finally, we rejected all the absolute observation value with the discrepancy more than 60 μgal,and used the remainders as the absolute control of our network, this can be seen in the last column of Table 3.

IV. Weight-radio

In adjustment, how to determine the proper weight of relative and absolute gravity observation equation is a interesting problem. For this reason, three programs are used to carry out the adjustment, namely, let weight-radio be: $P_a : P_r = 4:1$*, $P_a : P_r = 2:1$ and $P_a : P_r = 1:1$ (three cases). The adjustment results are listed in Table 4. We consider that, the weight of program III is taken reasonably, its correction sum $[PVV]_a$ in absolute observations is less than that of programs I and II. and the point accuracy of program III is almost the same as program I. Thus it can be seen that the absolute points of program III play more reasonable role in controlling gravity network, if program I is used, $[PVV]_a$ will suddenly increase, this shows that due to low accuracy of absolute observations and excessive weight adopted, the adjustment accuracy of the whole network is influenced. Indeed, the adjustment accuracy of program II is very high, but correction number of absolute point increases rapidly so that absolute points would lose the control role. In addition, because of low accuracy of absolute point observation in Fuzhou, thus in program III let its weight be 1. In the final adjustment, after rejecting 4 relative measurements with the correction more than 40 mgal, the adjustment accuracy of network can increase to $\pm$ 17 μgal.

V. A few views

1. For LCR-G model gravimeter, the use of mathematic model with period error can apparently decrease the observation discrepancy of various meters, and improve the observation accuracy.

2. We suggest to choose the program III as the final adjustment program in gravity network. In Table 5, partial final adjustment results are listed. The point accuracy of Chinese absolute gravity points and international gravity points is better than 10 mgal. Most of absolute gravity point value correction chosen are less than 20 mgal. Correction of international gravity point values aren't large. This indicates that gravity network in China coincides well with international gravity network. The accuracy of national gravity fundamental network is better than 20 mgal.

3. During the network adjustment for some of meters due to the lack of the measurements and small gravity range, it brings a greater error to the determination of gravimeter scale function. From the adjustment results we know that, the accuracy of 1st and 2nd order terms coefficients is good enough, but the accuracy of period term coefficient is not to be satisfied.

*The footnotes a and r represent the absolute and relative observations respectively.

However, the period term must be added to the adjustment model because the amplitude of some periodic terms can reach 20 mgal, in particular, when the period terms overlap together, their influences are verylarge.

4. Adjustment result shows that, the absolute gravity point error plays a important role in relative gravimeter scale calibration and gravity network accuracy, therefore, it needs to carry out the absolute gravity detection work in the future. According to the analysis of absolute point distribution, an additional measurement in Lhasa and Haerbin points is necessary in order to satisfy the needs of the large range scale calibration for the relative gravimeters.

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Tab. 1.

Instrument LCR-G	Linear term	Quadratic term	Amplitude of Periodic term		
			1206	603	70.94
085	0.999514 ±0.35×10⁻⁴	+0.1892×10⁻⁶ ±0.0059×10⁻⁶	15±5 μgal	10±4 μgal	18±4 μgal
147	1.000370 ±0.81×10⁻⁴		18±7		
				220	73.33
570	1.000470 ±0.75×10⁻⁴			8±6 μgal	
584	1.000486 ±0.36×10⁻⁴	−0.0144×10⁻⁶ ±0.0056×10⁻⁶		12±4	
589	1.000506 ±0.68×10⁻⁴			5±4	11±4 μgal
596	1.000765 ±0.54×10⁻⁴	−0.0268×10⁻⁶ ±0.0089×10⁻⁶		9±6	
625	1.000409 ±0.20×10⁻⁴				
676	1.000611 ±0.24×10⁻⁴				
681	1.000664 ±0.24×10⁻⁴				

Tab. 2.

Observation Side	Instrument number	Largest Difference Among Variant Instrument	
		Model I	Model II
Beijing — Narta	6	57 μgal	29 μgal
Beijing — Shanghai	9	73	37
Beijing — Guiyang	4	61	44
Guangzhou — Nanning	3	50	3
Hailar — Ulanhaot	4	75	41
Nenjiang — Harbin	4	110	52
Guilin — Nanning	5	41	16
Shanghai — Fuzhou	3	51	29
R.M.S.E (μgal)		±23	±19

* Model I is that the equation (3) includes 1st and 2nd order polynomial and Model II is that it includes 1st and 2nd polynomial and two periodic terms.

Tab. 3.

Station	Absolute gravimeter	Difference between adjustment and observation	Chose absolute gravity observation
Qingdao	Italy	33 μgal	Italy
Wuchang	China	24	China
Fuzhou	Italy	56	Italy
Kunming	China	98	Italy B*
Guanzhou	Italy	18	Italy
Nanning	China	17	China
Zhenzhou	Italy	90	China
Shanghai	Italy	60	no
Xian	Italy	184	no
ChangSha	Italy	76	no
Beijing	Italy		Italy

* Italy B is the first observation Result and It is 230 μgal less than Second.

Tab. 5

Station	Correction	Point accuracy
Beijing	+18 μgal	±6 μgal
Qingdao	-19	±8
Wuchang	+12	±6
Fuzhou	+39	±7
Kunming	+13	±8
Guanzhou	+3	±6
Nanning	-11	±7
Narta (Tokyo)	-8	±6
Tokyo B	-10	±6
Kyoto C	+4	±7
Chikunami	-14	±7
Hong Kong JT902	-1	±9
Zhengzhou	-12	±8

$\mu = \pm 17$ μgal

Tab. 4.

Station	Program I		Program II		Program III	
	Correction	Point accuracy	Correction	Point accuracy	Correction	Point accuracy
Beijing	+19 μgal	±7 μgal	+31 μgal	±8 μgal	+17 μgal	±7 μgal
Qingdao	-16	±8	-31	±11	-21	±8
Wuchang	+9	±7	+16	±8	+14	±7
Fuzhou	+30	±7	+49	±8	+37	±8
Kunming	+2	±8	+4	±12	+11	±8
Guanzhou	+1	±6	+7	±8	+4	±7
Nanning	-13	±6	-16	±9	-7	±8
Narta (Tokyo)	-14	±7	-23	±8	-9	±6
Tokyo B	-10	±6	-20	±8	-9	±6
Kyoto C	+8	±7	+9	±10	+5	±8
Chikunami	-4	±8	-9	±10	-13	±8
Hong Kong JT902	-2	±8	-4	±11	0	±10
Zhengzhou	-10	±8	-15	±10	-13	±9
r.m.s.e	±19 μgal		±16		±18	
$[pvv]_a$	9008		6232		4643	
$[pvv]_r$	71513		63167		74701	
$[pvv]$	80521		69399		79344	

Program I: $P_a = 4$, $P_r = 1$; Program II: $P_a = 1 = P_r$;

Program III: $P_a = 2$, $P_r = 1$, $P_f = 1$.

International Gravity Commission IGC
(IAG Commission III)

12th Meeting, September 22-26, 1986
Toulouse, France

Unified European Gravity Network UEGN
Status Report

Submitted by

Gerd Boedecker, Bayerische Akademie der Wissenschaften, Minchen
Iginio Marson, Istituto di Miniere e Geofisica appl. dell'Universita Trieste
Christian Poitevin, Centre de Geophysique Interne, Bruxelles
Govert Strang van Hees, Delft University of Technology, The Netherlands

1. Introduction

Gravity values of various types are needed for many different purposes: point or mean values, gravity values or anomalies, varying point densities and accuracies. A tentative reminder gives fig.1.

	Application	Type	Accuracy	Limitation
Metrology:	Standard of force Mercury-barometer electric current standards)	Point gravity	± 1 ... 0.1 mGal absolute	
Geophysics:	Local studies	Point anomalies, Bouquer type	± 0.1 ... 1 mGal relative	Topographic reduction
	Regional studies	Mean anomalies, Bouquer type	± 1 mGal relative	Topographic reduction & representation
Geodesy:	Global geoid	Mean anomalies, Free air type	± 1 mGal absolute	Representation & Earth model requirement
	Height	Point gravity	± 10 mGal absolute	Levelling accuracy
	Geodynamics	Points gravity	± 3 µGal absolute	Environmental effects

Fig. 1 Utilization of gravity values

In the past, gravity values could only be determined by terrestrial means. Since the advent of satellites a certain range of the spectrum of gravimetry can be covered by satellite methods: Satellite altimetry contributes to the higher frequency gravity field determination on the oceans, orbit analysis is a major support for global gravity field modelling. But also terrestrial data contributes to orbit determination. Because of political restrictions for the release of data, inaccessability of big regions for terrestrial methods and superior effectiveness, satellite methods will be refined and expanded.

Terrestrial methods, however, will remain superior as to the determination of point gravity values, high precision and potential high resolution for special investigations. Thus, e.g. for metrology and gravity changes monitoring, terrestrial gravimetry is indispensable, for many other purposes the better choice.

History confirms, that gravimetric methods to be applied depend on the existing spectrum of tools and on the requirements. First the gravimetric method was challenged - in the 17. century - to help judging on the shape of the Earth. Later, in the 19th and 20th century, applications to geophysical prospecting and metrology emerged. Currently the most demanding application is geodynamic gravity variations monitoring. For these applications different types of observation tools were developped: Whereas the early gravity observations primarily were carried out by different types of absolute and relative pendulums, these were succeeded by spring gravity meters for relative observations since the 1930's and by free fall or free rise and fall instruments for absolute observation s since the 1950's, c.f. figure 2.

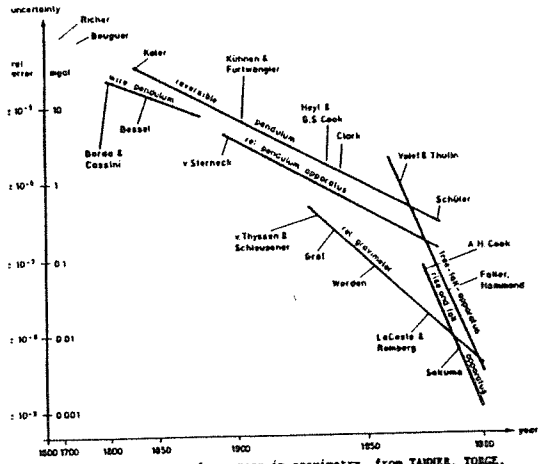

Fig. 1. Increase of accuracy in gravimetry, from TANNER, TORGE, and BAGY (1982).

Fig. 2 Gravimetric observation techniques

Because of differences in performance and cost of relative and absolute meters, for the determination of a multitude of point values a combination of both absolute and relative instruments is most efficient, leading to a hierarchy of networks from absolute stations over several orders of networks down to field stations. Base networks secure homogeneity throughout a country, a continent or the whole globe. With increasing availability and ease of use absolute meters, these will gain grounds compared to relative meters in the future.

On the basis of these general remarks we can understand the history of extended base networks such as the Vienna System, the Potsdam System and the First Order World Gravity Net FOWGN. In Europe, as the direct predecessor of the UEGN we could see the European Calibration System 1962 (KNEISSL & MARZAHN 1963) comprising 27 stations with formal standard errors of 0.05 ... 0.26 mGal 1) based on Bad Harzburg, which was closely connected to Potsdam.

Much more important, however, became the INTERNATIONAL GRAVITY STANDARDIZATION NET 1971 (IGSN71), comprising 24 000 gravimeter observations, 1200 pendulum and 10 absolute measurements on 473 primary and many excenter bases (MORELLI 1974). Figure 3a depicts the main gravimetric connections, 3b the European stations. The formal errors are less than 0.1 mGal, but also comparisons with recent absolute observations confirm this quality level in the absolute sense.

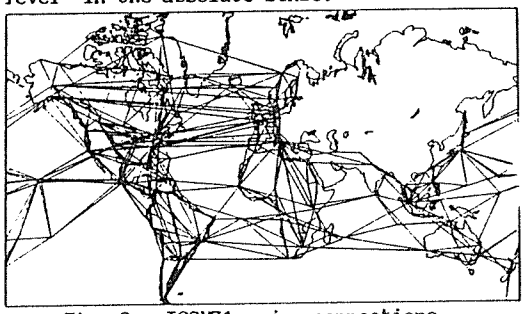

Fig. 3a IGSN71 major connections

1) 1 mGal = 1 .10-5 ms-2

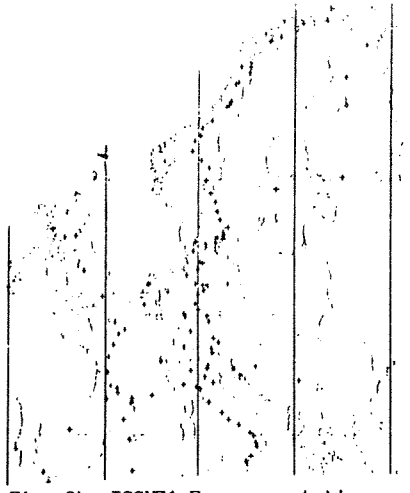

Fig. 3b IGSN71 European stations

If there is an existing base net such as IGSN71, why did the IGC-Subcommission Western Europe (SC-WE) initiate this adventure of a unified adjustment of gravimetric observations in many European countries? Considering that many markers of IGSN71 stations, which were distributed unevenly anyway, vanished and because meanwhile progress allows for much better observation accuracies, we see the following arguments in favour of this project:
Point gravity values still are important, in particular if they reach an accuracy which makes them a means for monitoring gravity changes originating from geodynamic processes. The UEGN should also be seen in the framework of the global International Basestation Network IAGBN. Point gravity stations should be distributed to meet various needs for reference purposes and gravity variations monitoring; the distribution of IGSN71 stations is not optimum at all. In the past two decades many new national base nets were established. Because a reference always should be as comprehensive as possible, the national nets should be unified in order to increase formal and factual homogeneity of gravity reference throughout Europe. Also growing political and economic cooperation requires homogeneous standards. This shows, e.g., also the very good resonance to the Catalogue of Coastal Gravimetric Stations for Marine Gravimetry edited by this SC-WE. The connection of the national nets also provides better mutual error control for existing data and makes better use of absolute stations. The Working Group (WG) No. 2 of the Directing Board (DB) of the Bureau Gravimetrique International concluded that the IGSN not be updated but that regional readjustments be supported 2). This policy also gave grounds for other regional net adjustments such as the Latin America Gravity Standardization Network 1977. Finally the Earth tide model was changed by IAG resolution, therefore the absolute observations after Earth tide reduction also changed.

Details of the UEGN network project will be presented in the following sections. The work is carried out by the four authors. It is hoped, that results will be ready within 2 years time.

2) (c.f. minutes of meetings, published in BGI-Bulletins dInformation no 53 (1983) p. 35ff, no. 51 (1982) p. 11ff, no 47 (1980) p.17ff, no 46(1980) p. I-29ff, no.44 (1979) p I-4ff, no.40 (1977) p. I-8ff)

2. The Existing Data

2.1 Absolute Data

Within the last ten years, several absolute sites have been established both using gravity meters constructed by the Istituto Metrologia G. Colonetti (IMGC, 28 stations) 3) and by the Jaeger Company in cooperation with the Bureau International Poids et Mesure (JAEGER-BIPM, 5 stations). In the next years three absolute gravimeters developed by Dr. Faller of the Joint Institute for Laboratory Astrophysics (JILA) will be operating in Europe and, therefore, both an improvement of the existing data and an increase of the number of absolute sites in Europe are expected.

According to the data collected up to now, and from acquired information, the following 29 absolute stations have been included in national networks:

Hammerfest (NO), Sodankylä (FI), Vaasa (FI), Gävle (SW), Göteborg (SW), Hamburg (GE), Braunschweig (GE), Wiesbaden(GE), München (GE), Bruxelles (BE), Graz (AU), Altenburg (AU), Kremsmünster (AU), Penk (AU), Zürich (CH), Chur (CH), Interlaken (CH), Jungfraujoch (CH) Brig (CH), Andermatt (CH), Gupisbach (CH), Dijon (FR), Marseille (FR), Sevres (FR), Toulouse (FR). (Annex 1).

The preprocessing of absolute data for the UEGN requires some considerations. In first place, since the earth tide correction will be computed using all the available parameters for each site, it is necessary to recompute this correction for each single absolute observation. This is certainly possible for the data collected with the IMGC instrument. The absolute data file will then contain records formed as follows:

> Base station identification, base station name, date and time of observation, observed value, earth tide correction, corrected absolute value. The final mean g value, any applied corrections and the height of the observed point will be added to the file, too.

Particular consideration deserves the reduction of the absolute observation, which normally refers to a point some decimeters above the ground, to the floor. Many observer have indicated the measurement of the vertical gradient as a crucial point in handling absolute and relative data. To reduce this source of error, all the available vertical gradient data or the respective derived gravity differences will be inserted in the network adjustment as a regular tie to the absolute point. This last will be introduced with its appropriate weigth estimated from the statistics, and error budget, of the absolute measurements. In this way, of course, the tie to the absolute point will be an "hanging" leg in the network structure, but this is just the way in which measurements have been taken. A better wayto include absolute sites in a gravity net would be performing the outer relative ties directly to the observed absolute point with an adequate tripod instead of using the intermediate point on the floor.

2.2 Relative Data

Original observations of relative data have been provided, so far, by Sweden, Norway, Finland, United Kingdom, Netherlands, Federal Republic of Germany, Austria and Italy. Data concerning Belgium, Luxemburg, Denmark, France and Switzerland are in preparation.

As expected, the actual data do not constitute a homogeneous file. Because of the different philosophies employed in the establishment of national networks, some countries offer a redundancy of stations and ties. This because it is not always possible to extract a first order base net from the field data, when first order points are not tied directly. Redundancy of data is, however, preferred to lack of them!

A separate mention, concerning the Scandinavian countries, has to be made. In the UEGN files are included also all the measurements performed along the 56o, 61o, 63o , 65o land uplift lines, with an increase of some 2500 readings, but providing also a strong interconnection between the different national networks.

Tab. 1 gives a resume of the data collected up to now:

Country	First order Base st.	Auxiliary Base st.	Readings
Norway	14	71	2219
Sweden	25	35	2744
Finland	8	36	1172
Netherlands	5	18	104
United Kingdom	34		434
Germany	25		1375
Austria	24	48	790
Italy	15		268
Total	150	208	9106

Tab. 1 Relative gravity measuremts

The high number of readings already collected will certainly create some problems in the final adjustment. The structure of the existing ties is shown in Annex 2.

Since the philosophy of the UEGN is based on the unification of national networks, it is obvious that the weakest points will be in the interconnections between the various networks. Except for the Scandinavian countries, there is little redundancy of data with this respect.

One means of standardization is provided by the high number of absolute measurements performed with one single instrument. Even though a debate concerning the accuracy of absolute data has been arisen by the last intercomparison held in Paris in 1985 (cf report of SSG 3.86), this might represent a valuable tool for the homogeneity of the final network.

Still on the same topic, fourteen absolute sites between Hammerfest and Catania have been chosen to form the European absolute Calibration Line. Several relative measurements have been performed along this line. If the various observers could provide all the field data, this could be of high benefit for at least two different aspects. In first place it will provide long range ties interconnecting networks of Italy, Germany, Denmark, Sweden, Finland, and Norway. In the second one, it will add another information toward a better homogenization because some of the gravimeters employed in the European calibration line have been used for national networks, too.

3 (CANNIZZO et al., 1978; MARSON et al. 1981; MARSON et al. 1981)

Finally the Subcommission is willing to organize and perform additional international ties in the weakest areas, i. e. Switzerland-Italy, Austria-Italy and United Kingdom-Continent.

While collecting missing and additional data, the work of the S.C. is actually devoted toward the preprocessing of existing data to create files with all the necessary information for the final adjustments.

The data related to the various networks have been organized in three files.

The first one contains information regarding the field observations. Namely: Base station identifation, date and time of observation, instrument, identification, original reading in c.u. (counter units), reading in mGal eq., observed temperature, air pressure and instruments height (if measured), earth tide correction.

The second one contains the calibration tables used for the conversions. To this respect, some problems concerning non linear terms of D meters, have to be clarified.

The third one contains information related to base stations. They are: Station identification, station name, latitude, longitude, elevation, earth tide parameters.

Monographs of all the stations, to be used in the UEGN have been requested from the various national representatives. This is necessary not only for a more complete data base, but also to clearify some ambiquities which appear when common stations have been used by different countries. It is not always clear, in fact, from the coordinates and station names if what might be a common station is really a single station and not two different ones.

These files, together with the one concerning the absolute observations, will also constitute a valuable data base.

3. Earth Tide Correction

Earth tide corrections can in principle be computed either by a direct evaluation of the global effect of the Moon and the Sun using the ephemeris positions, either from the development of the tidal potential into a sum of harmonic constituents or tidal waves. The second approach has the advantage that it allows to take into account the perturbations introduced by the physical properties of the Earth. It was implicitely recommended by the Standard Earth Tide Model Committee (RAPP, 1982) adopting the "rigid Earth tidal model known as the Cartwright-Tayler-Edden model with additional waves specified by the International Center for Earth Tides (ICET) to yield a total of 505 tidal constituents, including the M_oS_o term".

In order to discuss the following, let us introduce the vectorial diagram of figure 4 which can be established for any tidal wave.

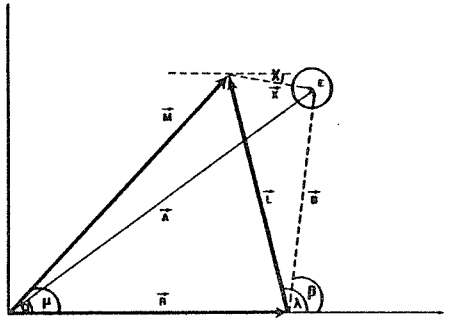

Figure 4: Vectorial representation of a tidal wave

The "solid Earth" model vector $\overline{R}$ calculated for an oceanless elastic Earth liquid core having a zero phase lies completely on the abscissa. This particularity has been exploited to study the residues of the observations with regard to the model, see for instance De Becker et al. (1986).

The ocean-continent tidal interactions, the "indirect effect" vector $\overline{L}$ (shortly the load vector), consist in a number of intricate effects:

- the direct attraction of the periodically moving masses of water upon the ground based instruments;
- the flexure of the ground under the load of these masses;
- the change of the Earth's potential due to this load deformation of the Earth.

The sum $\overline{M} = \overline{R} + \overline{L}$ represents the "total" model. The vectorial difference, between $\overline{M}$ and an observed wave $\overline{A}$, the final residue $\overline{X}$, should be minimum provided the Earth and oceanic models are adequate.

Until now more than 250 stations, including the 115 stations of the Trans World Profiles (TWP) developed by the ICET and the Royal Observatory of Belgium (MELCHIOR et al., 1984), were evaluated and collected into the "Data bank on Earth Tides" (DUCARME, 1984). For Europe, the radius ϵ of the error circle is currently less than 0.5 µgal. The strong correlation between the residue vector after analysis $\overline{B}$ and the "load" vector $\overline{L}$ computed from the Schwiderski's cotidal maps (MELCHIOR et al., 1984) led

to the adoption of these maps as a standard for the computation of the oceanic effects.

The more precise tidal gravity corrections are computed taking into account the observed gravimetric amplitude factors δ_0 and phase differences α_0 for the main diurnal and semi-diurnal components as discussed by (DUCARME et al., 1980).

At this stage we have to clearly define what is currently considered the observed tidal gravimetric amplitude factor δ_0 (in short gravimetric factor) as obtained from the analysis. For the considered wave δ_0 is the ratio of the measured tidal amplitude to the theoretical tidal force evaluated using the astronomical constants along the normal to the ellipsoid.

Figure 5 illustrates for the station Sevres-BIPM, the difference between tides computed using static (δ = 1.16, α =0°) and observed tidal factors. It results in a residue tide with an amplitude reaching 10 µgal.

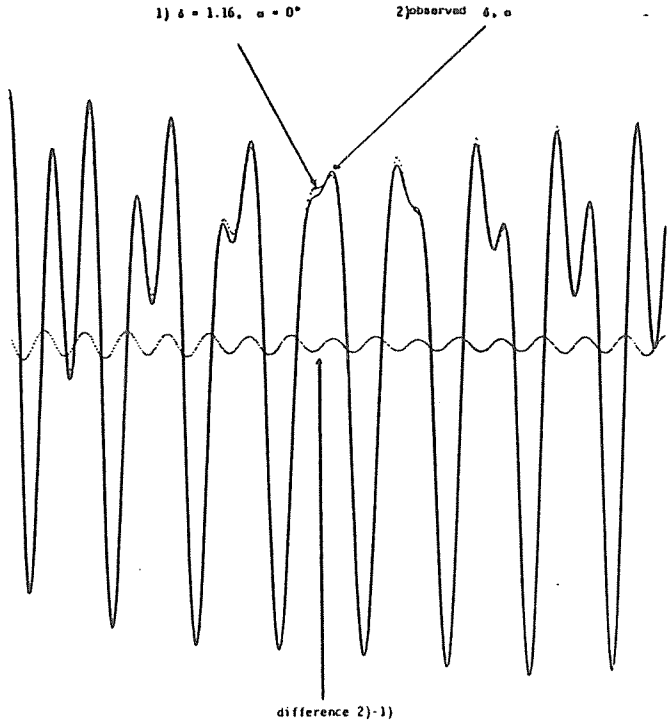

Figure 5: Comparison of the 3 curves (same scale).

As a matter of fact, there is not an observed tidal factor at each UEGN-station. It was thus decided for homogeneity and to follow as closely as possible the recommendations of the Standard Earth Tide Committee to compute these factors at each station on the basis of the "total model" vector $\bar{M}$ at least for the main waves.

The total model vector $\bar{M}$ contains two contributing models: the Earth model and the oceanic model.

These models are introduced into the tidal computation through the modelized gravimetric factors δ_M.

For what concerns the Earth model, one recommendation by the Standard Earth Tide Model Committee says:

"The calculations of Wahr using the 1066A Earth model should be adopted for the determination of the apparent gravimetric factor".

In Wahr (1981), we find: "G, ..., can be interpreted as an apparent gravimetric factor". In fact, the use of the words "gravimetric factor" is quite unhappy because this term does not correspond to the previous definition. This was pointed out by Dehant et al. (1986) who recomputed in the Wahr theory the effective gravimetric factor δ_W as on figure 6.

This decreases the latitude dependent part of the "gravimetric factor" which now is in quite good agreement with the observed δ_0. The discrepancy reduces to a constant term of about 0.6 % what corresponds to less than 2 µgal.

The observed δ_0 has been obtained by regression on the stations contained in the ICET data bank. Dots represent the mean station computed for each span of ten degrees latitude.

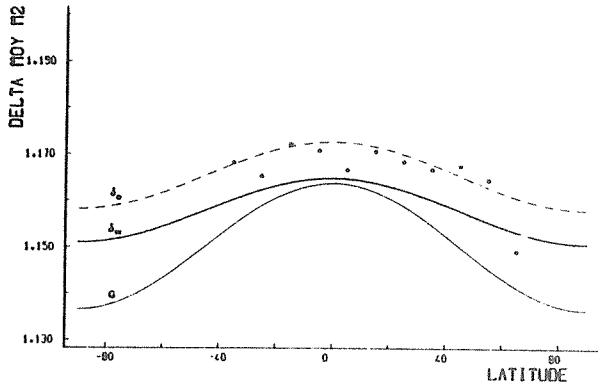

Figure 6: Latitude dependance of the gravimetric factor

The tidal correction for UEGN will be computed on the basis of the Wahr-Dehant gravimetric factors δ_W augmented for the oceanic effect.

This last effect contains the periodic attraction as well as loading effects of oceanic tides and change of Earth's potential. It is calculated by the Farrell procedure based upon Green's functions and using the Schwiderski cotidal maps.

The computation is based upon the following principles:

- The Newtonian attraction is directly calculated taking the altitude of the stations into account.

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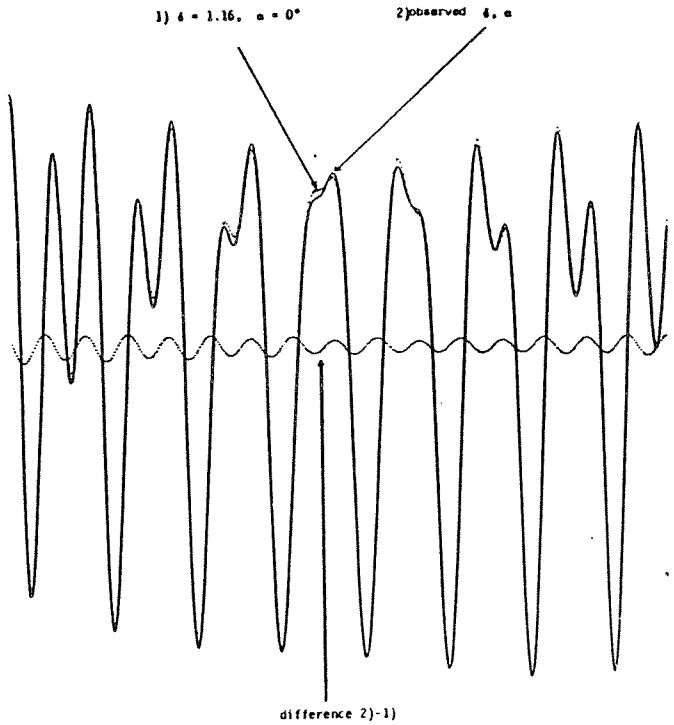

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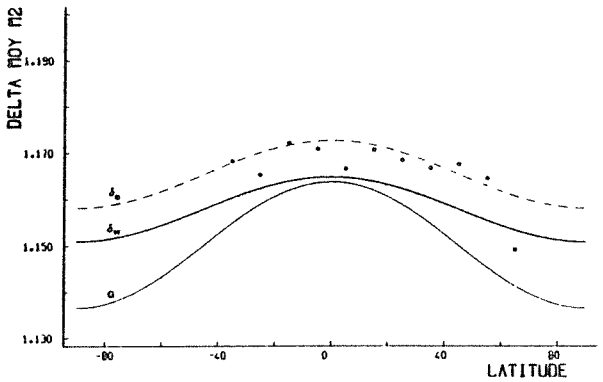

Figure 6: Latitude dependance of the gravimetric factor

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This last effect contains the periodic attraction as well as loading effects of oceanic tides and change of Earth's potential. It is calculated by the Farrell procedure based upon Green's functions and using the Schwiderski cotidal maps.

The computation is based upon the following principles:

- The Newtonian attraction is directly calculated taking the altitude of the stations into account.

- The load deformation of the ground is calculated by polynomial interpolation in the Farrell tables without considering the altitude, this effect being considered as negligible.
- Mass conservation of oceanic waters has been ensured by a correction proportional to the tidal amplitude, which is thus larger in the coastal areas.

There are about 45.000 polygones $1^0 \times 1^0$ in each Schwiderski cotidal map but, for near-shore stations, the nearby oceanic $1^0 \times 1^0$ zones are redivided into smaller and smaller squares up to $0.125^0 \times 0.125^0$ in size. When the centre of a small square is less than 10 km from a station, the corresponding effect is not taken into account. This is essential because if the station is very near to the centre of such a square, the evaluation loses any physical meaning.

The accuracy of the load vector is estimated to about 10 %. That is 0.2 to 0.5 µgal in Europe, corresponding to a little bit more than 5 cm error on the oceanic tidal amplitude.

Experimental evidence of the quality of the Schwiderski maps in a coastal area is demonstrated in table 2 by a tidal gravity profile across Belgium from the sea to 220 km inland in the Grand Duchy of Luxemburg. B. L, X are explained in fig. 4.

STATION	DISTANCE to the SEA (km)	B (µgal)	β (°)	L (µgal)	λ (°)	X (µgal)	χ (°)
Veurne	6	1.82	112	2.00	96	0.57	-148
Gistel	5	1.77	90	1.97	86	0.24	-127
Damme	10	2.01	69	1.90	74	0.19	18
Bruxelles	110	1.76	61	1.88	63	0.13	- 92
Louvain-la-Neuve	130	2.07	58	1.88	62	0.24	26
Walferdange	220	1.74	57	1.84	61	0.16	- 70

Table 2. Tidal profile across Belgium (M2 wave)

In practice for UEGN, programmes have been written and tested at the ICET to complete the reduction program package described in Poitevin (1981). We can briefly distinguish three steps in the new part:

- check and homogeneization of the station files and formating for compatibility with the gravity field measurement reduction software already existing.
- computation of the indirect effect using the Schwiderski maps for four main tidal diurnal waves (Q1, O1, P1. K1) and semidiurnal ones (N2, M2, S2, K2). For programming reasons, the results are stored wave by wave in eight different files. This step is the more time consuming taking one hour to compute 20 stations on a UNIVAC 1180 computer.
- merging of the eight files and computation of the modelized tidal factors as described previously.

Tidal corrections are then computed using the existing programme package at the precise epoch of measurement using the coordinates and, for the eight main waves, the tidal factors of the stations.

4. Adjustment

The adjustment of a gravity network is in principle not very difficult because the relations between the observations and the unknown gravity values are simple linear expressions. However the following problems should be considered carefully:

1. Drift of the instruments
2. Correlation between the observations
3. Calibration functions of the instruments
4. Connection to given absolute gravity points
5. Testing for gross errors in the observations data base

Several approaches are possible, especially for the drift function and the calibration function, but also as to the treatment of the stochastic properties as e.g. variance component estimation or covariance functions of the residuals.

Because all of the authors have developed and applied own methods for the adjustment of national gravity base networks, different procedures will be applied to the UEGN adjustment for intercomparison of results (c.f. BOEDECKER & RICHTER 1981 for Germany, Poitevin for Belgium and MARSON & MORELLI 1978 for Italy; latter program developed by Earth Physics Branch for adjustment of IGSN71). In the sequel the approach of Strang van Hees is presented with the specific features of application of collocation and data snooping (for gross errors) to the observation data.

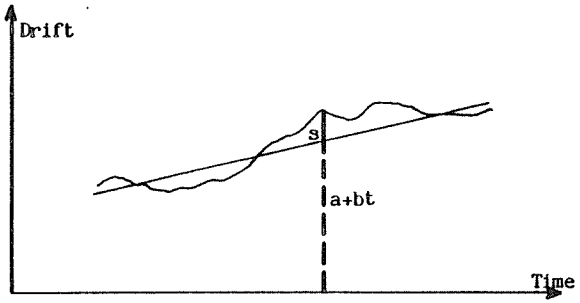
4.1 Modelling the Drift

The gravimeter drift has a linear component in time, periodical terms of different length, irregular noise and sudden jumps. Most people try to model the drift by a mathematical function, containing different components with unknown coefficients. The problem with this approach is that the drift does not satisfy a mathematical function, so it is difficult to decide what function is realistic. More unknown parameters describing the function decreases the redundancy, less parameters produce a probably unrealistic function.

The approach given below is based on collocation theory. Instead of a functional model, the drift is described as a random signal, which satisfies a chosen covariance model. Only the linear part of the drift is modelled deterministically because it has a physical background. Drift at time t :

$$d_i = a + bt_i + s_i$$

a and b are unknown parameters. Each measurement series (usually one day) has a different parameter a . Parameter b is taken the same for a long period of measurements, e. g. several months. s_i is the random signal on time t_i , and is also unknown. However, the signal satisfies the covariance matric C_{ij} , which we will determine



The observations equations become:

$$l_i + v_i = g_p + a + bt_i + s_i \qquad (1)$$

l_i	= observation on point P
v_i	= correction
s_i	= signal
g_p, a, b	= unknown parameters
D	= Error covariance matrix of the observations

Collocation theory says that the covariance matrices C and D should be added in the adjustment, so a covariance matrix (C+D) enters into the adjustment. As the drift is usually long periodic, the signal covariance function is rather broad, which means strong correlation, even if the time between the observations is not short. High correlation also results in a full covariance matrix.

Much better conditions are obtained if we transform the observations to gravity differences between successive observed gravity points.

Subtracting successive observation equations gives:

$$(l_i - l_j) + (v_i - v_j) = g_p - g_Q + b(t_i - t_j) + (s_i - s_j)$$

or

$$l_{ij} + v_{ij} = g_p - g_Q + bt_{ij} + s_{ij}$$

The first advantage is that the parameter a (orientation parameter) drops out. As each series of observations (usually one day) has its own parameter a , it means that many parameters are eliminated in this way. Gravity differences are only computed between observations of the same series, and therefore the behaviour of the drift between the series (during the night and weekends) is eliminated. Also a jump during a day can easily be eliminated by starting in new series.

l_{ij} are the new observations. The variance matrix is obtained by the law of variance propagation

$$D(l_{ij}, l_{ij}) = D(l_i, l_i) + d(l_j, l_j) - 2D(l_i, l_j)$$

Suppose: $D(l_i, l_i) = D(l_j, l_j) = D_o$ for each i, j

and: $D(l_i, l_j) = 0$ for $i \neq j$

Then: $$D(l_{ij}, l_{ij}) = 2\, D_o \qquad (3a)$$

For the covariances follow in the same way:

$$D(l_{ij}, l_{jk}) = -\, D_o \qquad (3b)$$

$$D(l_{ij}, l_{kl}) = 0 \qquad (3c)$$

D_o is the variance of the gravimeter recording.
The signal covariance matrix should be handled accordingly:

$$C(s_{ij}, s_{ij}) = C(s_i, s_i) + C(s_j, s_j) - 2C(s_i, s_j)$$

$$C(s_{ij}, s_{jk}) = C(s_i, s_j) - C(s_i, s_k) - C(s_j, s_j) + C(s_j, s_k)$$

$$C(s_{ij}, s_{kl}) = C(s_i, s_k) - C(s_i, s_l) - C(s_j, s_k) + C(s_j, s_l)$$

From these formulas follows that, if the covariance function C decreases slowly with time, $C(s_i, s_j)$ is only slightly smaller than $C(s_i, s_i)$, and consequently $C(s_{ij}, s_{ij})$ becomes small! The cross covariances $C(s_{ij}, s_{jk})$ and $C(s_{ij}, s_{kl})$ become even smaller and can be neglected in practice. So the signal covariance matrix C for the gravity differences becomes a diagonal matrix. All the large correlations are eliminated by taking gravity differences!

The diagonal elements of C: $C(s_{ij}, s_{ij})$ are dependent on the time interval between the measurements i and j . If the time interval becomes bigger, the variance of the drift increases. A reasonable assumption is to set C proportional to Δt:

$$C(s_{ij}, s_{ij}) = C_o \cdot \Delta t. \qquad (4)$$

Collocation theory says that in the adjustment the variance matrices C and D should be added (MORITZ, 1980; STRANG VAN HEES, 1981).

The diagonal elements of (C+D) become (3a) + (4):

diag.elem.: $C_o \Delta t + 2 D_o$ (5a)

Successive gravity differences share one common gravimeter reading, so the covariance is (3b):

1^e side diag. elem.: $- D_o$ (5b)

The other elements of (C+D) are zero. So the matrix (C+D) is almost diagonal. Only the first side diagonal has non zero elements. D_o is the variance of the gravimeter reading, e.g. $D_o = (5 \text{ Gal})^2$. C_o is the variance of the drift per hour (Δt is in hours) e.g. $C_o = (10 \text{ Gal})^2$.

The correlation coefficient r between successive gravity differences is:

$$r = \frac{- D_o}{C_o \Delta t + 2 D_o} \qquad (6)$$

e.g. for $\Delta t = 1$ hour, $D_o = 5^2$. $C_o = 10^2$,

$$r = \frac{- 25}{100 + 50} = -0.17.$$

This small correlation and the fact that all other elements of (C+D) are zero indicates that for large networks with high redundancy it is allowed to neglect the correlation.

The magnitude of C_o and D_o can be estimated from the adjustment of the network. Network adustment gives the variance of the unit weight, which holds for a gravity difference with $\Delta t = 1$ hour. This gives $C_o + 2 D_o$. Repeated readings of the gravimeter give the reading precision D_o. So C_o can be solved. Besides, it is not necessary for the adjustment to know the absolute values of C_o and D_o. Only the proportion $C_o : D_o$ enters in the weight matrix.

Another advantage of the variance model (5a), (5b) is that a bad observation at one point influences only the gravity value of that point and not of all other points. This can be seen as follows: Observations l_i, l_j, l_k Suppose: l_j is bad, so l_{ij} and l_{jk} are also bad, however l_{ik} is not affected

$$l_{ik} = l_{ij} + l_{jk} = (l_i - l_j) + (l_j - l_k) = (l_i - l_k)$$

Variance propagation gives:

$$C(l_{ik}, l_{ik}) = C(l_{ij}, l_{ij}) + C(l_{jk}, l_{jk}) + 2C(l_{ij}, l_{jk})$$

$$= (C_o \Delta t_{ij} + 2D_o) + (C_o \Delta t_{jk} + 2D_o) - 2D_o$$

$$= (C_o \Delta t_{ij} + \Delta t_{jk}) + 2D_o = C_o \Delta t_{ik} + 2D_o$$

This is exactly the covariance (5a) if l_j would be eliminated, so the adjustment gives the same result for Δg_{ik}. with or without observation l_j.

4.2 The Calibration Factors of the Instruments

The observed gravity differences that enter in the observation equations are already multiplied by the calibration factor and corrected for tides. The effect of the non linearity in the calibration table is taken into account by a correction to the observations, as described in (STRANG VAN HEES, 1986). If more than one gravimeter is used and if given gravity basepoints are included in the network, it is possible to check and perhaps to correct the calibration factors of the instruments. For each instrument one additional parameter is introduced to correct the calibration factor: $f = f_o (1 + \Delta f)$. Δf is solved for in the adjustment. On the other hand f is also introduced as a pseudo-observation $\Delta f_o = 0$. with a certain standard deviation. With this standard deviation we are able to control the calibration factor. If the standard deviation is taken small, the adjustment gives the calibration factor a small correction Δf, and the scale of the network is strongly determined by the calibration factor of this instrument. If the standard deviation of Δf is large, the calibration factor is free, and the scale of the network will be determined by the other instruments or by the absolute base points. So the program is very flexible to fix or free the calibration factor of the instruments.

4.3 Gravity Base Points

The given gravity base points are introduced as observations in the observation equations with a standard deviation. The magnitude of the standard deviations determines how close the network will be fitted to these points. It also effects the scale of the network and the corrections to the calibration factors of the instruments. If the standard deviations are small, the network will be deformed to fit to the basepoints. If the standard deviations are large the network will not be deformed, but the basepoints get corrections. It is therefore important to give realistic standard deviations to the base points and to the calibration factors.

The observation equations become finally:

$$l_{ij} + (v_{ij} - s_{ij}) = g_p - g_Q + b_k t_{ij} - l_{ij}\,\Delta f_k$$

$$\vdots$$

$$\Delta f_o + v_f = \Delta f_k$$

$$\vdots$$

$$\tilde{g}_R + v_g = g_R$$

l_{ij} = observed gravtiy difference
v_{ij} = correction to observation
s_{ij} = drift correction
g_p, g_Q = gravity values, unknown parameters
b_k = linear drift, one parameter for each instrument (k) and each period
t_{ij} = time interval
Δf_k = correction calibration factor
Δf_o = zero, observed Δf_k
v_f = correction
$\tilde{g}_R$ = given base gravity value.
v_g = correction

The adjustment gives estimates of the gravity values, the linear drift components of the instruments and the improved calibration factors. After the adjustment, the long term drift of the instruments is computed over the whole measurement period.:

$$\text{drift} = \text{reading} * f_o(1+\Delta f) + \text{tide} - g_p + C$$

reading = reading of the instrument on poin P
g_P = computed gravity after adjustment
c = constant such that the drift at the first observed point is zero

4.4 Quality Control and Testing

Gravity networks contain usually many observations (thousands). In practice it turns out that large data sets always contain gross errors. These gross errors, if not detected, will cause errors in the adjusted gravity values, which are much bigger than the standard deviations. It is therefore very important to have an automatic procedure to screen the data set and to detect all the gross errors. Gross errors can be caused by the following reasons:

1. Instrumental errors like jumps in the drift,
2. Reading and writing errors of the observer,
3. Processing errors like typing errors in the input data set (e.g. errors in observations, point numbers, coordinates).

The testing method used in the gravity adjustment program is based on the theory developed by BAARDA (1968) and is described by STRANG VAN HEES (1985).

The principle is, that functions of the corrections of the observations, computed from the adjustment, are tested against the estimated standard deviations. These functions depend on the covariance matrix of the observations. The functions are computed such that they have a maximum power of discrimination. For uncorrelated observations these functions reduce to the corrections itself. Roughly, an observation that gets a big correction might be in error. Each observation is checked individually (data snooping). After correcting the gross errors or eliminating the observation, the adjustment and testing is repeated. Usually the second time new errors are detected. This process is repeated until no significant errors are found.

The capability to find errors is very much dependent on the redundancy. Each observation should be checked in the network by at least two other observations. Fortunately, gravity networks contain usually many redundant observations, so the test is rather discriminative.

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Adjustment and quality control of gravity networks.

G.L. Strang van Hees
Delft University of Technology
The Netherlands.

Introduction.

The adjustment of a gravity network is in principle not very difficult, because the relations between the observations and the unknown gravity values are simple linear expressions.
However the following problems should be considered carefully:

1. drift of the instruments;
2. correlation between the observations;
3. calibration factors of the instruments;
4. connection to given absolute gravity points;
5. testing for gross-errors in the observations.

Several approaches are possible, especially to model the drift of the instrument. In the next sections the approach of G. Strang van Hees (Delft, The Netherlands) is described.

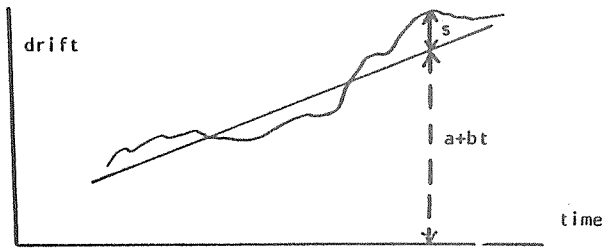
Modelling the drift.

The gravimeter drift has a linear component in time, periodical terms of different length, irregular noise and sudden jumps. Most people try to model the drift by a mathematical function, containing different components with unknown coefficients. The problem with this approach is that the drift does not satisfy a mathematical function, so it is difficult to decide what function is realistic. More unknown parameters describing the function decreases the redundancy, less parameters produce a probably unrealistic function.

The approach given below is based on collocation theory. Instead of a functional model, the drift is described as a random signal, which satisfies a chosen covariance model. Only the linear part of the drift is modelled deterministical because it has a physical background.

Drift at time t_i: $d_i = a + bt_i + s_i$.

a and b are unknown parameters. Each measurement series (usually one day) has a different parameter a. Parameter b is taken the same for a long period of measurements, e.g. several months. s_i is the random signal on time t_i, and is also unknown. However the signal satisfies the covariance matrix C_{ij}, which we will determine.



The observation equations become:

$$l_i + v_i = g_p + a + bt_i + s_i \qquad (1)$$

l_i = observation on point P.
v_i = correction.
s_i = signal.
g_p, a, b are unknown parameters.
D = Error covariance matrix of the observations.

Collocation theory says that the covariance matrices C and D should be added in the adjustment, so a covariance matrix (C+D) enters into the adjustment. As the drift is usually long periodic the signal covariance function is rather broad, which means strong correlation, even if the

time between the observations is not short. High correlation also results in a full covariance matrix.

Much better conditions are obtained if we transform the observations to gravity differences between successive observed gravity points. Subtracting successive observation equations gives:

$$(l_i - l_j) + (v_i - v_j) = g_P - g_Q + b(t_i - t_j) + (s_i - s_j)$$

or

$$l_{ij} + v_{ij} = g_P - g_Q + bt_{ij} + s_{ij} \qquad (2)$$

The first advantage is that the parameter a (orientation parameter) drops out. As each series of observations (usually one day) has its own parameter a, it means that many parameters are eliminated in this way. Gravity differences are only computed between observations of the same series, and therefore the behaviour of the drift between the series (during the night and weekends) is eliminated. Also a jump during the day can easily be eliminated by starting a new series.

l_{ij} are the new observations. The variance matrix is obtained by the law of variance propagation.

$$D(l_{ij}, l_{ij}) = D(l_i, l_i) + D(l_j, l_j) - 2D(l_i, l_j)$$

Suppose: $D(l_i, l_i) = D(l_j, l_j) = D_0$ for each i, j
and : $D(l_i, l_j) = 0$ for $i \neq j$
Then : $D(l_{ij}, l_{ij} = 2D_0$ (3a)

For the covariances follows in the same way:

$$D(l_{ij}, l_{jk}) = -D_0 \qquad (3b)$$
$$D(l_{ij}, l_{kl}) = 0 \qquad (3c)$$

D_0 is the variance of the gravimeter reading.

The signal covariance matrix should be handled accordingly.

$$C(s_{ij}, s_{ij}) = C(s_i, s_i) + C(s_j, s_j) - 2C(s_i, s_j)$$

$$C(s_{ij}, s_{jk}) = C(s_i, s_j) - C(s_i, s_k) - C(s_j, s_j) + C(s_j, s_k)$$

$$C(s_{ij}, s_{kl}) = C(s_i, s_k) - C(s_i, s_l) - C(s_j, s_k) + C(s_j, s_l)$$

From these formulas follow that, if the covariance function C decreases slowly with time, $C(s_i, s_j)$ is only slightly smaller than $C(s_i, s_i)$, and consequently $C(s_{ij}, s_{ij})$ becomes small!
The cross covariances $C(s_{ij}, s_{jk})$ and $C(s_{ij}, s_{kl})$ become even still smaller and can be neglected in practice.
So the signal covariance matrix C for the gravity differences becomes a diagonal matrix. All the large correlations are eliminated by taking gravity differences!

The diagonal elements of C: $C(s_{ij}, s_{ij})$ are dependent on the time interval between the measurements i and j. If the time interval becomes bigger the variance of the drift increases. A reasonable assumption is to set C proportional to Δt:

$$C(s_{ij}, s_{ij}) = C_0 \cdot \Delta t \qquad (4)$$

Collocation theory says that in the adjustment the variance matrices C and D should be added (Moritz, 1980; Strang van Hees, 1981).
The diagonal elements of (C+D) become (3a) + (4):

$$\boxed{\text{diag.elem.: } C_0\ \Delta t + 2D_0} \qquad (5a)$$

Successive gravity differences share one common gravimeter reading, so the covariance is (3b):

$$\boxed{\text{1e side diag.elem.: } -D_0} \qquad (5b)$$

The other elements of (C+D) are zero. So the matrix (C+D) is almost diagonal. Only the first side diagonal has non zero elements.

D_0 is the variance of the gravimeter reading, e.g. $D_0 = (5\ \mu Gal)$.
C_0 is the variance of the drift per hour (Δt is in hours), e.g. $C_0 = (10\ \mu Gal)$.
The correlation coefficient, r, between successive gravity differences is:

$$r = \frac{-D_0}{C_0\ \Delta t + 2D_0} \qquad (6)$$

e.g. for $\Delta t = 1$ hour, $D_0 = 5^2$, $C_0 = 10^2$:

$$r = \frac{-25}{100 + 50} = -0.17$$

This small correlation and the fact that all other elements of (C+D) are zero indicates that for large networks with many redundancy, it is allowed to neglect the correlation.

The magnitude of C_0 and D_0 can be estimated from the adjustment of the network.
Network adjustment gives the variance of the unit weight, which holds for a gravity difference with $\Delta t = 1$ hour. This gives: $C_0 + 2D_0$.

Repeated reading of the gravimeter give the reading precision: D_0. So C_0 can be solved. Besides, it is not necessary for the adjustment to know the absolute values of C_0 and D_0. Only the proportion $C_0 : D_0$ enters in the weight matrix.

An other advantage of the variance model (5a), (5b) is that a bad observation at one point influences only the gravity value of that point and not at all other points. This can be seen as follows: Observations l_i, l_j, l_k. Suppose: l_j is bad, so l_{ij} and l_{jk} are also bad, however l_{ik} is not affected

$$l_{ik} = l_{ij} + l_{jk} = (L_i - l_j) + (l_j - l_k) = (l_i - l_k)$$

Variance propagation gives:

$$\begin{aligned} C(l_{ik}, l_{ik}) &= C(l_{ij}, l_{ij}) + C(l_{jk}, l_{jk}) + 2C(l_{ij}, l_{jk}) \\ &= (C_0\Delta t_{ij} + 2D\ ) + (C_0\Delta t_{jk}) + 2D_0) - 2D_0 \\ &= C_0(\Delta t_{ij} + \Delta t_{jk}) + 2D_0 = C_0\Delta t_{ik} + 2D_0. \end{aligned}$$

The calibration factors of the instruments.

The observed gravity differences that enter in the observation equations are already multiplied by the calibration factor and corrected for tides. The effect of the non-linearity in the calibration table is taken into account by a correction to the observations, as described in (Strang van Hees, 1986). If more than one gravimeter is used and if given gravity basepoints are included in the network, it is possible to check and eventually correct the calibration factors of the instruments. For each instrument one additional parameter is introduced, to correct the calibration factor: $f = f_0(1+\Delta f)$. Δf is solved for in the adjustment. On the other hand Δf is also introduced as a pseudo-observation $\Delta f_0 = 0$ with a certain standard deviation.
With this standard deviation we are able to control the calibration factor. If the standard deviation is taken small, the adjustment gives the calibration factor a small correction Δf, and the scale of the network is strongly determined by the calibration factor of this instrument. If the standard deviation of Δf is large, the calibration factor is free, and the scale of the network will be determined by the other instruments or by the absolute base points. So the program is very flexible to fix or free the calibration factor of the instruments.

Gravity base points.

The given gravity base points are introduced as observations in the observation equations, with a standard deviation. The magnitude of the standard deviation determines how close the network will be fitted to these points. It also effects the scale of the network and the corrections to the calibration factors of the instruments. If the standard deviations are small the network will be deformed to fit to the base points. If the standard deviations are large the network will not be deformed, but the base points get corrections.
It is therefore important to give realistic standard deviations to the base points and to the calibration factors.
The observation equations become finally:

$$
\begin{array}{lllll}
l_{ij} + (v_{ij} - s_{ij}) & = & g_P - g_Q + b_K t_{ij} & - & l_{ij}\Delta f_k \\
\vdots & & \vdots & & \vdots \\
\Delta f_0 + v_f & = & & & \Delta f_k \\
\vdots & & & & \vdots \\
\tilde{g}_R + v_g & = & = & & g_R \\
\vdots & & & & \vdots
\end{array}
$$

l_{ij} = observed gravity difference.
v_{ij} = correction to observation.
s_{ij} = drift correction.
g_P, g_Q = gravity values, unknown parameters.
b_K = linear drift, one parameter for each instrument (K) and each period.
t_{ij} = time interval.
Δf_k = correction calibration factor.
Δf_0 = zero, observed Δf_k.
v_f = correction.
$\tilde{g}_R$ = given base gravity value.
v_g = correction.

The adjustment gives estimates of the gravity values, the linear drift components of the instrument and the improved calibration factors.
After the adjustment, the long term drift of the instrument is computed over the whole measurement period:

$$\text{drift} = \text{reading} \times f_0(1+\Delta f) + \text{tide} - g_P + c$$

reading is the reading of the instrument on point P.
g_P is the computed gravity after adjustment.
c is a constant, such that the drift at the first observed point is zero.

Quality Control and Testing.

Gravity networks contain usually many observations (thousands). In practice it turns out that large datasets always contain gross-errors. These gross-errors, if not detected, will cause errors in the adjusted gravity values, which are much bigger than the standard deviations. It is therefore very important to have an automatic procedure to screen the dataset and to detect all the gross-errors.

Gross-errors can be caused by the following reasons:
1. Instrumental errors like jumps in the drift.
2. Reading and writing errors of the observer.
3. Processing errors, like typing errors in the input dataset (e.g. errors in observations, point numbers, coordinates).

The testing method used in the gravity adjustment program is based on the theory developed by Baarda (1968) and is described by (Strang van Hees, 1985).

The principle is that functions of the correction of the observations, computed from the adjustment, are tested against the estimated standard deviations. These functions depend on the covariance matrix of the observations. The functions are computed such that they have a maximum power of discrimination. For uncorrelated observations these functions reduce to the corrections itself.
Roughly, an observation that gets a big correction might be in error. Each observation is checked individually (data-snooping).
After correcting the gross-errors or eliminating the observation, the adjustment and testing is repeated. Usually the second time new errors are detected. This process is repeated until no significant errors are found

The capability to find errors is very much dependent on the redundancy. Each observation should be checked in the network by at least two other observations. Fortunately, gravity networks contain usually many redundant observations, so the test is rather discriminative.

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SINO - ITALIAN JOINT ABSOLUTE GRAVITY MEASUREMENTS IN CHINA

Xu Shan, Qiu Qixian, Jian Zhiheng (Research Institute of Surveying and Mapping, Beijing)

F. Alasia, G. Cerutti, S. Desogus, (Istituto di Metrologia "G. Colonnetti", Torino)

I. Marson, (University of Trieste)

SINO - ITALIAN JOINT ABSOLUTE GRAVITY MEASUREMENTS IN CHINA

August - November 1981

1. Introduction

With reference to Article 25 of cultural and scientific cooperation program for 1980 and 1981 between China and Italy, to the Minutes of talks on the subject of joint absolute gravity measurements between China and Italy, and to the Memorandum of talks on the implementation of these Minutes, absolute gravity measurements have been carried out in China from August 4 to November 11, 1981 through the joint work of Chinese and Italian technical staffs. The Chinese party selected and equipped the observation sites, provided facilities for instrument transportation, and accomodation. The Italian party provided the apparatus and observation techniques. Through the close cooperation of both parties and the active support of the concerned respective organizations, measurements and computation concerning 11 stations (with closing measurements in Beijing) were completed one month earlier than originally scheduled.

Modern precise absolute gravity measurements are of great significance in the following fields:

(1) in geodesy, to define the gravity datum, establish gravimetric standard nets and gravity calibration bases for field gravimeters;

(2) in geophysics, to study non-periodic secular gravity variations due to recent crustal movements, or relative movements of masses within the Earth;

(3) in metrology, to realize the standards of the measurement units of some physical quantities, such as force.

The results obtained from the joint absolute gravity measurements of both parties will greatly contribute to application and research work in these fields.

The experts that carried out the joint measurements are:

- Chinese party: Xu Shan, engineer at the Research Institute of Surveying and Mapping (RISM); Qiu Qixian, engineer at RISM ; Jian Zhiheng, technician at RISM.

- Italian party: G. Cerutti, physicist, researcher at the Istituto di Metrologia "G.Colonnetti" (IMGC), of the National Research Council of Italy, I. Marson, assistant professor at the University of Trieste; F. Alasia, higher-grade technician at IMGC, S. Desogus, higher grade-technician at IMGC.
Mr. Gao Jiyuan and Mr. Gao Lianbao of RISM took charge of logistics.

2. Description of the measurement method and of the apparatus

2.1 Measurement method

The method adopted consists in observing the symmetric free fall of a body in the gravitational field of the Earth. The main advantages of this method are a relative freedom from residual air resistance and a higher accuracy in time measurement.

When an object is projected vertically upwards, in the course of its rise and fall it crosses twice an upper station and a lower station. Let t be the time interval between two passages at the upper point; T be the time interval between two passages at the lower point; L the distance between the upper and lower stations. These three quantities can be measured by the apparatus, and the gravity acceleration, g, is given by

$$g = 8L/(T^2-t^2) \quad (1)$$

Assuming that the vertical gravity gradient along the trajectory of the object is constant, the value of g obtained from eq. (1) corresponds to a point situated at a distance

$$z \cong L/6 \quad (2)$$

below the apex of the trajectory.

2.2 Apparatus

The apparatus in question is the absolute transportable gravimeter developed by IMGC in cooperation with the Bureau International des Poids et Mesures (BIPM), Sèvres (France). The apparatus has an uncertainty of the order of 10 μGal. Thirty absolute stations have been established in Europe in the past five years by using this apparatus to improve the International Gravity Standardization Net (IGSN 71) and study non-periodic secular gravity variations associated with the Alpine uplift. The same apparatus had been used for establishing another eleven stations in the United States in Autumn 1977 and Summer 1980.

2.2.1 Description of the apparatus

The essential parts of the apparatus are a Michelson interferometer and a long-period (20 s) seismometer both located inside an airtight low-pressure chamber (Fig. 1). A cube corner (cc2), forming one mirror of the interferometer and a fixed reference point, is placed on the inertial mass of the seismometer. The laser beam emitted from a He-Ne laser is used as a light source. A second cube corner (cc1) is projected vertically in a vacuum cylinder and forms the movable mirror of the interferometer. While cc1 moves vertically, two photodetectors (ph a, ph b) detect the interference fringes and control electronic counters, which record flight times and trajectory length. A damping oil system is used to isolate the low-pressure chamber from ground vibrations.

cc1 travels in a vacuum of a few tenths of pascal, inside a glass cylinder approx. 1 m long, which contains a catapult for cube corner launching. The effective height reached by the cube corner in its upward motion is 50 cm.

2.2 Measurement technique

No material standard of the unit of length is used in this apparatus. Measurements are started at a pre-determined instant, a few milliseconds after the cube corner is released. This instant corresponds to the bottom station where the measurement begins. To determined L, T, and t in eq. (1), three counters are used, i.e., a two-way counter to count the number of fringes, and two time counters. The two-way counter is controlled by the signals of two photomultipliers. All the counters start counting at the exact instant when the movable cube corner passes through the lower station (fringe zero). The first time counter records the total flight time T. The second time counter resets to zero each time an integer number of fringes is reached in the course of the upward motion of the body, and stops counting when the first fringe appears in the downward motion of the cube corner.

This fringe is detected by the phase reversal of the interferometer signals (Fig. 2). t is the time interval recorded by the second time counter. The point at which the last fringe appears in the upward motion is the top station of the trajectory. When the body reaches this point, the total number, N, of fringes recorded by the two-way counter corresponds to distance L between the top and the bottom stations. The wavelength of the laser beam being λ , then

$$L = N \cdot \lambda/2 \quad (3)$$

When the movable cube corner falls downward, the two-way counter will count the number of fringes in decreasing order and reaches zero again; meanwhile the first time counter stops counting and T is obtained.

However, the logic system for fringe counting introduces a difference equal to half a fringe in decounting operation (i.e., $\lambda/4$): this means that the bottom station reached by the body in its downward motion is actually higher by $\lambda/4$ than the starting station in the upward motion. As is shown in Fig. 2, t is the actual time interval between two successive passages at the top station; T is the time interval, which, in addition to t, includes the time interval elapsed when the body passes through N fringes in the upward motion and the $(N-\frac{1}{2})$ fringes in the downward motion. Computation indicates that in practice $(N-1/4)$ instead of N ought to be adopted in eq. (3).
According to eqs. (1) and (3), the following practical computing formula is obtained

$$g = \frac{4\lambda\ (N-0.25)}{T^2 - t^2} \qquad (4)$$

2.3 Analysis of errors and corrections

A brief description is given of the errors intrinsically dependent on the apparatus and of those due to surrounding conditions.

(a) Time measurement

A rubidium time standard with a stability of approximately 10^{-10} is used. Time interval T is measured by means of a Hewlett-Packard counter with a resolution of ± 1 ns. Therefore, the effect of the error in measuring T on the g value must be reckoned with. The start and stop pulses from the two-way counter are subject to the effect of the delay time of the circuit used. A systematic error of the order of 5 ns ± 0.5 ns is introduced in the determination of g. The correction for delay time (DTC) of the circuit applied to g is computed by the formula

$$DTC = -\frac{2g}{T}\,dT\ , \qquad (5)$$

where dT is the error in the measurement of T and is of 5 ns with the apparatus used. The counter for t measurements has a resolution of $\pm$ 100 ns. Although the error in measuring t is somewhat large, its effect on t is negligible, since $t \ll T$.

(b) Length measurement

The accuracy of length measurements is directly connected with the wavelength of the laser beam and its stability. The maximum relative error in length measurements amounts to 5×10^{-9}, corresponding to an error of $\pm$ 5μGal in g. Therefore, the wavelength of the laser beam is measured before and after the measurement campaigns. If any appreciable variation occurred appropriate corrections must be applied to the computed results.

Microseisms, by altering the position of the fixed mirror, affect length measures; consequently, the body is launched only when microseisms, as revealed by a seismograph, are at the lowest level. This effect was reduced by about 20 times by placing the fixed mirror (fixed cube corner on the inertial mass of the seismometer.

In order to make the movable cube corner free from the influence of the mechanical vibrations of the catapult at the beginning of launching, measurements are started at a pre-determined instant a few milliseconds after launching.

(c) Verticality of the laser beam

The verticality of the laser beam is adjusted by means of a mercury pool and an autocollimator. Any inclination of the laser beam will give rise to an error in length measures. To make the effect on g less than 5μGal, the inclination should be kept below 10^{-4} rad. No correction for this effect was applied to the measurement of g, but in the estimation of the overall uncertainty a value of $\pm$ 5μGal is introduced to take care of this error.

(d) Verticality of the trajectory

In order to have adequate visibility (>80%), the trajectory should not deviate from verticality by more than 10^{-4} rad over the whole distance travelled by the body.

(e) Rotation of the movable cube corner

This rotation should be kept less than 0.03 rad/s. The movable cube corner must be adjusted in such a way as to make the optical centre coincide with the centre of mass within 0.1 mm.

The verticality of the trajectory and the rotation of the movable cube corner are monitored with a storage oscilloscope. When the curves appearing on the oscilloscope are not sufficiently smooth and symmetrical, or when they change

too abruptly, the corresponding measurements must be discarded.

(f) Other affecting factors

The presence of a magnetic field induces electrical current in the metallic parts of the cube corner during its motion. To prevent this effect all metallic parts are made of amagnetic material.

The rubber cord of the catapult is likely to have a static charge, and the movable cube corner as well can be charged electrically, owing to friction with residual air. The rubber cord is therefore protected by a grounded metallic tube. Moreover, if the trajectory is vertical, the tube will be perfectly symmetrical with respect to the cube corner, so that the capacitance between them keeps constant during the movement of the cube corner and its effect is negligible.

No correction for buoyancy caused by residual air is applied to the wavelength of the laser beam.

The following corrections should be applied in computation :

(a) Correction for Earth tides

This correction is made necessary because of the changing positions of the Sun and the Moon relative to the Earth, and because of the consequent change in the Sun and Moon attraction. The computation of this correction is made by means of a computer program provided by IMGC.

(b) Reduction to reference level

The measured value of g corresponds to a point situated at a distance Z below the apex of the trajectory. The position of this point is nearly 0.8 m above ground level or the top surface of the pillar. In order to obtain the gravity value at this level, a correction for vertical gradient Δg_{grad} must be applied to the mean of the measured values of gravity. This correction is expressed by the formula

$$\Delta g_{grad} = \frac{\partial g}{\partial H} H ,$$

where $\partial g/\partial H$ is the vertical gradient at that point, and is determined by a relative high-precision gravimeter; H is the distance of the point where g is determined from the ground surface, or from the top surface of the pillar. As can be seen from Fig. 3, H is obtained by determination of distance K of the apex of the trajectory from the ground surface or the pillar surface. All measurements are referred to the optical centre of the cube corner; the distance between the top surface of the cube corner and its optical centre is 25 mm. Therefore, Z being equal to L/6 + 25 mm,

$$H = K - Z.$$

3. Measurement results

From August 4 to November 8, 1981, absolute gravity measurements were carried out with an absolute gravimeter made in Italy at 11 stations, the situations of which had been selected carefully (Fig. 4). The final closing measurements were made at the Beijing station. The observation conditions at the individual stations are given hereafter.

Beijing : The observation station is located in the room for rod calibration, Beijing Division of Surveying and Mapping. The gravimeter was placed on a pillar. The room was air-conditioned. At the time of the first measurement, the temperature was at 24°C ± 1 °C. During the close determination the temperature in the room was kept at 23 °C ± 1 °C by means of an electric heater. The microseismic noise level was high.

Qingdao : The observation station is located on the first floor of the Guanxianshan Astronomical Observatory, Oceanographic Institute of the Academy of Sciences of China. The gravimeter was installed on a pillar. The room was air conditioned, the temperature being 24 °C ± 1 °C. The microseismic noise level was low; the power supply showed frequent variations.

Zhengzhou: The observation station is located in the Room of Seismic Observation (in the basement of Houzhai Seismic Station, 20 km distant from Zhengzhou City), Bureau of Seism of the Henan Province. The gravimeter was placed on a pillar. The average temperature remained at 22 °C ± 1 °C. The microseismic noise level on the ground surface was very low.

Xian : The observation station is located in the gravity Room of the Observatory for the Geodetic Origin of China (50 km from Xian). The gravimeter was placed on a pillar. The room was not air-conditioned, but the room temperature kept, on the average, at 23 °C ± 1 °C. The microseismic noise level on the ground surface varied with the surrounding seismic noise due to industrial factories, and changed from low to high.

Shanghai: The observation station is located in a room of the Sheshan Working Station, Astronomical Observatory of

Shanghai of the Academy o. Sciences of China. The gravimeter was placed on a pillar. The room was air-conditioned. The temperature in the room kept at 23 °C ± 1 °C.
Apart from a short period of time, the microseismic noise level on the ground surface was low during the measurement time.

Wuhan : The observation station is located in the room for Gravimeter Calibration, the Wuhan College of Geodesy, Photogrammetry, and Cartography. The gravimeter was placed 0.91 m above the ground on a pillar. The room was air-conditioned and the temperature was 23 °C ± 1 °C; the microseismic noise level on the top surface of the pillar was high.

Nanning: The observation station is located in the Glass Cleaning Room of the Printing House of the Bureau of Surveying and Mapping, Guangxi Zhuangzu Autonomous Region. The gravimeter was placed on a pillar. The room was air-conditioned, with a temperature of 23 °C ± 1 °C. The microseismic noise level on the ground surface was high.

Changsha: The observation station is located in Room n° 5 of the dormitory Building of the second Survey Party, Bureau of Surveying and Mapping of the Hunan Province. The gravimeter was placed on a pillar. The room was not air-conditioned, and the temperature kept at 20 °C ± 1 °C. The microseismic noise level on the ground surface was low.

Guangzhou: The observation station is located in the Office of the Second Party of Surveying and Mapping of the Guangdong Province. The gravimeter was placed on a pillar. The room was air-conditioned, the temperature being 22 °C ± 1 °C. The microseismic noise level on the ground surface was high.

Fuzhou : The observation station is located in the Office of the Field Base of the Bureau of Surveying and Mapping of the Fujian Province. The gravimeter was placed on a pillar. The room was air-conditioned, the temperature being 22 °C ± 1 °C. The microseismic noise level on the ground surface was high.

Kunming : The observation station is located on the ground surface in the Observation Cave for Kunming Seismic Station, Bureau of Seism of the Yunnal Province. The temperature in the cave was lower than that of the other stations and was constant at 18 °C; humidity was very high, the relative humidity being about 85%. The microseismic noise level on the ground surface was very low.

About 100 measurements were made at each station, though at some points they were more numerous. The Earth-tide correction (T.C.) was added to the computed results of each measurement. The mean gravity value, standard deviation (mean error for single observation) and standard error (mean error for the mean values) for each point were then calculated, and the gradient reduction and the correction for circuit time delay were added to the gravity mean value. A synopsis of measurement results is given in Table I. Histograms are supplied in Figs. from 5 to 15 .

The estimation of the overall uncertainty includes the following terms :

1. Standard error
2. Uncertainty in T (total time) determination corresponding to 5 μGal
3. Uncertainty in circuit time delay correction corresponding to 3 μGal
4. Uncertainty in laser wavelength determination, corresponding to 5 μGal
5. Uncertainty in trajectory verticality determination, corresponding to 5 μGal

The overall uncertainty in the value of g is calculated as the square root of the sum of the squares of the individual errors.

The uncertainty in the vertical gradient value is negligible, and therefore is not included.

Back to Italy at the end of the Chinese campaign, the laser wavelength was measured at IMGC as had been done before leaving Italy, by comparison against a He-Ne iodine-absorption cell laser. The initial and final values are the following

λ (14 july 1981) = $0{,}632991417_E$ μm

λ (15 January 1982) = $0{,}632991420_G$ μm

The difference is $\Delta\lambda = 22 \cdot 10^{-10}$ μm. Consequently, by assuming a linear drift in time, the correction to be applied to the value of the laser wavelength is $0.1189 \cdot 10^{-10}$ μm/day.

The corresponding correction to g is $\Delta g = 0.0184$ μGal/day, so that the g values given in Table I must be corrected as indicated in Table II.

TABLE 1. SYNOPSIS OF RESULTS OF MEASUREMENTS

SITE	DATE	NUMB.OF MEAS.	GRAVITY MEAN VAL. (mGal)	STAND. DEVIA. (mGal)	STAND. ERROR (mGal)	g REDUCED (mGal)	TOTAL ERROR (mGal)
BEIJING	AUG. 4-7 1981	164	980119.456	0.049	0.004	980119.646	0.010
QINGDAO	AUG.17-19 1981	98	979802.341	0.041	0.004	979802.583	0.010
SHANGHAI	AUG.27-30 1981	117	979395.702	0.050	0.005	979395.978	0.010
ZHENGZHOU	SEP. 7-10 1981	131	979629.890	0.050	0.005	979630.050	0.010
XI AN	SEP.13-14 1981	100	979466.704	0.047	0.005	979466.924	0.010
WUHAN	SEP.19-20 1981	99	979348.586	0.056	0.006	979348.800	0.011
NANNING	SEP.28-29 1981	123	978750.036	0.050	0.004	978750.237	0.010
CHANGSHA	OCT. 3-5 1981	104	979133.343	0.038	0.004	979133.547	0.010
GUANGZHOU	OCT.12-13 1981	103	978815.511	0.040	0.004	978815.717	0.010
FUZHOU	OCT.19-21 1981	121	979000.790	0.063	0.006	979000.985	0.011
KUNMING	OCT.31-32 1981	79	978347.826	0.064	0.007	978347.980	0.012
BEIJING	NOV. 6-6 1981	46	980119.436	0.037	0.006	980119.646	0.011

TABLE II

Site	Drift days	Correction to g(μGal)
Beijing	20	+ 0,4
Qingdao	32	+ 0,6
Shanghai	42	+ 0,8
Zhengzhou	53	+ 1
XiAn	58	+ 1
Wuchan	65	+ 1,2
Nanning	74	+ 1,4
Changsha	79	+ 1,5
Guangzhou	88	+ 1,6
Fuzhou	95	+ 1,7
Kunming	106	+ 2
Beijing	112	+ 2,1

A number of measurements were made with a relative La Coste Romberg gravimeter and two Chinese relative Worden gravimeters.
The results of the measurements carried out at all the stations were recalculated by the Research Institute of Surveying and Mapping of China. The computation work was carried out on a HP 2108 computer by Mr. Zhang Wei Jian.

Subsequently, in the period from 1983 to 1984, the vertical gradient of g was determined again in some stations, using La Coste - Romberg gravity meter.
New values have been obtained.
The difference between the previous values and new ones is shown in table III.

TABLE III

Name of the stations	Value of g obtained in 1981	Value of g obtained in 1984
Wuhan	979 348.800	979 348.796
Nanning	978 750.237	978 750.243
Fuzhou	979 000.985	979 000.997
Kunming	978 347.980	978 347.977

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The present report concerns the absolute gravity measurement campaign carried out in the Chinese territory in 1981. It was prepared jointly by the Chinese and Italian experts, mentioned in the Introduction, who were directly responsible in carrying out the measurement campaign, which took place within the framework of a cooperation program of the People's Republic of China and the Republic of Italy, under the provisions of an agreement between the Sinic Academy of Sciences (SAS) and the National Research Council of Italy (CNR), through the National Bureau of Surveying and Mapping of Beijing and the Istituto di Metrologia "G.Colonnetti", respectively.

A. Bray - Director
Istituto di Metrologia
"G.Colonnetti" - CNR

Bray

Wang Zengfan
Deputy Director
National Bureau of
Surveying and Mapping

王曾凡
1982年9月10日

July 1982

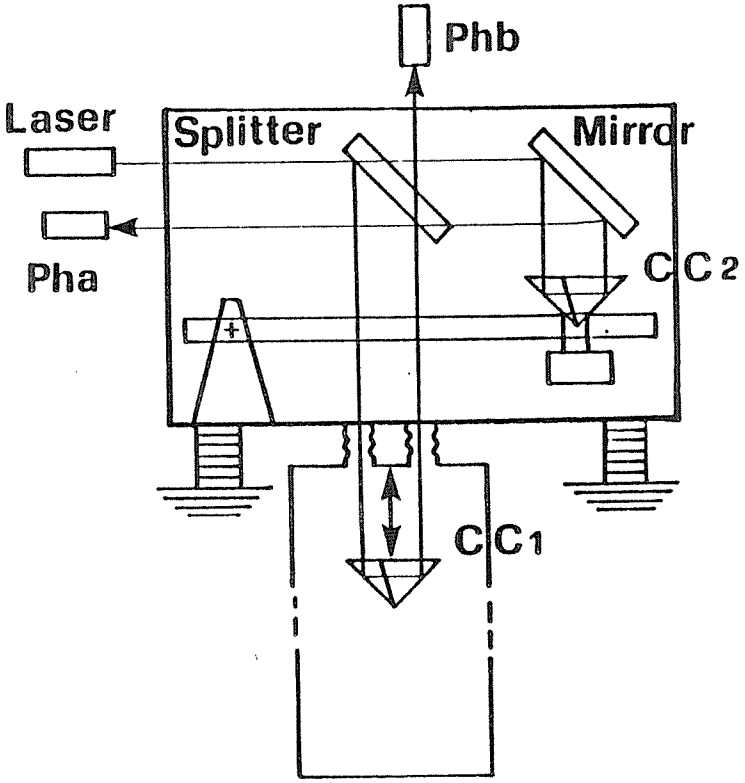

Fig. 1 Schematic drawing of IMGC gravimeter

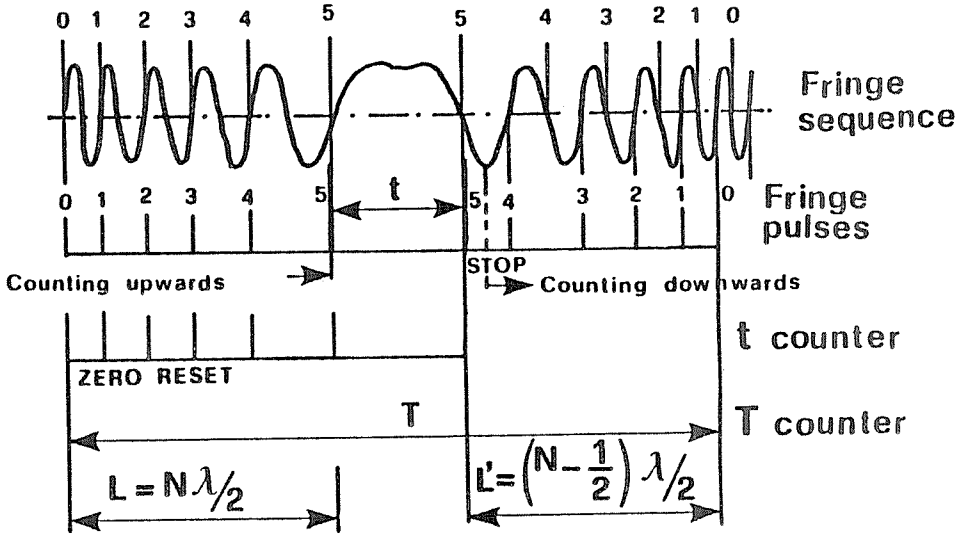

Fig. 2 Counting logic

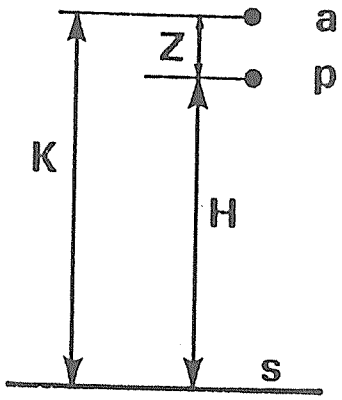

Fig. 3 Position of measurement point

a — apex of trajectory
p — point where g is determined
s — ground or pillar surface

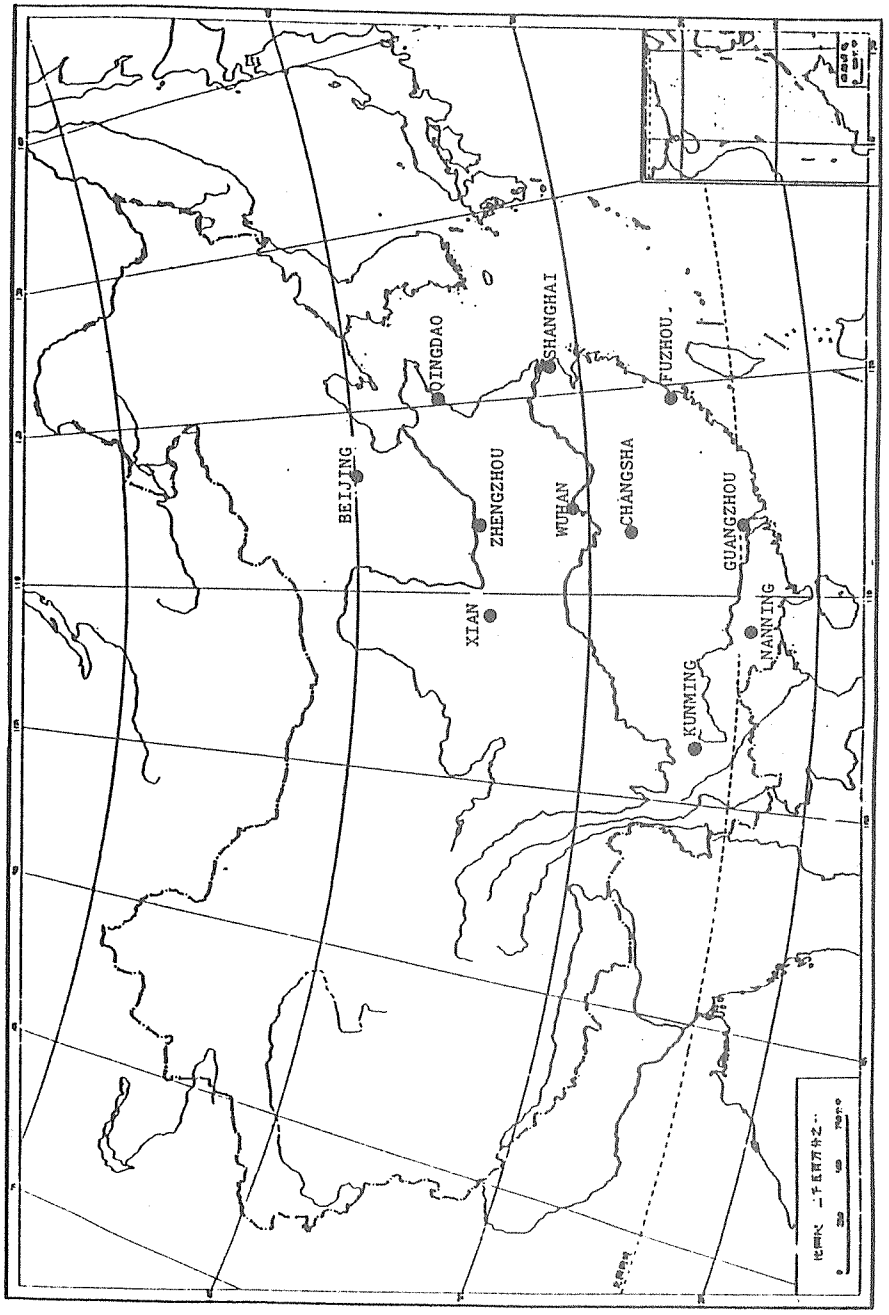

Fig. 4 Measurement Stations

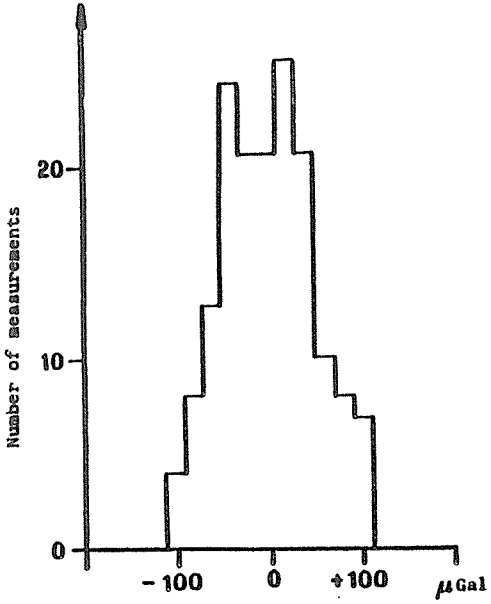

Fig. 5 - Histogram for the station of BEIJING

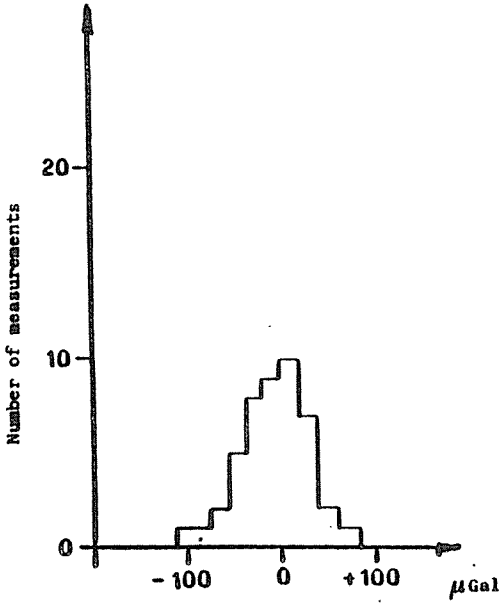

Fig. 5a - Histogram for the station of BEIJING (Closing measurements)

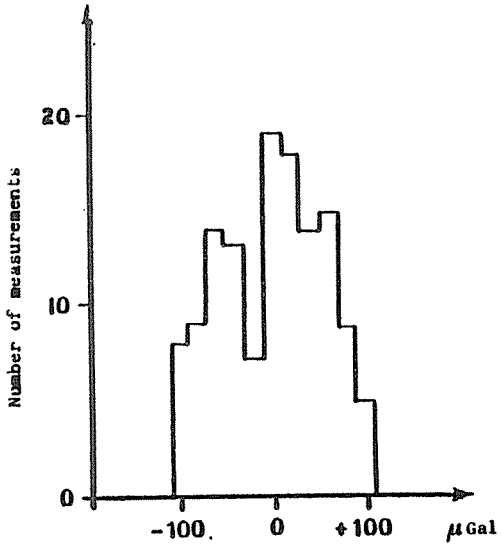

Fig. 8 - Histogram for the station of ZHENGZHOU

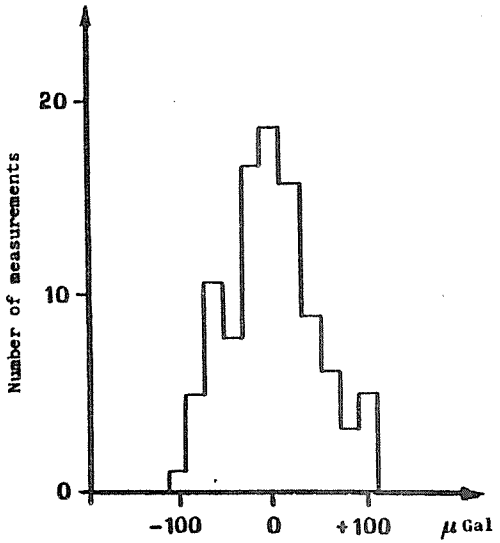

Fig. 9 - Histogram for the station of XI AN

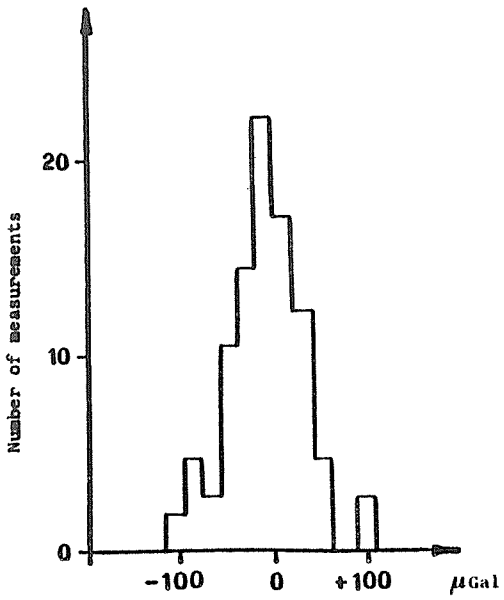

Fig. 6 - Histogram for the station of QINGDAO

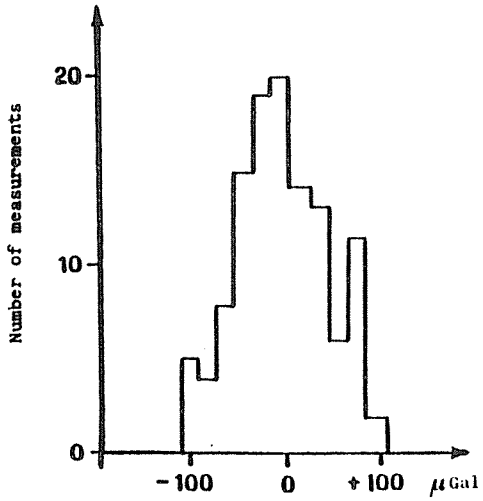

Fig. 7 - Histogram for the station of SHANGHAI

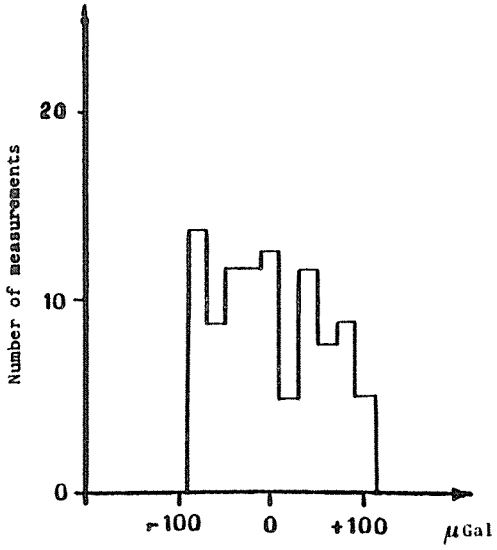

Fig. 10 - Histogram for the station of WUHAN

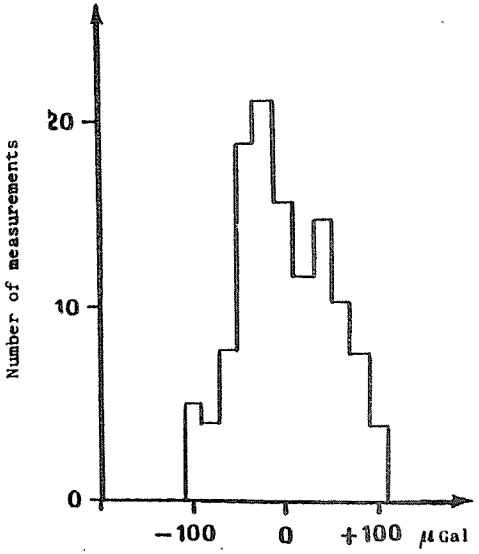

Fig. 11 - Histogram for the station of NANNING

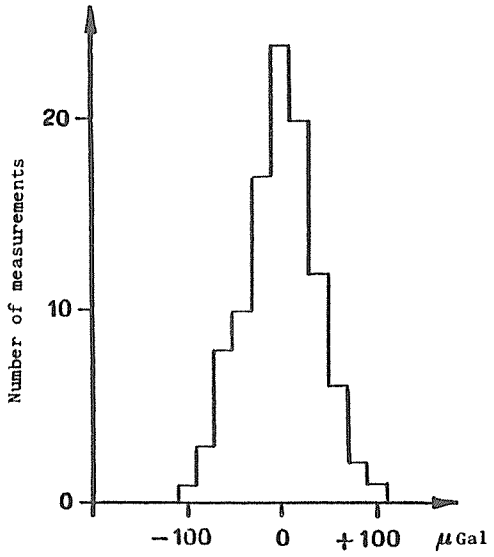

Fig. 12 - Histogram for the station of CHANGSHA

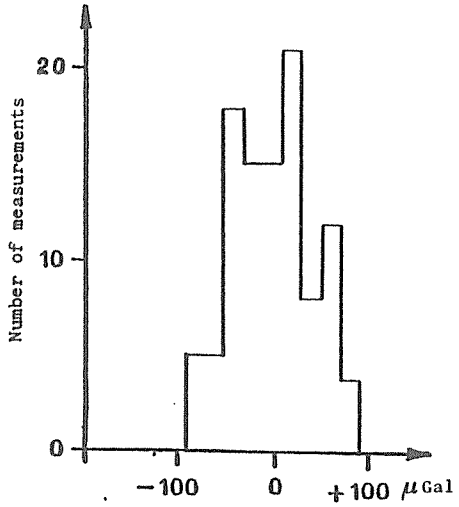

Fig. 13 - Histogram for the station of GUANGZHOU

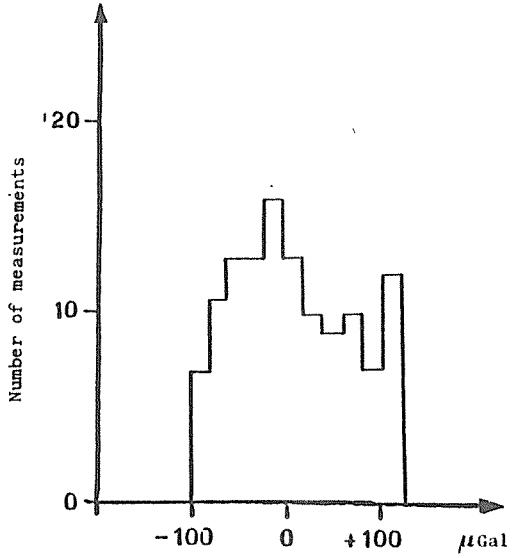

Fig. 14 - Histogram for the station of FUZHOU

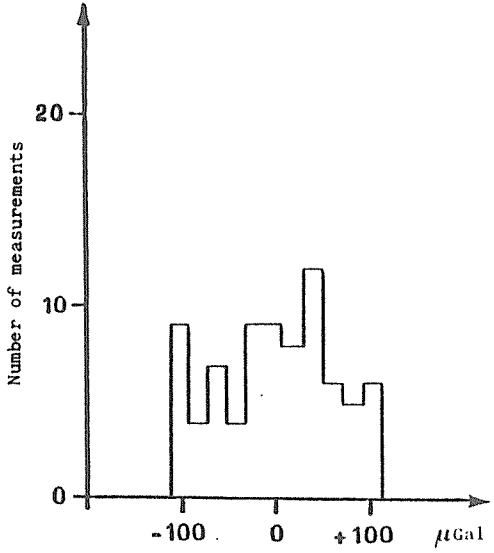

Fig. 15 - Histogram for the station of KUNMING

STATUS OF THE INTERNATIONAL ABSOLUTE GRAVITY BASESTATION NETWORK

G. Boedecker

The arguments communicated through circular letters, questionnaires, other written and oral communication and particularly at the SSG meeting 1985 in Paris were compiled and utilized as a basis for a proposal for an IAGBN station set comprising 36 stations. For these stations crustal age, seismicity, availability of tidal parameters, link to space geodetic sites and many other viewpoints have been considered and it was tried to find a good compromise. It is hoped that, after discussion and revision, the IGC will approve the proposal.

A REVIEW OF THE DETERMINATION OF THE GEOGRAVITATIONAL CONSTANT, THE NEWTONIAN GRAVITATIONAL CONSTANT AND THE MASS OF THE EARTH

C. Boucher

Theoretical models for the definition of the mass of newtonian gravitational constant G, the mass of the Earth M, and the geogravitational constant $\mu = GM$ are discussed, in the frame of recent theories of gravitation. Possible causes of variations are also reviewed.

Finally, the paper gives a short survey of numerical estimations of those parameters.

Large Scale Measurements of the Newtonian Gravitational Constant: A Summary

G.J. Tuck, F.D. Stacey, S.C. Holding, and G.I. Moore

Department of Physics, University of Queensland,

Brisbane, 4047. Australia.

Abstract

The most reliable kilometre-scale estimate of the Newtonian gravitational constant G has been obtained from mines in Queensland, Australia. The value is $(6.72 \pm 0.024) \times 10^{-11}\ m^3 kg^{-1} s^{-2}$ which is about 1% higher than the laboratory value. The uncertainty is due to possible systematic errors in the densities derived from the well known geological structure.

Preliminary results from an experiment which uses a vacuum balance to weight the gravitational forces exerted by layers of water on 10 kg masses suspended in evaculated tubes at different levels in a pumped-storage hydroelectric lake are discussed.

Introduction

For several years there has been speculation that the inverse square law of gravitation may be defective over a range between that of laboratory measurements (up to about 1m) and satellite and planetary scales ($>10^6$m) [1]. Laboratory techniques which are modern variants of the Cavendish torsion balance experiment give a value of the Newtonian Gravitation Constant, G, of $6.6726(5) \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$ [2]. Although measurements of planetary and satellite orbits have confirmed the iniverse square law with remarkable precession [3] they do not provide an estimate of G. Only the product of G and the mass of one of the orbiting bodies is determined. Since astronomical calculations assure the laboratory value of G to give an estimate of masses it follows that a 1% discrepancy between G on laboratory and planetary scales would require a reappraisal of these masses.

Until we revied the geophysical technique used by Airy in 1856 of measuring gravity in mines at Mount Isa in Australia [4,5,6] there were no reports of geophysical measurements in the range $1\text{-}10^6$m which specifically sought a value of G. In fact, of those reports which compared gravimetrically inferred densities from mine and bore-hole measurements with sample densities [8] only two [9,10] reported discrepancies and in neither case was an explanation sought in terms of a high value of G.

The favoured form for a modification of Newton's law of gravity [1] is the addition of one or more Yukawa terms to the conventional gravitational potential due to a point mass m at a distance r:

$$V(r) = -\frac{G_\infty m}{r}\left[1 + \sum \alpha_k\, e^{-r/\lambda_k}\right] \qquad (1)$$

where α_k are the amplitudes of the "short range" components that are superimposed on normal graivty and λ_k are the effective ranges of the short range forces. Such forces assume the interchange of pseudo-particles with wavelengths λ_k:

$$\lambda_k = \frac{\hbar}{m_k c}$$

where m_k is the mass of the particle, $\hbar$ is $\frac{h}{2\pi}$, h being Plank's constant and c is the speed of light.

Although the present theoretical viewpoint is that there is a multiplicity of short range components most recent analysis including our own, assume only one non-Newtonian term.

Values of G obtained form measurements in mines at Mount Isa and a hydro-electric lake have been used to estimate constraints on values of α and λ, the details of which are reported by Stacey et al. [12], and will not be discussed here.

Recently evidence of another kind for a non-Newtonian force has been presented by Fischbach et.al. [11]. They reanalysised data of the original experiments of Baron Roland von Eötvös and claim that it shows a statistically significant dependence of gravity on the chemical composition of the materials. Although these results have been severly criticised [13] their general conclusions, which broadly agree with those from our geophysical data, remain. However the source of the non-Newtonian force is yet to be positively identified and new experiments (including one of our own) for determining it are already occuring.

2. Gravity Profile within the Earth

The variation of gravity with depth in the Earth, assuming Newtonian physics and a layered structure, was given by Stacey et al. [4,12]. Here we assume an arbitrary and unknown value of the constant G and the equations for calculating it from the gravity profile and layer density are:

$$g(z) - g(o) = U(z) - 4\pi G\, X(z) \qquad (2)$$

where g(z) is the gravity at a depth z. U(z) is a purely geometric term representing the fact that at depth z one is nearer to the centre of mass and also incorporates effects of rotation and ellipticity and X(z) accounts for the the fact that the mass outside the level of measurement does not contribute to the measured gravity, leading to a reduction of gravity with depth:

$$U(z) = 2\,\frac{g(o)\,z}{R}\left[1 + \frac{3}{2}\frac{z}{R} - 3\,J_2\left[\frac{3}{2}\sin^2\phi_o - \frac{1}{2}\right]\right] + 3\,\omega^2\,z\,(1 - \sin^2\phi_o) \qquad (3)$$

$$X(z) = \frac{c}{a}\left[1 + 2\,\frac{z}{R} + \frac{1}{2}\left[1 - \frac{c^2}{a^2}\right]\right]\int_o^z \rho\,dz - \frac{Z}{R}\int_o^z \rho z\,dz \qquad (4)$$

Here R is the radius of the Earth's surface at the site of measurements, ϕ_o is the geocentric latitude, J_2 is the inertial ellipticity coefficient, ω is the angular velocity, a and c are equatorial and polar radii and ρ is the density.

Initially we are concerned to know whether a departure from Newtonian gravity is clearly indicated so we use these equations to infer a value of G from the measured gravity profile.

A discrepancy between the inferred vlaue of G and the laboratory value, G_{lab}, indicate such a departure. A more extensive analysis [12] is then required to constrain the parameters α and λ.

3. Results from Hilton and Mount Isa Mines

A preliminary report [5] on gravity measurements in the mine at Hilton, about 20 km north of Mount Isa, outlined the geological structure of the area and reported values for the densities of the major rock units. To a good approximation the geological structure is two dimensional with layers inclined at about 76° to horizontal, striking almost due north-south. However and gravity measurements along a 600 m deep tunnel connecting two access shafts, provided small corrections to the model for north-south irregularities that were not evident in surface gravity survey data. Our method was first to assume a regional average density, $\bar{\rho}$, (2750 kg m^{-3}) and then to correct the individual gravity data g(z) for the departure of densities of the rock units from this average (using G_{lab}). Thus U(z) and X(z) are straightforward

analytical expressions. The corrected values of $[g(z) - g(o)]$ give a value of $G \neq G_{lab}$ by Eq.(2). A small iterative adjustment was then made using the new value of G applied in the corrections but the effect on the estimate of G was not significant.

Accuracy of the density data is crucial to the whole experiment. Over 2,300 core sample densities were used to establish densities of the major rock units and two sources of error are recognized. First densities of individual bore-core samples are determined to only the nearest 10 kg m^{-3}. Although variability is greater than this, extensive sampling reduced the random error below 10 kg m^{-3}. In the case of the rock unit with the regional average density there were four separate cores covering the depth range 100 to 1000 m and the average density of each drill core was within 10 kg m^{-3} of 2750 kg m^{-3}. Thus the limit (10 kg m^{-3}) becomes the upper bound on the possible error in G arising from a systematic error in density measurement. The second problem arises from nonrandom sampling in the rock unit with the mineralization. However, since the region of mineralization within this unit was more than 600 m from the measured gravity profile even a variation in density of 270 kg m^{-3}, representing an extreme assumption, gives a very small variation in the value of G (less than 0.2%).

Although the geological structure at Mount Isa is essentially similar to that at Hilton, there were a number of recognized complications with both the structure and the density pattern obtained from 12,000 bore density values at Mount Isa. The analysis procedure for the Mount Isa data was the same as that for the Hilton data but these factors resulted in values of G with larger fitting errors. The results of the analysis and values of G for Mount Isa and Hilton data are reported elsewhere [6] and summarized here (Table 1).

The values in Table 1 are consistently higher than the conventional laboratory estimate as are previously reported mine, and bore-hole results [8].

4. Hydro-electric lake gravity experiment

The hydro-electric pumped-storage lake, Splityard Creek reservoir, used for the experiment, has an area of about 1 km^2 at a surface level about 70 m above a much larger lake impounded by the Wivenhoe Dam on the Brisbane River. The smaller lake level rises and falls by as much as 10 m in the course of a day according to the demand for electricity.

A vacuum balance which compares the weights of 10 kg masses hanging in evacuated tubes at different levels in the lake has been used to measure the gravitational attraction of layers of lake water up to 10 m in depth. Balance deflections are measured relative to a reference plane using capacitance micrometry. The reference plane in turn is maintained horizontal by capacitance reference to interconnected mercury pools activating a servoed support leg. The balance is mounted on a 38 m electricity pylon which is about 140 m from the nearest shoreline and although it is subjected to wind vibration the control system permits weighing with a sensitivity better than 1 part in 10^8. During more favourable periods a significant improvement is expected. The early result from data obtained during a few brief, relatively favourable, periods give $G = (6.668 \pm 0.040) \times 10^{-11}\ m^3 kg^{-1} s^{-2}$ which agrees with recent laboratory estimates. The mean effective distance between interacting masses in this experiment is 25 m, which makes it the largest scale measurement of G using precisely controlled masses and provides tighter constraints on possible non-Newtonian effects than laboratory-type measurements in a range previously explored by only geophysical methods. We expect to soon have data for a revised estimate of G with an improved uncertainty and intend to then publish full details. A description of the balance and details of its operation in a disturbed environment have been submitted [7].

5. Discussion

The most serious doubts about mine and borehole data arise from an inadequate knowledge of density in the areas of the mines and boreholes where gravity measurements have been made and the possibility that laboratory measured core densities systematically underestimate the 'in situ' densities of rocks. We now claim to have overcome these doubts by extensive sampling in areas where the geological structures were well known and by the fact that, except near the surface, the porosities were too low (< 0.5%) for dilation by the release of overburden pressure to have materially affected the densities. The remaining doubt arises from the possibility of a regional or extensive local bias in gravity gradient caused by deep seated mass irregularities that have not been recognized. Measurements of the gravity gradient above ground in a 260 m refinery chimney, surface gravity data, and a Bonguer anomaly map of the region showed no conclusive evidence of a deep seated mass that would explain the anomalous vertical gradient within the mine. These conclusions are discussed in detail by Holding and Tuck [5] and Holding et al. [6].

6. Conclusions

With recent attention being focussed on the possibility of a previously unrecognized force in nature there is a need for new geophysical experiments to examine the range between 50 m to several kilometres. The need for a marine experiment in the deep ocean as originally proposed [14]is now urgent. Our series of mine observations were specifically undertaken to investigate the range dependence of G and have yielded a positive non-Newtonian result that has not been refuted. We expect to soon have improved data from the hydroelectric lake experiment to give an estimate of G a scale of about 20m.

Acknowledgement

This work is supported by the Australian Research Grants Committee and Mount Isa Mines Limited.

Table 1. Values of G obtained by Eq.(2): a comparison of the Hilton result with four semi-independent values from Mount Isa. The unit is $10^{-11}\ m^3 kg^{-1} s^{-2}$. The fitting error is the formal standard deviation of a least squares fit of the data. The listed possible systematic errors arise from a lack of precision in the density determinations.

Mine	G	Fitting Error	Systematic Error
Hilton	6.720	± 0.002	± 0.024
Mount Isa	6.691	± 0.007	
	6.693	± 0.010	± 0.089
	6.729	± 0.009	0.022
	6.702	± 0.007	

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It is with great sadness that I take the stand today instead of my colleague Michel Ogier. Mr. Balmino kindly suggested that we devote the time intended for his paper to recalling the work of Michel Ogier and that this session be dedicated to his memory.

We, the community of gravity scientists, the BRGM and all those concerned with geophysical exploration owe a great deal to Michel Ogier. All who knew him were impressed by the importance that he attached to his work of calibrating the French gravity network with reference to absolute gravity measurements. During his last few years, although he knew that he was suffering from an implacable disease, he continued to maintain the very high standard of his work on gravimetry.

Born in 1945, Michel Ogier obtained a Master's degree in applied geology and in 1971 was awarded his thesis on "The thermoluminescence of the alkaline feldspars" for his "Doctor's degree" in Tectonophysics.

In 1970 he joined the BRGM's Geophysics Department, where he was to spend his entire career, he began with the control and interpretation of airborne geophysics, working for 6 months in Mozambique, a year in India and in the Cameroon, Upper Volta and Gabon.

He carried out numerous geophysical assignments abroad, applied to water exploration in Egypt, Niger and Senegal in particular, and applied to mineral exploration in Senegal, Upper Volta, New Caledonia, Yemen and Sudan. He then began work on what was to become his vocation - gravimetry. From 1977, he took part in the compilation of the southern sheet of the 1:1,000,000 scale gravity anomalies map of France ; in 1978 he established an international gravity network between France and neighbouring countries ; in 1979 he worked at the creation of a French gravity database and in 1980 began work on integrating European gravity data.

At the same time as making determinations of absolute gravity in collaboration with Dr. Sakuma, Michel Ogier worked on restructuring the French gravity network, in cooperation with the Bureau international des poids et mesures, a long and exacting job which he brought to completion despite the onset of the disease that was finally to bear him away.

Michel Ogier was a member of the French National Committee of Geodesy and Geophysics and the French representative on the European gravity sub-commission.

DETERMINATION STATISTIQUE DU GRADIENT VERTICAL
DE LA PESANTEUR SUR LE PILIER A3
DE SEVRES (HAUTS-DE-SEINE)

par

M. OGIER et R. MILLON

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R E S U M E

Les différences constatées dans les diverses déterminations du gardient vertical de la pesanteur sur le pilier A3 de Sèvres, nous ont amené à faire, en 1986, une nouvelle série de mesures (350 environ) au moyen de trois gravimètres.

Sans qu'on puisse apporter d'explication, il semble bien que la valeur de 273 µGal/m (Sakuma, 1977) ne soit plus valable actuellement et que pour 1986, une valeur de 288 µGal/m soit plus adaptée.

Il est proposé de normaliser les procédures de détermination de ce gradient et d'effectuer d'autres mesures au moment des campagnes de comparaison des gravimètres absolus à Sèvres.

Ce rapport contient : 12 pages de texte et 3 figures.

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1. INTRODUCTION

La connaissance du gradient vertical de la pesanteur est nécessaire pour la réduction au sol des mesures faites par les gravimètres absolus (à 1-1,2 m de hauteur).

Dès 1981, une différence sensible a été constatée entre les mesures de Sakuma de 1977 (273 µGal/m) et celles faites par l'A.I.G..

C'est pourquoi le B.R.G.M. a été amené à effectuer en 1986 une nouvelle série de mesures, suffisamment nombreuses (350) pour qu'un traitement statistique soit applicable.

Nous rappellerons d'abord les différentes campagnes de mesures du gradient vertical effectuées jusqu'en 1985 avant de présenter nos propres résultats.

2. LES DIFFERENTES CAMPAGNES DE MESURE DU GRADIENT VERTICAL SUR SEVRES A3

2.1. Campagne d'octobre 1981 (A.I.G.) (tableau 1)

Des déterminations de gradient vertical ont été effectuées en 1981 par M. Becker et E. Groten (I.P.G. Darmstadt)** au cours de la série de liaisons entre les quatres sites A3, A4, A5 et A6 de Sèvres avec six gravimètres Lacoste et Romberg (trois modèles D et trois modèles G).

Les résultats, sur le site A3, sont donnés dans le tableau 1 ci-après.

** M. Becker - E. Groten
Relative gravimeter measurements at the 1981 absolute gravity campaign in Paris-Sèvres. Bulletin B.G.I. n° 52 - Juin 1983.

TABLEAU 1

Valeur du gradient vertical moyen en 1981 sur le pilier A3 (données A.I.G.)

Instrument*			W_{zz} (µGal/m)	σ	Nombre de mesures
L.R.	D 14	I.A.G.	286,8	2,0	9
	D 21	I.A.G.	285,0**	0,2**	5
	D 38	I.P.G.	282,1	2,2	6
	G 131	D.M.A.	288,2	0,8	11
	G 253	D.M.A.	281,3	2,0	7
	G 258	I.P.G.	277,9	0,9	6
	Moyenne		283,6**	1,6**	
				TOTAL	44

Remarques : a) La moyenne calculée est la moyenne de chaque instrument sans pondération par le nombre de mesures ; avec pondération, la moyenne serait 284,2 µGal/m pour le gradient.

b) Il apparaît étonnant d'avoir des écarts-types aussi petits (de l'ordre du µGal/m) avec aussi peu de mesures pour des gravimètres modèle G où la précision de lecture est de 10 µGal/m : si l'on remonte les calculs pour le G 258, par exemple, où le W_{zz} moyen est 277,9 µGal/m, on trouve que le $\Delta\bar{g}$ devait être 331,5 µGal, ce qui, pour six mesures correspond aux lectures suivantes : 5 à .33
1 à .34
et donc à un écart-type de 3,7 µGal pour Δg et 3,1 µGal/m pour W_{zz} (au lieu de 0,9).

2.2. Campagne 1984 (B.R.G.M.) (tableau 2)

Une petite série de mesures a été faite en 1984 avec trois gravimètres Lacoste et Romberg du B.R.G.M. (un modèle D et deux modèles G) toujours sur le site A3 de Sèvres.

Les résultats sont donnés sur le tableau 2 ci-après.

* I.A.G. : Institut für Angewandte Geodäsie, Frankfurt. R.F.A..
I.P.G. : Institut für Physikalische Geodäsie, Darmstadt. R.F.A..
D.M.A. : Defence Mapping Agency, Cheyenne, U.S.A..

** Valeurs respectives de 284,6 ; 0,8 (pour D 21) 283,5 ; 0,6 (pour moyenne) citées dans J. Boulanger et al. : "Determinations of absolute gravity by GABL gravimeter in Sèvres. Bull. d'Inf. B.G.I. n° 52 - Juin 1983.

TABLEAU 2

Valeurs du gradient vertical moyen en 1984
sur le pilier A3 (données B.R.G.M.)

Appareils : D 24, G 588, G 742

Résultats : $n = 6$

$\overline{\Delta g} = 349{,}8$ µGal

$\sigma = 4{,}7$ µGal

$H = 1{,}193$ m

$W_{zz} = 293{,}2$ µGal/m

Remarques : Ces six mesures correspondent à deux déterminations par appareil, soit un seul aller-retour entre trépied et sol : cette procédure est à proscrire car il n'y a qu'une seule mesure par appareil à la station haute.
Cependant, comme nous n'avons pas d'autres mesures pour 1984, nous donnons ces résutlats pour ce qu'ils valent, sans autre commentaire.

2.3. Campagne de décembre 1985 (A.I.G.) (tableau 3)

Des déterminations de gradient vertical ont été effectuées en décembre 1985 avec dix gravimètres Lacoste et Romberg (3 D et 7 G), à l'occasion d'une campagne de liaisons entre les six stations de Sèvres. Les résultats ont été publiés par M. Becker* : nous les reproduisons dans le tableau 3.

Remarques : a) Cette campagne est le reflet de beaucoup plus de mesures (nombre total 125), mais elles ont été réalisées avec dix appareils, soit une moyenne de 12,5 mesures par appareil. Cela nous semble encore peu, surtout qu'il y a des séries de six mesures seulement pour certains appareils.

b) Comme pour la campagne de 1981, la précision affichée nous apparaît étonnante, surtout pour les modèles G : cependant, l'article de M. Becker décrit davantage les procédures de calcul d'erreur : il apparaît que cette précision résulte

* M. Becker : Relative gravimeter measurements at the 1985 absolute gravity campaign in Sèvres. Bull. B.G.I. n° 57 - Déc. 1985.

TABLEAU 3

Valeurs du gradient vertical moyen en 1985
sur le pilier A3 à Sèvres (données A.I.G.)

Instrument *		W_{zz} (µGal/m)	Nombre de mesures	σ (µGal/m)	Δh (m)
D 8 F	I.E.T.U.	296,0 ± 0,5	15	2,8	1
		296,4 ± 1,2	13		
G 298 F	I.E.T.U.	290,0 ± 0,7	11	2,4	1
		291,3 ± 1,0	11		
G 709	I.E.T.U.	296,8 ± 1,6	13	2,3	1
		297,0 ± 0,7	11		
G 563	I.A.G.	292,1 ± 0,9	8	2,6	1
D 21	I.A.G.	291,5 ± 0,5	6	1,2	0,999
G 54	Suède	295,7 ± 1,3	6	2,8	0,819
G 290	Suède	303,9 ± 0,5	8	2,6	0,820
G 305	Japon	300,4 ± 1,3	6	3,2	1
G 258	I.P.G.	299,4 ± 3,3	8	3,9	1
D 38 F	I.P.G.	302,3 ± 1,0	9	2,8	1
	Moyenne	295,3 1,2	125 (total)		

* I.E.T.U. : Institut für Erdmessung Technische Universität. Hanovre. R.F.A..
I.A.G. : Institut für Angewandte Geodäsie. Francfort. R.F.A..
Suède : Land Survey of Sweden. Gävle.
Japon : International Latitude Observatory. Mizusawa.
I.P.G. : Institut für Physikalische Geodäsie, Technische Hochshule, Darmstadt. R.F.A..

d'un calcul de minoration de norme de matrice. Par contre, les écarts-types donnés dans un autre tableau par M. Becker sont plus élevés et sont établis par composition d'une précision théorique et d'une erreur systématique et non pas comme le résultat d'un calcul statistique sur les mesures faites à Sèvres : c'est donc ce dernier écart-type que nous retiendrons pour une meilleure comparaison avec nos propres résultats.

c) Nous ne savons pas exactement comment a été calculée la valeur moyenne : 295,3 µGal/m, ce n'est ni la moyenne des séries (296,4), ni celle des gravimètres (296,9), ni celle pondérée par le nombre de mesures (296,2) ; il semble que ce soit par une procédure d'ajustement combinée avec une pondération dépendant de la précision propre de chaque gravimètre.

2.4. Campagne B.R.G.M. de décembre 1985 (tableau 4)

Un rapide contrôle a été réalisé en décembre 1985 toujours sur le pilier A3 de Sèvres avec deux gravimètres Lacoste et Romberg, modèle G. La procédure de traitement statistique des données est exposée dans le paragraphe 2.5.1. et les résultats sont donnés dans le tableau 4 ci-dessous :

TABLEAU 4

Valeurs du gradient vertical moyen en décembre 1985 sur le pilier A3 de Sèvres (données B.R.G.M.)

Instrument		W_{zz} (µGal/m)	σ (µGal/m)	Nombre de mesures	h = 1,193 m
L.R.	G 588	286,7	9,7	16	
	G 742	308	2	6	
			TOTAL	22	
Moyenne pondérée par le nombre de valeurs		292,5			

Remarques : a) les mesures faites avec le gravimètre G 588 peuvent se décomposer en deux séries consécutives :

série n° 1, n = 5, W_{zz} = 301 µGal/m, σ = 1,8 µGal/m

série n° 2, n = 11, W_{zz} = 280,8 µGal/m, σ = 4,7 µGal/m

Nous n'avons pas pu établir la cause de cet écart significatif : il ne peut guère s'agir que d'un saut brusque et inexpliqué du coefficient du gravimètre.

b) Comme dans les précédentes campagnes, le nombre de mesures effecutées avec chaque gravimètre est encore insuffisant. Cependant, la concordance entre les résultats de 1985 (A.I.G. et B.R.G.M.) est convenable (295,3 contre 292,5) et reste dans la fourchette de précision des déterminations.

2.5. Campagnes B.R.G.M. de janvier, avril et mai 1986

Après cette succession de campagnes où beaucoup de gravimètres ont été utilisés pour faire chacun un faible nombre de mesures, nous avons préféré opérer avec moins de gravimètres (3) et faire davantage de mesures (360 au total), de façon à avoir des séries de mesures plus justiciables d'un traitement statistique.

2.5.1. Procédure opératoire

- Mesures :

Les gravimètres Lacoste et Romberg utilisés étaient le D 24 et les G 588 et 742 ; les mesures étaient faites par séries d'une quinzaine pour chaque gravimètre, toujours par le même opérateur : F. DUPONT.

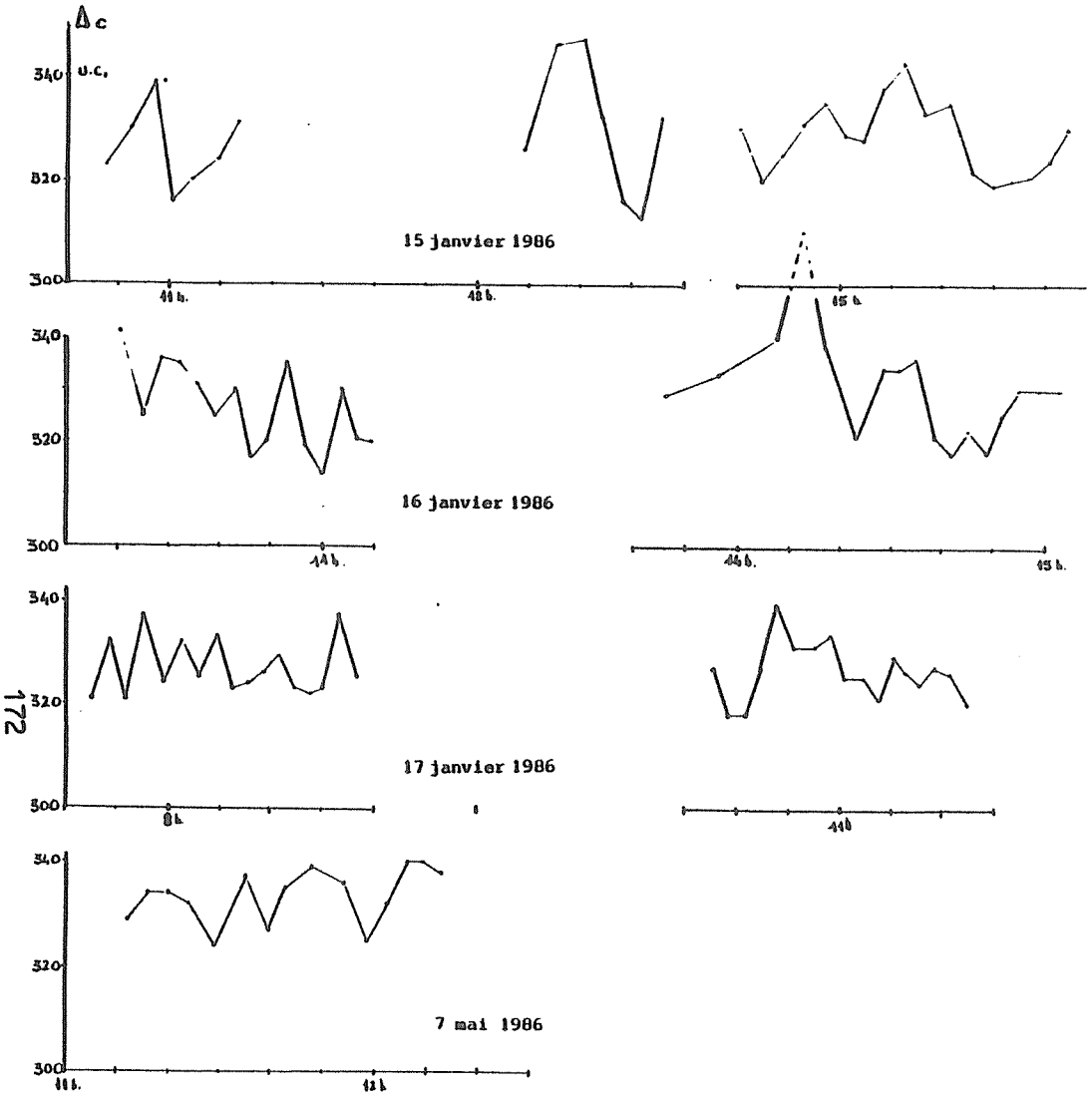
A la station basse, le gravimètre était posé à même le sol, sur le repère du pilier. A la station haute, le gravimètre était posé sur le trépied de hauteur 1,193 m, à la verticale de la station basse.

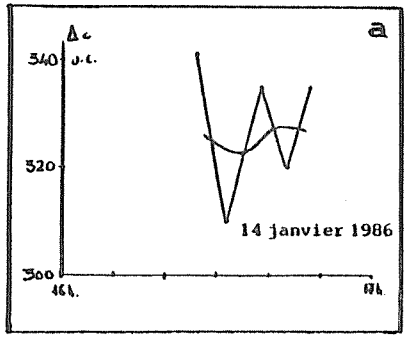
L'intervalle de temps entre chaque mesure d'une même série était de 4 à 5 minutes.

- Traitement des mesures :

. On calcule la différence brute Δc entre chaque couple de lectures (haute et basse), exprimée en unité de compteur (U.C.).

. On reporte les différences sur un diagramme en fonction du temps (Δc, t) (voir fig. 1a).





SEVRES Pilier A3

Détermination du gradient vertical.

Diagramme des différences de lecture en fonction du temps.

Gravimétrie
LR D24

Fig. 1

Ce diagramme a l'aspect d'une dent de scie dont l'enveloppe représente l'amplitude de l'effet cumulé de phénomènes comme la dérive du gravimètre, la variation luni-solaire, l'effet de la variation de pression atmosphérique. Nous corrigeons donc ces effets en prenant les moyennes de différences consécutives, ce qui amène à la courbe grasse de la figure 1.a : cette dernière opération doit être considérée comme une correction et non comme un lissage.

. La présentation sous forme de diagramme (Δc, t) permet de juger visuellement de la qualité des résultats : on voit ainsi que les résultats du matin du 17 janvier 1986 sont excellents, alors que ceux de la veille au soir sont beaucoup plus dispersés. On voit mieux aussi quelles sont les mesures aberrantes à éliminer.

. On calcule ensuite, série par série, les moyennes et écarts-types, que l'on convertit alors en gradient vertical.

2.5.2. Déterminations avec le Lacoste et Romberg D 24

En janvier et mai 1986, nous avons réalisé avec cet appareil 123 mesures réparties en huit séries équilibrées (mis à part la première). Les résultats sont présentés sur le tableau 5 et sur la figure 1.

TABLEAU 5

Déterminations du gradient vertical moyen en janvier et mai 1986 avec le L.R. D 24 sur le pilier A3 de Sèvres (données B.R.G.M.)

Date	Nombre de mesures	Δg U.C.	σ U.C.	W_{zz} µGal/m	σ µGal/m	h = 1,193 m 1 U.C. D 24 = 1,03347 µGal
14/1 a.m.	5	325,7	2	282,2	1,8	
15/1 mat.	15	326,6	6,8	282,9	5,9	(1 valeur éliminée)
" a.m.	17	328,3	6,2	284,4	5,4	
16/1 mat.	16	326,5	5,3	282,9	4,6	
" a.m.	16	328,6	6	284,7	5,2	(1 valeur éliminée)
17/1 mat.	17	327,1	2,6	283,4	2,2	
a.m.	17	326,5	4,4	282,8	3,8	
7/5 mat.	20	332,7	3,4	288,2	2,9	
TOTAL	123					
	Moyenne	328,1	5,5	284,3	4,7	

On remarquera l'excellente précision obtenue avec la série du matin du 17/1/86 (écart-type de 2 µGal/m) : la moyenne de cette série est toutefois très proche (à moins de 1 µGal/m près) de la moyenne générale.

Sur les 123 mesures, deux seulement ont été jugées aberrantes et n'ont pas été prises en compte dans les calculs statistiques.

2.5.3. Déterminations avec le Lacoste et Romberg G 588

En janvier, avril et mai 1986 nous avons effectué huit séries totalisant 126 mesures avec le G 588. Les résultats sont présentés sur le tableau 6 ci-dessous.

TABLEAU 6

Détermination du gradient vertical moyen en janvier et mai 1986 avec le L.R. G 588 sur le pilier A3 de Sèvres (données B.R.G.M.)

Date	Nombre de mesures	Δc U.C.	σ U.C.	W_{zz} µGal/m	σ µGal/m	h = 1,193 m 1 U.C. G 588 = 10,1509 µGal
14/1 a.m.	8	33,1	0,9	281,9	7,9	
15/1 mat.	15	34,1	0,4	289,9	3,4	
a.m.	16	33,7	0,6	286,9	5	
16/1 mat.	15	34,2	0,5	291,3	4	
a.m.	16	34,3	0,4	292,2	3,3	
17/1 mat.	16	33,6	0,5	286,1	4,6	
a.m.	15	34,5	0,4	293,8	3,6	
7/5 mat.	25	33,9	0,6	288,1	4,9	
TOTAL	126		Moyenne	289	6,2	

2.5.4. Déterminations avec le Lacoste et Romberg G 742

En janvier 1986, nous avons effectué sept séries totalisant 101 mesures avec le G 742. Les résultats sont présentés sur le tableau 7 ci-après.

TABLEAU 7

Détermination du gradient vertical moyen en janvier 1986 avec le L.R. G 742 sur le pilier A3 de Sèvres (données B.R.G.M.)

Date	Nombre de mesures	Δc U.C.	σ U.C.	W_{zz} µGal/m	σ µGal/m	h = 1,193 m 1 U.C. G 742 = 10,2072 µGal
14/1 a.m.	7	33,6	0,35	287,8	3	
15/1 mat.	15	34,4	0,5	294,6	4	
a.m.	16	33,7	0,6	288,5	5	
16/1 mat.	15	33,9	0,75	290,3	6,4	
a.m.	16	34,4	0,86	294,1	7,3	
17/1 mat.	16	34,4	0,86	294,1	7,3	
a.m.	16	34,5	0,9	295,2	7,7	
TOTAL	101		Moyenne	293,3	7,6	

2.5.5. Comparaison des derniers résultats (données B.R.G.M.)

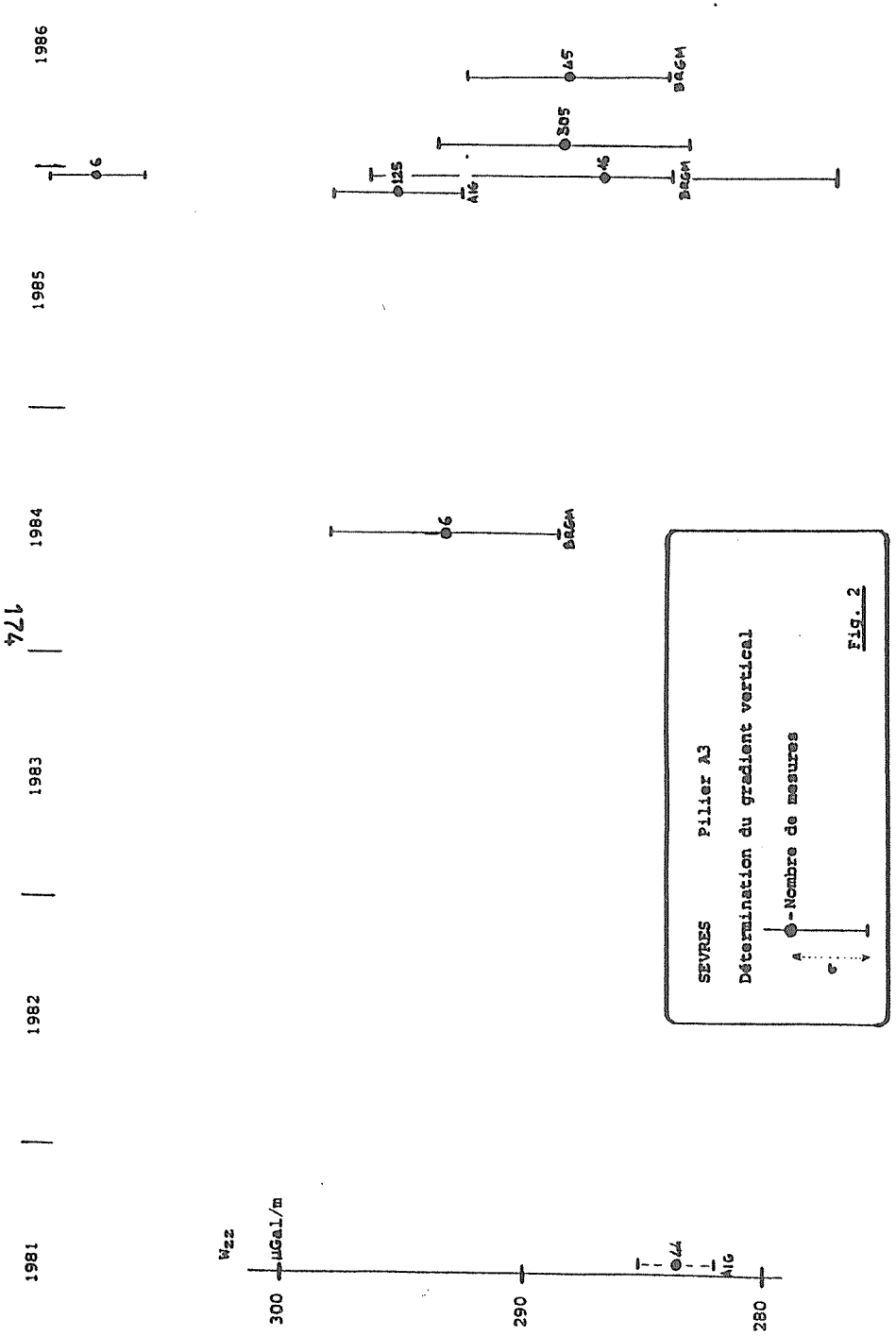
TABLEAU 8

Appareils \ Dates	Décembre 1985	Janvier 1986	Avril-Mai 1986	Moyenne par appareil
D 24		283,5 ± 4,6 (103)	288,2 ± 2,9 (20)	284,3 ± 4,7 (123)
G 588	286,7 ± 9,7 (16)	289,3 ± 5,7 (101)	288,1 ± 4,9 (25)	288,9 ± 6,2 (142)
G 742	308 ± 2 (6)	292,5 ± 6,3 (101)		293,3 ± 7,6 (107)
Moyenne par dates	292,5 (22)	288,4 (305)	288,1 (45)	288,6 (372)

Moyenne et écarts-types donnés en µGal/m

( ) nombre de mesures.

Pour chaque appareil, le nombre de mesures est compris dans une fourchette de 100 à 150 : on remarque cependant que les moyennes présentent des différences qui sont du même ordre que les écarts-types. Il ne semble pas que le coefficient des gravimètres doive être mis en cause.



2.6. Comparaison de toutes les déterminations de gradient vertical dans le temps pour le pilier A3 de Sèvres

TABLEAU 9

		W_{zz} (µGal/m)	Ecart-type	Nombre de gravimètres	Nombre de mesures
Oct. 1977	Sakuma	273 ± 3			
1981	A.I.G.	283,6 ± 1,6		6	44
1984	B.R.G.M.	293,2		3	6
1985	A.I.G.	295,3 ± 1,2	2,7	10	125
Déc. 1985	B.R.G.M.	292,5	8,3	2	22
Jan. 1986	B.R.G.M.	288,4	5,2	3	305
Avril-Mai 1986	B.R.G.M.	288,1	4,1	2	45

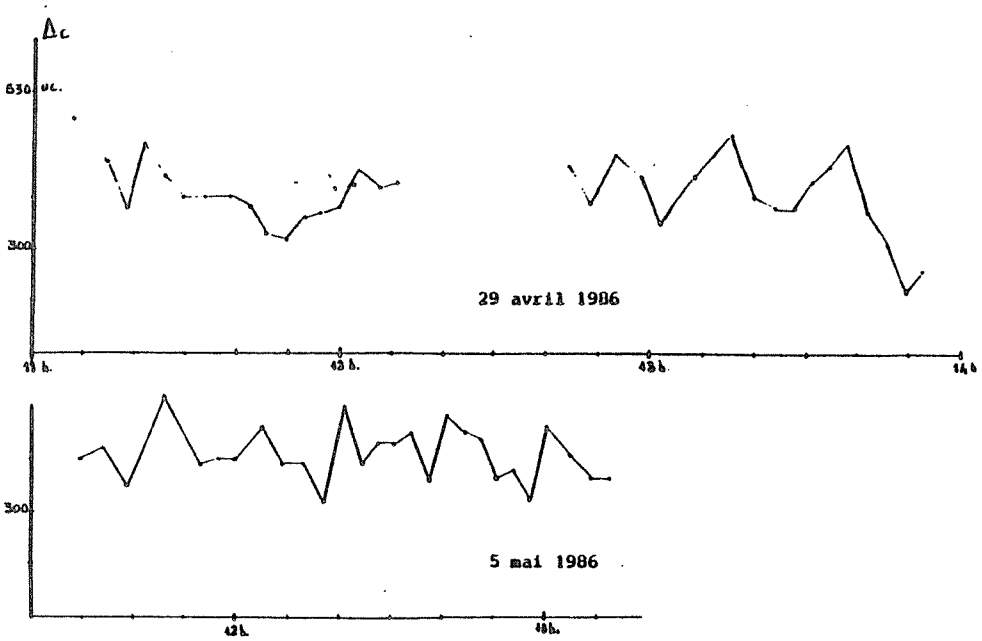
Nous avons représenté, sur la figure 2, les différentes séries de mesures en fonction du temps depuis 1981. Les écarts-types sont figurés sous forme de barrettes.

Mis à part une petite série de six valeurs pour le G 742 de décembre 1985, toutes les autres séries apparaissent normalement groupées, eu égard aux écarts-types représentés.

Si l'on excepte la valeur anormalement basse trouvée par Sakuma en 1977 (273 µGal/m), il est difficile de vouloir trouver une variation significative du gradient vertical sur le pilier A3 de Sèvres dans la dernière décennie.

3. LES DETERMINATIONS DU GRADIENT VERTICAL SUR LE PILIER D'ORLEANS

Il est intéressant de comparer les mesures de gradient vertical faites en 1981 et 1986 sur le pilier du B.R.G.M. à Orléans. En 1986, trois séries de mesures ont été faites avec chaque appareil.



ORLEANS Pilier B.R.G.M.

Détermination du gradient vertical.

Diagramme des différences de lecture en fonction du temps.

Gravimétrie
LR D24 Fig. 3

TABLEAU 10

Détermination du gradient vertical à Orléans

Date	Appareil	Nombre de mesures	W_{zz} (µGal/m)	σ (µGal/m)
1981	D 24	37	272	1,7
1986	D 24	58	269,4	4,2
	G 588	57	273,3	3,6

Les séries de mesures pour le D 24 sont représentées, sur la figure 3, de la même manière que pour Sèvres : Δc en fonction du temps : on voit que la série du 5 mai 1986 est très régulière (l'écart-type correspondant n'est que de 3,2 µGal/m).

On ne note pas de différence significative entre les valeurs de 1981 et celles de 1986.

CONCLUSION ET RECOMMANDATIONS

La valeur du gradient vertical sur le pilier A3 de Sèvres a été déterminée à plusieurs époques depuis 1981, avec des gravimètres Lacoste et Romberg variés et par plusieurs organismes, plus de 500 mesures ont été faites.

Il semble bien que la valeur déterminée en 1977 par Sakuma (273 µGal/m) ne soit plus adaptée à la situation actuelle : en 1986, le gradient doit etre proche de 288 µGal/m.

Il serait intéressant de continuer à faire périodiquement de telles mesures pour surveiller l'évolution de ce gradient et notamment au moment des campagnes de détermination de gravité absolue. Il serait toutefois judicieux de normaliser les procédures de traitement des mesures afin que les résultats des différentes équipes puissent être comparés avec profit. Il faudrait aussi effectuer des séries de mesures assez longues, une centaine de mesures serait une quantité convenable.

Nous recommandons d'opérer plutôt avec des gravimètres Lacoste et Romberg, modèle D, qui ont une précision de lecture de 1 µGal/m. L'utilisation du modèle G est possible, mais la précision de lecture n'est que de 10 µGal et le traitement statistique qui suit les mesures est probablement faussé.

Relative Gravity Observations at BIPM, Sèvres in 1985 and 1986

by

R.H. Röder and H.-G. Wenzel

Institut für Erdmessung
Universität Hannover
Nienburger Str.6
D-3000 Hannover 1

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ABSTRACT:

Gravity measurements have been carried out in 1985 and 1986 at BIPM Sèvres on and between stations A1, A3, A4, A5, A6 and A7 with three LaCoste-Romberg gravity meters, equipped with electrostatic feedback system SRW. Additionally, the fine structure of the gravity field has been investigated at station A3.

1. Introduction

In 1981 and 1985, a comparison of different absolute gravity meters has been carried out at Bureau International de Poids et Mesures (BIPM), Sèvres (BOULANGER et al. 1983, BOULANGER et al. 1986). The observations were performed on stations A1...A6 in 1981 and A1...A7 in 1985, located in the same laboratory building (Fig. 1.1). During both campaigns, relative gravity observations have been carried out by a number of different institutions in order to center the absolute gravity observations to station A1 (BECKER and GROTEN 1983, BECKER 1985). Whereas six LaCoste-Romberg gravity meters have been used in 1981, fourteen LaCoste-Romberg instruments were employed in 1985. With three of these instruments, measurements were repeated on five stations in course of measurements with the JILAG-3 absolute gravimeter of Institut für Erdmessung (IFE) at BIPM in 1986. The overall observation conditions for relative gravity measurements at BIPM are considerably good (maximum distance between stations 50 m, maximum gravity difference 660 microgal, stable environmental conditions), and the obtained precision is in the order of 1 microgal. But comparing the 1981 and 1985 results (Table 1.1 and 1.2), the gravity gradients differ by up to 12 microgal/meter and the gravity differences between the stations by up to 9 microgal.

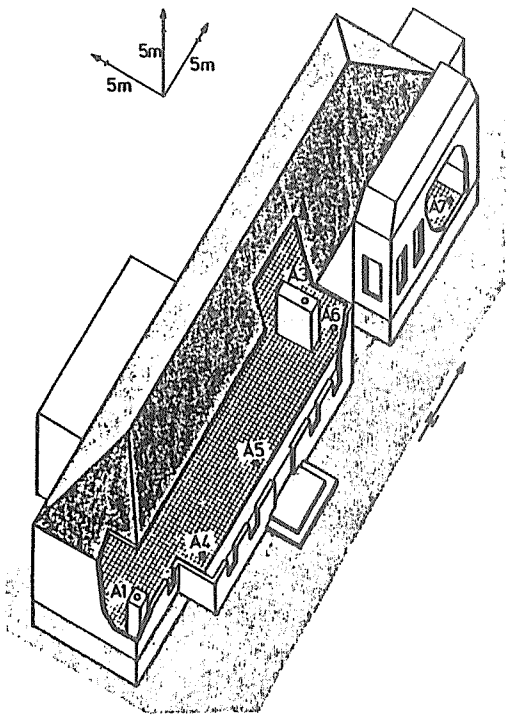

Fig. 1.1: Gravity Stations at BIPM Main Laboratory Building

Station	Gradient 1981 [microgal/m]	Gradient 1985 [microgal/m]	Discrepancy [microgal/m]
A1	not observed	311.8 ± 0.6	
A3	283.6 ± 1.6	295.3 ± 1.2	+ 11.7
A4	253.5 ± 1.3	255.3 ± 1.0	+ 1.8
A5	250.8 ± 1.1	252.4 ± 0.7	+ 1.6
A6	251.8 ± 1.2	258.9 ± 0.9	+ 7.1
A7	not observed	259.0 ± 0.5	

Table 1.1: Comparison of Gravity Gradients from 1981 and 1985 Campaigns
1981 results are taken from BECKER and GROTEN 1983, Table 2
1985 results are taken from BECKER 1985, Table 3.7

Stations	Difference 1981 [microgal]	Difference 1985 [microgal]	Discrepancy [microgal]
A3-A1	-79.6 ± 1.5	-70.5 ± 0.5	+ 9.1
A4-A1	577.8 ± 1.4	583.8 ± 0.5	+ 6.0
A5-A1	579.6 ± 1.2	578.5 ± 0.4	- 1.1
A6-A1	606.8 ± 1.4	609.4 ± 0.5	+ 2.6
A7-A1	not observed	659.8 ± 0.5	

Table 1.2: Comparison of Gravity Differences from 1981 and 1985 Campaigns
1981 results are taken from BECKER and GROTEN 1983, Table 4
1985 results are taken from BECKER 1985, Table 4.1

Some more values for the gravity difference between stations A1 and A3 and for the vertical gravity gradient on A3 are listed in Table 1.3 and 1.4, as they have been found in the literature. Discrepancies between the different results are even larger than those computed from the measurements in 1981 and 1985.

Epoche	Value [microgal]	Source
1976	-90.1 ± ?	CANNIZZO et al. 1978
1977	-90.6 ± 0.6	BECKER and GROTEN 1983 (Marson)
1978	-91.0 ± ?	BECKER and GROTEN 1983 (Poitevin)
1981	-79.6 ± 1.5	BECKER and GROTEN 1983 (excentric on A3)
1985	-70.7 ± 0.4	BECKER 1985

Table 1.3: Gravity difference between stations A1 and A3

Epoche	Value [microgal/m]	Source
1977	273 ± 3	CANNIZZO et al. 1978
1980	273 ± ?	OGIER 1986 (Sakuma)
1981	283.6 ± 1.6	BECKER and GROTEN 1983 (excentric)
1984	274.8 ± 1.9	OGIER 1986
1985	295.3 ± 1.2	BECKER 1985
1985	296.9 ± 4.6	OGIER 1986

Table 1.4: Vertical gravity gradient at station A3

There might exist four reasons for the discrepancies:

1.) The results are affected by severe errors in the evaluations.

In order to check this item, we have completely re-evaluated the 1985 observations using a quite different method (adjustment of gravity differences instead of gravity readings). For the results of single instruments, we found discrepancies in the order of 3 microgal, but the average results agree better than one microgal.

2.) The results suffer from excentric measurements. In 1981 the observations have been carried out only at A1 on the station center, whereas the other stations have been observed excentric with horizontal distances of up to 0.8 m to the station centers (BECKER and GROTEN 1983). This problem is discussed in chapter 3.

3.) The results suffer from systematic errors of the instruments, even though observations from a large number of different instruments have been used. More about that in chapter 4.

4.) The gravity field changed due to the construction of a new laboratory building between 1981 and 1985 about 10 m apart from station A1. See chapter 5.

2. Observations by IFE in 1985 and 1986

The gravity observations of IFE at BIPM have been carried out with gravity meters LaCoste-Romberg model D No.8, model G No.298 and model G No.709. The instruments are equipped with electronic feedback systems type SRW (SCHNÜLL et al. 1984, RÖDER et al. 1985) and were calibrated in the gravity meter calibration system Hannover immediately before and after the observation campaigns. Consequently, the IFE gravity observations are not affected by periodic screw errors of the instruments, and the calibration accuracy is estimated to be better than 0.1 %, which means less than 1 microgal error for both the gradients and the gravity differences at BIPM.

In 1985, gravity observations have been carried out by IFE on and between stations A1, A3, A4, A5, A6, and A7 in the framework of the SSG 3.85 relative campaign at BIPM (BECKER 1985). The observations were partly restricted because of the observation scheme fixed by SSG 3.85 and the fact, that 14 instruments were running over 6 stations; the reading of SRW feedback instruments needs less time than the reading of conventional instruments, and therefore we could obtain much more observations than planned in the observation scheme. In 1986, there were no restrictions to the observation scheme, but unfortunately we could not access station A1.

For the determination of gravity gradients, observation sets were performed, consisting of 10 gravity differences each. The gravity meters were read on the station center and on a tripod, which was installed exactly 1 m above the station. In some cases, sets were repeated. For the determination of gravity differences between the stations, micro gravity networks have been observed (Fig. 2.1 and 2.2).

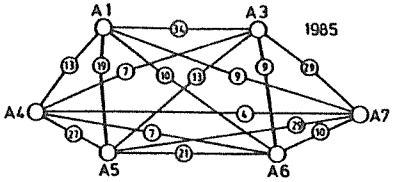

Fig.2.1: Micro Net 1985

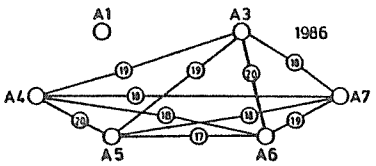

Fig. 2.2: Micro Net 1986

3. Effect of Excentric Observations

The gravity field in buildings is characterized by anormal horizontal and vertical gravity gradients, due to the complicated mass distribution. The large discrepancies between several determinations for the gravity difference between stations A1 and A3 and the vertical gravity gradient on A3 (Table 1.3 and 1.4) gave rise to perform some numerical studies on the fine structure of the gravity field at station A3. The geometric situation around A3 is shown schematically in Fig. 3.1. Station A3 is located close to one end of concrete pillar 'A' (size 3.10 m * 1.35 m * 2.90 m), on which a suspended table (1.22 m * 2.13 m * 0.34 m) made from granite is placed. Near pillar 'A' pillars 'B' and 'C' with similar dimensions are located.

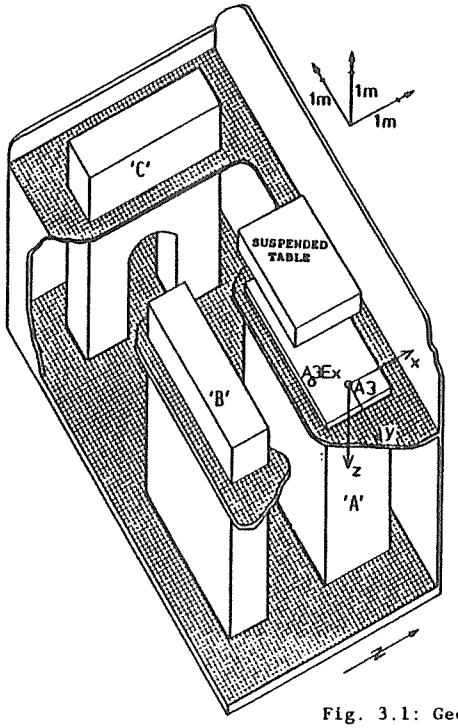

Fig. 3.1: Geometric Situation at Station A3

Taking the geometric dimensions of the pillars and a material density of 2.5 g/cm**3 for concrete resp. 2.8 g/cm**3 for granite, we have computed the gravity effect of these masses on A3 and A3ex. The result is +4.2 microgal (A3 minus A3ex). For the gravity gradients on A3 and A3ex, the difference is 10.0 microgal/meter (the absolute value of the gradient is smaller on A3ex).

The estimation of gravity attraction effects from numerical computation may be uncertain, because the model is incomplete and the material densities are not known exactly. To verify the computations, the gravity differences between A3, A3ex and the two stations 1 m above them have been measured with an accuracy better than 2 microgal (see Appendix A and Fig. 3.2). The difference between the vertical gradients agrees perfectly with the numerical computation, and the difference between A3 and A3ex agrees within 3 microgal. The gravity gradients measured in 1981 and 1985 are also in excellent agreement (Table 3.1).

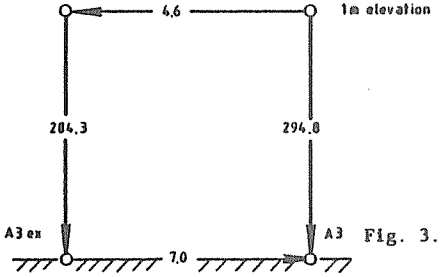

Fig. 3.2: Observed Gravity Differences in microgal at Pillar 'A'

In order to investigate the fine structure of the gravity field around A3, we have established a small network on pillar 'A' consisting of 9 stations, one of them being A3ex. Gravity values were determined for these stations with respect to the center A3 with an accuracy better than 2 microgal. The maximum gravity difference is -14.5 microgal (Fig. 3.3). The non-linearity of the gravity field in vertical direction on station A3 has been investigated by observing at 0.0 m, 0.4 m, 0.6 m, 0.8 m, 1.0 m and 1.2 m elevation. The non-linearity between 0.0 m and 1.2 m is 3 microgal at maximum (Fig. 3.4).

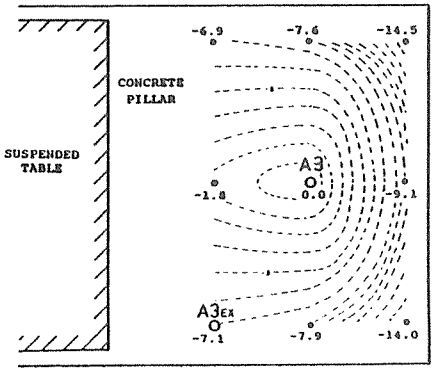

Fig. 3.3: Gravity Values in microgal at Pillar 'A' with Respect to Station A3

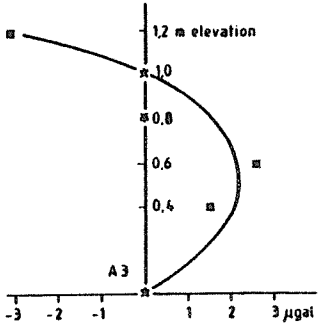

Fig. 3.4: Non-linearity of the Gravity in Vertical Direction on A3; (-294.8 microgal/m Subtracted from the Observations)

The gravity gradient on station A6ex was also reobserved in 1986, the result agrees within 3 microgal to the value obtained in 1981 (Table 3.1).

Station	1981 [microgal/m]	IFE 1986 [microgal/m]	Discrepancy [microgal/m]
A3ex	283.6 ± 1.6	284.3 ± 1.5	+ 0.7 ± 2.2
A6ex	251.8 ± 1.2	254.8 ± 1.9	+ 3.0 ± 2.2

Table 3.1: Comparison of Gravity Gradients

4. Influence of Systematic Errors of the Instruments

When comparing the results of the 1981 and 1985 campaigns in more detail, one can find discrepancies between single instruments of at maximum 10 resp. 15 microgal/m for the gravity gradients and up to 11 resp. 13 microgal for the gravity differences (BECKER and GROTEN 1983, BECKER 1985). Possible sources for these discrepancies are imperfect calibration (periodic errors produced by the screw and gears) and magnetic field effects. For the 1981 campaign, three of six instruments have not been corrected for periodic errors, and for the 1985 campaign, no corrections for periodic errors were applied to five of fourteen instruments. Although the observed gravity differences are small, the influence of the periodic errors can reach 5 microgal. Even for well calibrated instruments, there might exist residual errors not compensated by the used evaluation models in the order of two microgal (e.g. RÖDER et al. 1985). For gravity meters equipped with electrostatic feedback systems, there exist no periodic errors and the remaining calibration errors are normally less than 1 microgal for gravity differences less than 1 mgal. Comparing the results of the three SRW feedback instruments used in the 1985 campaign, we find maximum discrepanices of 8 microgal/m for the gravity gradients and 4 microgal for the gravity differences (both occuring at station A3). The results of a reobservation of gravity gradients and differences with these three instruments in 1986 are given in Appendix A and B. For a comparison with the 1985 results see Table 4.1 and 4.2. The discrepancies between our average values obtained in 1985 and 1986 are with one exception less than 2 microgal. The average results of both campaigns agree well with those given in BECKER 1985, which are computed from the measurements of 10 gravity meters (Table 1.1 and 1.2).

Station	IFE 1985 [microgal/m]	IFE 1986 [microgal/m]	Discrepancy [microgal/m]
A1	312.3 ± 0.7	not observed	
A3	294.8 ± 1.3	294.8 ± 1.2	0.0 ± 1.8
A4	254.6 ± 0.9	254.9 ± 1.4	+ 0.3 ± 1.7
A5	253.2 ± 1.2	249.0 ± 1.3	- 4.2 ± 1.8
A6	258.2 ± 0.7	258.7 ± 1.9	+ 0.5 ± 2.0
A7	258.2 ± 0.6	256.4 ± 0.9	- 1.8 ± 1.1

Table 4.1: Comparison of Gravity Gradients Observed with D-8F, G-298F, and G-709F

Stations	IFE 1985 [microgal]	IFE 1986 [microgal]	Discrepancy [microgal]
A3-A1	-68.6 ± 0.7	-68.2 ± 0.6	+ 0.4 ± 1.0
A4-A1	583.1 ± 0.8	583.4 ± 0.6	+ 0.3 ± 1.0
A5-A1	578.3 ± 0.7	578.3*	
A6-A1	610.3 ± 0.8	610.3 ± 0.6	0.0 ± 1.0
A7-A1	659.0 ± 0.8	660.7 ± 0.6	+ 1.7 ± 1.0

Table 4.2: Comparison of Micro Gravity Networks Observed with D-8F, G-298F, and G-709F
*: constraint to 578.3 microgal because A1 could not be observed in 1986

For the discrepancies between our instruments, we suppose the anormal magnetic field to be the major error source. In our laboratory in Hannover, we have observed the effects given in Fig. 4.1, when rotating the instruments on an amagnetic table. There can clearly be seen variations in the readings with amplitudes between 3 and 5 microgal. Therefore, we have measured the magnetic field on station A3 at BIPM with a RFL Industries model 101 magnetometer. The accuracy is estimated to be about 2 microtesla. The vertical component of the magnetic field was found to be 29 microtesla at station A3 and 38 microtesla 1@m above; for the horizontal component we got 14 microtesla at station A3 and the same value 1 m above. For the gravity meter G-298F, the magnetic influence is known to be 0.19 microgal/microtesla for the vertical component and 0.1 microgal/microtesla for the horizontal components. These results confirm, that the magnetic field at BIPM varies considerably over short distances and that magnetic effects have to be taken into account for high precision gravity observations in buildings.

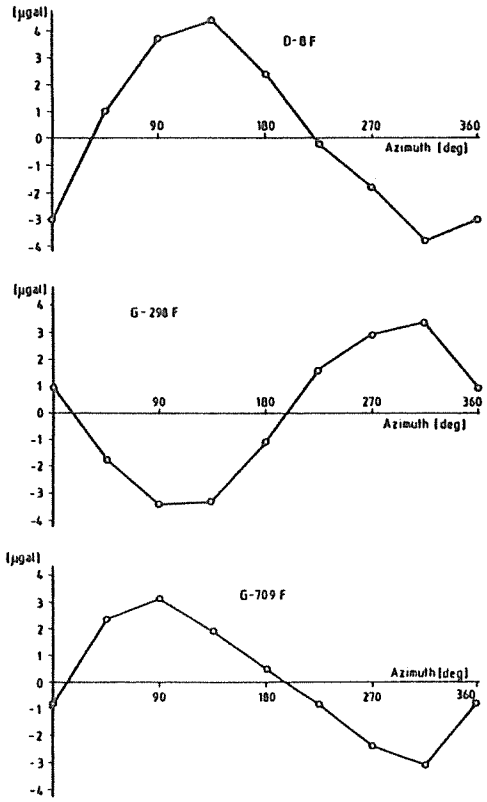

Fig. 4.1: Variation of the Gravimeter Readings in Different Azimuths at Station Hannover 101

5. Gravity Change due to Construction of a New Laboratory Building

Between 1981 and 1985, a new laboratory building has been constructed at BIPM (SAKUMA 1986). Considering a model of this building, as extracted from the contruction plans, and a rough estimation of the material densities, the gravity changes due to the building have been computed for the gravity stations and are given in Table 5.1. The construction of the building cannot at all affect the gravity gradients on the stations and the gravity values on stations A3, A5, A6 and A7. But the gravity value on station A1 should have been decreased significantly by about 18 microgal. Converting the 1985 gravity difference A3 - A1 with the 1986 gravity difference A3ex - A3 (see Table 5.2), the expected gravity change at station A1 cannot be found.

A1	A3	A4	A5	A6	A7
-18	0	-1	0	0	0

Table 5.1: Computed Gravity Changes in microgal Due to the Construction of a New Laboratory Building at BIPM

	1981 [microgal]	1985 + 1986 [microgal]	Discrepancy [microgal]
A3ex - A1	-79.6 ± 1.5	-77.5 ± 1.0	2.1 ± 1.8

Table 5.2: Comparison of Gravity Difference A3ex - A1

6. Conlusions

The investigations in 1985 and 1986 at BIPM have shown that

- by averaging the results of 6 or more conventional LCR gravity meters, an accuray of 1 ... 2 microgal can be achieved for small gravity differences under good environmental conditions; the same accuracy can be achieved by means of two or three SRW feedback instruments in less time,
- no significant variation of the gravity differences occured at BIPM between 1985 and 1986,
- excentric gravity observations in buildings can cause errors up to 10 microgal, and must be avoided,
- magnetic fields in buildings vary strongly and can cause errors up to several microgal in observations with LaCoste-Romberg gravity meters.

Acknowledgements

We greatfully acknowledge the friendly support of the BIPM staff during the observations. Our colleagues C.T. Schneider and M. Schnüll contributed to this investigation.

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APPENDIX A: Observed Gravity Gradients at BIPM

n - number of observed gravity differences
gr - gradient in microgal/meter
s - standard deviation of one observation in microgal/meter
S - standard deviation of the average of n observations in microgal/meter

Station	Instr.	Date	n	gr	s	S
A1	D-8F	05.07.85	10	312.5	1.2	0.4
A1	G-298F	04.07.85	12	313.5	3.9	1.1
A1	G-709F	05.07.85	10	311.0	2.0	0.6
A1	average 1985:		32	312.3		0.7
A3	D-8F	26.06.85	13	295.9	1.7	0.5
A3	D-8F	05.07.85	11	296.7	2.8	0.8
A3	G-298F	04.07.85	10	290.0	1.8	0.6
A3	G-298F	05.07.85	10	291.3	2.5	0.7
A3	G-709F	01.07.85	11	297.7	2.2	0.6
A3	G-709F	05.07.85	10	296.9	2.0	0.6
	average 1985:		65	294.8		1.3
A3	D-8F	07.06.86	10	293.5	3.5	1.1
A3	G-298F	09.06.86	10	293.7	4.2	1.3
A3	G-709F	07.06.86	10	297.2	3.1	0.9
A3	average 1986:		30	294.8		1.2
A4	D-8F	05.07.85	11	257.3	3.1	0.9
A4	D-8F	05.07.85	10	254.3	4.5	1.3
A4	G-298F	04.07.85	10	254.9	3.1	0.9
A4	G-709F	05.07.85	12	251.7	4.1	1.1
A4	G-709F	05.07.85	10	254.9	2.1	0.6
A4	average 1985:		53	254.6		0.9
A4	D-8F	06.06.86	10	252.0	2.5	0.8
A4	G-298F	06.06.86	10	256.4	2.8	0.9
A4	G-709F	06.06.86	10	256.3	2.1	0.6
A4	average 1986:		30	254.9		1.4

A5	D-8F	05.07.85	11	251.7	1.4	0.4
A5	G-298F	04.07.85	10	256.3	2.0	0.6
A5	G-298F	05.07.85	10	253.5	3.0	0.9
A5	G-709F	05.07.85	10	251.2	1.3	0.4
A5	average 1985:		41	253.2		1.2
A5	D-8F	06.06.86	10	247.8	2.7	0.8
A5	D-8F	10.06.86	11	245.9	3.5	1.0
A5	G-298F	06.06.86	10	251.8	3.0	0.9
A5	G-709F	06.06.86	10	250.6	1.5	0.5
A5	average 1986:		41	249.0		1.3
A6	D-8F	04.07.85	12	260.3	2.4	0.7
A6	D-8F	05.07.85	10	257.4	3.0	0.9
A6	G-298F	04.07.85	10	257.4	2.6	0.8
A6	G-709F	05.07.85	10	257.5	1.3	0.4
A6	average 1985:		42	258.2		0.7
A6	D-8F	06.06.86	10	255.9	2.2	0.7
A6	G-298F	06.06.86	10	262.3	4.4	1.3
A6	G-709F	06.06.86	10	257.8	2.4	0.7
A6	average 1986:		30	258.7		1.9
A7	D-8F	01.07.85	10	260.1	1.9	0.6
A7	D-8F	05.07.85	10	257.8	2.0	0.6
A7	G-298F	04.07.85	11	256.2	2.8	0.8
A7	G-709F	01.07.85	10	258.8	1.8	0.5
A7	G-709F	05.07.85	9	258.1	2.8	0.9
A7	average 1985:		50	258.2		0.6
A7	D-8F	09.06.86	10	258.1	1.4	0.4
A7	G-298F	09.06.86	10	255.2	3.8	1.1
A7	G-709F	09.06.86	10	255.9	2.6	0.8
A7	average 1986:		30	256.4		0.9
A3ex	D-8F	09.06.86	10	282.3	1.6	0.5
A3ex	G-298F	09.06.86	10	283.2	3.3	1.0
A3ex	G-709F	09.06.86	10	287.3	2.8	0.8
A3ex	average 1986:		30	284.3		1.5
A6ex	D-8F	13.06.86	10	251.5	1.5	0.5
A6ex	G-298F	13.06.86	9	258.2	1.8	0.6
A6ex	G-709F	13.06.86	10	254.6	1.6	0.5
A6ex	average 1986:		29	254.8		1.9

APPENDIX B: Observed Micro Gravity Networks at BIPM

s - standard deviation of one observation in microgal
n - number of observed gravity differences

Instr.	Epoch	A3-A1	A4-A1	A5-A1	A6-A1	A7-A1	s	n
D-8F	1985	-67.0±1.4	582.1±2.0	578.4±1.5	610.3±1.7	659.5±1.7	±6.0	75
G-298F	1985	-71.7±1.1	585.2±1.5	580.0±1.2	610.7±1.6	659.8±1.3	±5.3	76
G-709F	1985	-67.3±0.8	582.4±0.8	577.2±0.8	610.3±0.9	658.2±0.8	±3.4	90
common adjustment 1985:								
	1985	-68.6±0.7	583.1±0.8	578.3±0.7	610.3±0.8	659.0±0.8		241
D-8F	1986	-67.5±1.0	583.3±1.0	578.3*	611.2±1.1	662.9±1.1	±4.1	60
G-298F	1986	-70.5±0.9	582.7±0.9	578.3*	608.1±0.9	657.4±0.9	±3.7	63
G-709F	1986	-66.4±0.9	584.0±0.9	578.3*	611.7±0.9	661.8±0.9	±3.6	63
common adjustment 1986:								
	1986	-68.2±0.6	583.4±0.6	578.3*	610.3±0.6	660.7±0.6		186

* : constraint to 578.3 because A1 could not be observed in 1986

OBSERVATIONS WITH A FULLY-DAMPED LCR G-GRAVIMETER

The 12th Meeting of the International Gravity Commission,
Toulouse, France, September 23-26, 1986.

by

Aimo Kiviniemi
Finnish Geodetic Institute

Abstract

Observation methods with a fully-damped LCR G-gravimeters are studied. Test measurements were carried out at the calibration lines, 66 and 1 mgal. The gravity survey was carried out on the heaving ice of the Bothnian Sea.

1. Introduction

Gravity measurements should preferably be carried out on firm base. In certain cases it is necessary to measure on a soft or heaving base, as e.g. on the bottom of the sea or on the ice of the sea or a lake. For such measurements LaCoste and Romberg Inc. has manufactured their models H and W which have very high damping, U. S. Patent 2,977,799. Model G can also be equipped with similar damping equipment. This equipment is desribed in a prospectus of LaCoste and Romberg Inc., the LaCoste and Romberg Underwater Gravity Meters, as follows:

"The gravity meter is adjusted for an almost infinite sensitivity in addition to having the high damping previously mentioned. With infinite sensitivity, the moving system will stay wherever it happens to be if the spring tension is adjusted to balance gravity. It behaves like a sphere on a flate plate when the plate is horizontal. If the spring tension does not guite balance gravity, then the speed at which the moving element moves through the damping medium is proportional to the difference between the spring tension and gravity. Gravity is therefore measured by the speed of the moving element."

A recorder is recommended for measurement of the speed. Sufficient accuracy can also be obtained by an optical method, observing the speed of the moving element in the eyepiece.

The Finnish Geodetic Institute, National Land Survey of Sweden and Geological Land Survey of Sweden carried out gravity measurements as a joint project on the ice of the Bothnian Sea during the winter seasons of 1985 and 1986. LCR G-gravimeters with full-damping were used. Observations have been made with a recorder and using the optical method. This paper only deals with observations made with the optical method.

2. Observation method

As the manufacturer has not published any detailed descriptions of the mechanism of the damping system, the paper does not include theoretical study. It is expected that the moving element would move according to an exponential function. However, first experiments showed that the speed is proportional to the spring tension as shown in Fig. 1.

The gravimeter reading can be taken as follows: The damped gravimeter is equipped with an electrostatic beam positioner. With this beam positioner it is possible to change the spring tension temporarily by about 75 mgal, or to move the crosshair in the eyepiece upscale or downscale /LACOSTE AND ROMBERG INC./. By following the movement of the crosshair in the eyepiece the dial reading is determined so that it is 1-3 mgal too high, whereat the crosshair moves upscale. Then the time interval needed for the crossing of two lines in the eyepiece is measured with a stop watch. Then the dial is turned until the dial reading is symmetrically 1-3 mgal too low, whereat the crosshair moves downscale. The speed is observed as above. The real gravimeter reading is the weighted mean of the dial readings, when the time intervals observed are the weights respectively.

In Table 1 $H_i = 2 \cdot \Delta R_i$, where ΔR_i is a spring tension causing the movement of the crosshair. The gravimeter readings are $R_o + \Delta R_i$ and $R_o - \Delta R_i$, where R_o is the real gravimeter reading. T_1 and T_2 are time intervals needed for crossing of the two lines in the eyepiece upscale and downscale. $T_1 \sim T_2$. $H_i, H_i - H_{1+n}$, H_i are real gravimeter readings after tidal correction.

H_i RU	T_1 s	T_2 s	H_i, H_i 5388	H_1, H_{1+n} 5388	H_{1+n}, H_1 5388
2.0	35.6	37.4	042	042	042
2.2	33.3	33.6	063	047	057
2.4	30.4	30.5	066	053	054
2.6	27.6	28.0	060	055	045
2.8	25.8	26.4	053	046	048
3.0	23.8	24.1	061	059	041
3.2	22.4	22.9	052	050	043
3.4	21.3	21.7	054	047	049
3.6	20.5	20.2	084	055	060
3.8	19.2	19.7	047	036	053
4.0	18.0	18.1	067	058	044
4.2	17.7	17.6	078	044	066
4.4	16.5	16.8	052	044	050
4.6	15.5	15.6	066	064	037
		Mean	060.4	050.0	049.2
Standard error of an observation			±11.6	±7.7	±8.1

Table 1. The gravimeter readings when different speeds of the crosshair are used.

On the basis of Table 1 we see that the dial readings do not have to be symmetrical within R_o, or the real gravimeter reading can be obtained using e.g. gravimeter readings $R_o + \Delta R_{i+n}$ and $R_o - \Delta R_{i+m}$, when the time intervals are observed.

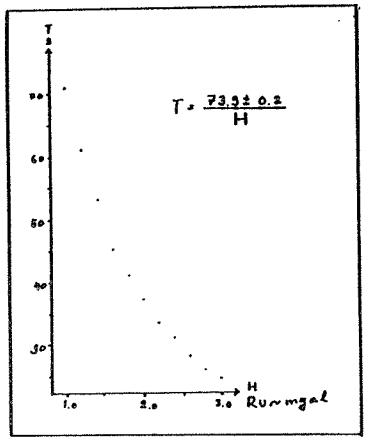

Fig. 1. Differences between the gravimeter readings (H) producing equal time intervals (T) upscale and downscale.

3. Testing the accuracy of the observation method

The observation method was tested with an LCR G-gravimeter No 600. The first test was made against the Vihti Calibration Line /KIVINIEMI 1962/ performing five single measurements on July 7, 1986, and the following gravity difference was obtained:

With fully-damped gravimeter	66.065 ± 0.0029 mgal
With two non-damped gravimeters	66.059 "

On the basis of Table 1 the spring tension, $\frac{1}{2} H_i$, does not have to be symmetrical upscale and downscale. This allows the measurements of small gravity differences without periodic errors, when the dial readings are the same at every station, and only the time intervals, T, are measured. This method was tested against a calibration line of 1 mgal on July 10, 1986, and the following results were obtained:

	Gravity differences, µgal				
With fully-damped gravimeter	215.7	439.6	640.0	850.7	1047.8
With two non-damped gravimeters	216.4	431.4	643.0	847.8	1036.4
Difference	-0.7	+8.2	-3.0	+2.9	+11.4

The standard error of gravity difference is ±5.1 µgal computed on the basis of two double measurement series.

4. Measurements on the ice of the Bothnian Sea

A gravity survey was carried out on the ice of the Bothnian Sea during the winter seasons of 1985 and 1986. In 1985 Mr. J. MÄKINEN, Finnish Geodetic Institute, and Mr. B. WÅLLBERG, Geological Survey of Sweden, carried out measurements on the southern part of the Bothnian Sea. They measured 335 new station with a fully-damped LCR G-gravimeter No 600 altogether. The successful observations were made with a recorder.

In 1986 the author and B. WÅLLBERG carried out measurements on the northern part of the Bothnian Sea, where 220 new stations were measured with a fully-damped LCR G-gravimeter No 788. As measurements on ice require helicopter transport and suitable weather conditions and the measuring season is short, it is necessary to get reliable observations as quickly as possible. Therefore, the time interval of the speed of the crosshair upscale, about 20-70 s, and

the dial reading were observed first. Assuming a curve similar to that presented in Fig. 1, a dial reading was predicted, which caused equal speed downscale. The observation was made as above. If the time intervals observed were approximately the same, the measurement was checked and was successful. The time intervals between the successive station varied between 7 and 10 minutes. This time interval also included transportation over distance of 5 kilometers by helicopter and the navigation. On the basis of the field computations, accuracies of a few ten microgal were obtained depending on weather conditions. Observations were possible up to a wind speed of about 6 m/s. Observations with Worden or non-damped LCR gravimeters are nearly impossible on the Bothnian Sea. Details of the gravity measurements on the ice are presented in the Publication of the Finnish Geodetic Institute No 86 (P. LEHMUSKOSKI, J. MÄKINEN).

5. Conclusions

The fully-damped LCR G-gravimeter makes possible gravity measurements on the ice of the Bothnian Sea in the conditions, when measurements with Worden gravimeter or a non-damped LCR G-gravimeter are impossible. Altogether 200-300 new stations were measured each season. The calibration measurements on the Vihti calibration line showed no systematic error between the results observed with fully-damped and non-damped LCR G-gravimeters. The first tests show that the observational accuracy with fully-damped and non-damped LCR G-gravimeters are approximately equal in good circumstances. The inaccuracy increases, when the heaving of the observation base increases. Gravity differences of 0- about 2 mgal can be measured successfully without periodic errors.

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SCREW ERROR AND ELECTROSTATIC EFFECTS ON THREE LCR GRAVIMETERS WITH FEEDBACK SYSTEM VRL 8350

Zhou Kungen[**], B. Ducarme[*] and C. Poitevin[*]

Abstract

The screw errors and the electrostatic effects on the calibration of LaCoste Romberg (LCR) gravimeters G336, G487 and D31 equipped with feedback system VRL 8350 are discussed in this paper.

1. INTRODUCTION

In 1985, LCR gravimeters G487 and D31 were joined in the relative gravimeter measurements for the absolute gravimetric campaign in Sèvres and most of the measurements were performed in the feedback mode of operation. In order to determine a possible non linearity and screw effect repeated calibrations with a step of 100 μgals were made at different screw positions before, during and after the campaign. Later, the same procedure was carried out with the instrument G336 in Bruxelles and Brazzaville (Republic of Congo) for the Trans World Tidal Gravity Profile.

First we reduce the calibration data using a constant factor to convert the output voltage of the feedback electronics and we eliminate the gravimetric tides and a linear drift (table 1). When we draw the resulting curve there are two effects:

1) non-linearity of the calibration due to electrostatic effects (Zhou and Van Ruymbeke, 1985), (Larson & Harrison, 1985), (Van Ruymbeke & al, in preparation). It depends only of the value of the feedback voltage.

2) screw errors $e(x) = \sum_i e_i \cos\left(\frac{2x}{T_i} + \psi_i\right)$

where X - screw position (counter unit: CU)
T_i - screw error period
e_i - amplitude
ψ_i - phase

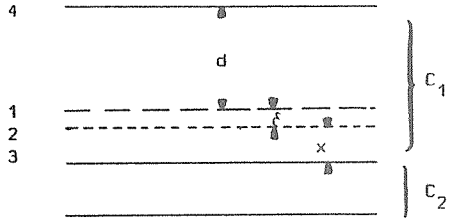
[*] Observatoire Royal de Belgique - Bruxelles, Belgium

[**] Institute of Seismology - Wuhan, Chine

We can fit a low order polynomial on the calibration data to represent the electrostatic non linearity (fig.2). The residuals will still contain the screw errors (fig.3).

2. ELECTROSTATIC EFFECTS

The gravimetric beam position in the capacitive transducer is shown



1 : middle position between the fixed plates
2 : zero position of the capacitive transducer
3 : actual position of the moving plate
4 : the upper plate
5 : the lower plate

with $\alpha_o = \delta/d$: a dimensionless null position

$\alpha = x/d$: a dimensionless displacement from α_o

2d : distance between the fixed plates

The net electrostatic force on the beam of gravity meters with feedback can be written by Larson and Harrison (1985)

$$f(\alpha) = \frac{Co}{2d}\left[\frac{V^2_{C1}}{(1+\alpha_o+\alpha)^2} - \frac{V^2_{C2}}{(1-\alpha_o-\alpha)^2}\right]$$

where $V^2_{C1} = e^2 + E^2 + V^2 + 2eE$

$V^2_{C2} = K^2 e^2 + P^2 E^2 + V^2 - 2KPeE$

$C_o = (C_1 + C_2)/2$

e and Ke are the feedback voltages

E, -PE are the biases on the two fixed plates

V is an AC plate drive voltage.

According to the definition of sensitivity of a gravimeter (Melchior, 1978), the sensitivity of the instrument to a variation of electrostatic force can be derived as follows

$$S = \left|\frac{df}{d\alpha}\right| = \frac{Co}{d}\left(\frac{V^2 C1}{(1+\alpha+\alpha_o)^3} + \frac{V^2 C2}{(1-\alpha-\alpha_o)^3} + \frac{(Ke - KpE)k}{(1-\alpha-\alpha_o)^2} - \frac{(e+E)k}{(1+\alpha+\alpha_o)^2}\right)$$

In the case of LCR gravimeters with VRL 8350 feedback system, the theoretical calibration behaviour is shown in fig.2 (a) and the experimental one in fig.2 (b).

From our experiments, we revised the calibration factor for different values of the output voltage (see table 2). With this new calibration table, the results in the Paris campaign were slightly improved for G487. However, for D31 the improvement was not sufficient to meet the accuracy requirements and we decided to reject all observations with negative feedback voltage. This behaviour is due to the fact that the K factor of D31 was smaller than the value corresponding to the quasi linear condition (fig.2b). Thus, with negative feedback voltage, the gravimeter was operating far from the flat part of the calibration curve.

The G487 and G336 have a linearity better than 10^{-3} for a range comprised between -1 mgal and + 0.5 mgal.

These characteristics are very satisfactory for microgravimetry and earth tides.

Table 2 a) Calibration factor of G487

V (v.)	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5
f (mv/µgal)	2.520	2.520	2.520	2.520	2.520	2.520

V (v.)	0	0.5	1.0	1.5	2.0	2.5	3.0
f (mv/ µgal)	2.520	2.520	2.520	2.520	2.524	2.531	2.540

TABLE 2 b) Calibration factor of D31

V	-3.2	-2.9	-2.5	-2.2	-1.9	-1.6	-1.3	-0.9	-0.6	-0.3	0.0
f (mv/ µgal)	3.213	3.200	3.183	3.163	3.149	3.139	3.129	3.115	3.111	3.105	3.100

V	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.5	2.8	3.0
f (mv/ µgal)	3.100	3.100	3.100	3.100	3.101	3.102	3.104	3.098	3.095	3.097

Table 2 c) Calibration factor of G336.

V	-4.0	-3.6	-3.2	-2.8	-2.4	-2.0	-1.6	-1.2	-0.8	-0.4	0
f (mv/ µgal)	3.983	3.982	3.982	3.981	3.980	3.980	3.980	3.980	3.980	3.980	3.980

V	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.3	3.7	4.1
f (mv/ µgal)	3.980	3.980	3.982	3.985	3.986	3.987	3.988	3.989	3.989	3.990

3. Screw errors

Using the different screw error period suggested by LaCoste (Röder et al, 1985), the 1.00, 1.625 and 0.722 CU errors were found for G336 and D31 respectively while for G487 no screw error was observed with an amplitude larger than 0.5 µgal (see table 2 and fig.3).

Table 2

meter	error period T (CU)	Amplitude e (µgal)	phase (°)
G 336	1.000	0.75 ± 0.25	133 ± 20
D 31	0.722	0.50 ± 0.26	106 ± 25
D 31	1.625	1.18 ± 0.25	32 ± 12

4. Acknowledgement

We are greatly indebted to Ing.J.F. Thimus from the "Laboratoires du Génie Civil" of the Catholic University of Louvain who accepted to loan his LaCoste & Romberg gravimeter D31 for our experiments and for the gravimetric campaign in Sèvres.

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TABLE 1

Calibration Procedure

LCR 336

86 june 24

Time	Counter Units	Output Voltage (mV)	Reduced* Value (µgal)	Drift Correction (µgal)	Corrected Value (µgal)
14 50	45585.00	-18	4034012.6	0.0	4034012.6
52	77.00	-3109	815.2	-0.2	815.0
54	78.00	-2725	814.5	-0.5	814.0
56	79.00	-2345	814.9	-0.8	814.1
58	80.00	-1962	814.4	-1.0	813.4
15 00	81.00	-1580	814.2	-1.3	812.9
02	82.00	-1205	815.9	-1.5	814.4
04	83.00	-829	817.4	-1.8	815.6
06	84.00	-444	816.3	-2.0	814.3
08	85.00	-58	814.9	-2.3	812.6

* with a constant calibration factor for the output voltage.

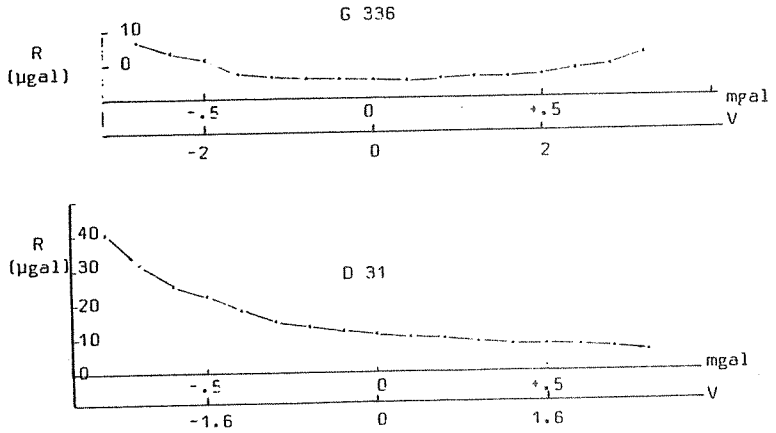


Figure 1

R: Residuals of the calibration.
V: output voltage of the feedback electronics
This curve is the mean of several experiments.

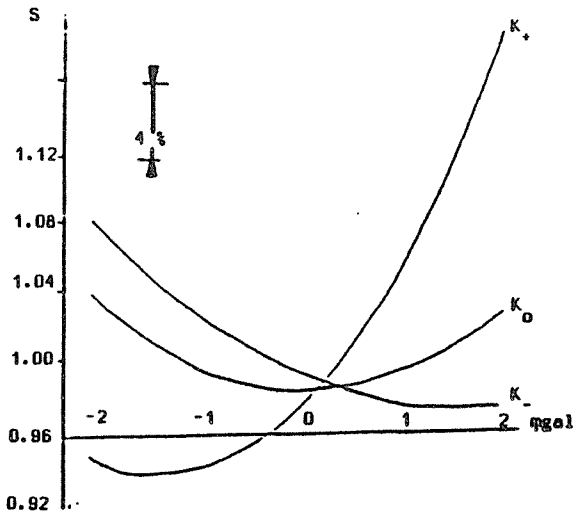


Figure 2(a)

Theoretical sensitivity curve in arbitrary units
for different values of K
K_0: quasi linear condition
$K_- < K_0 < K_+$
α_0 is put equal to zero

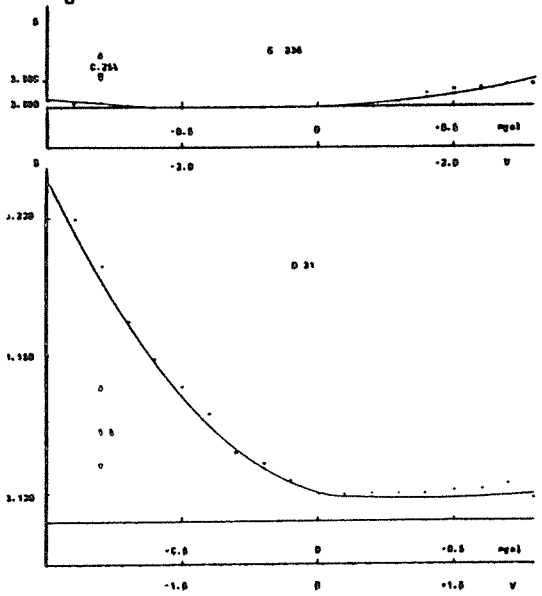
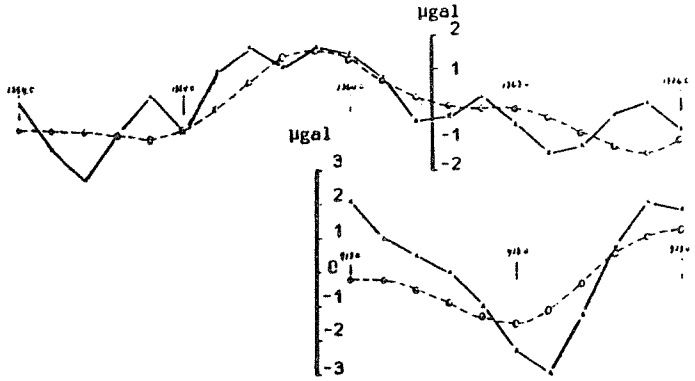
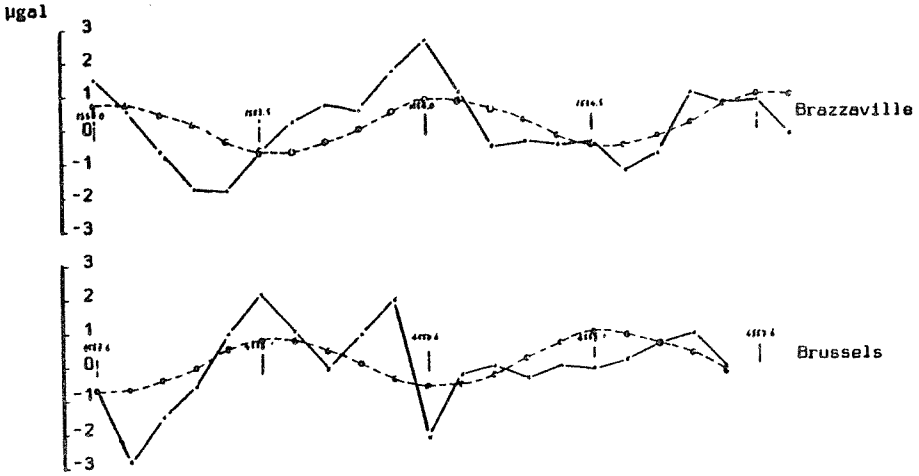


Figure 2(b)

Experimental results
The sensitivity is expressed in m V μgal^{-1}



(a) Screw errors of D31 showing 0.722 and 1.625 CU periods.



(b) Screw errors of G336 showing 1.000 CU period.

Fig.3.: Screw errors versus micrometer positions.

HIGH PRECISION GRAVITY MEASUREMENTS FOR THE DETECTION OF CRUSTAL DEFORMATION BY SURFACE LOADS

(A b s t r a c t)

S. Bakkelid+, M. Becker*, E. Groten*, B.G. Harsson+, A. Midtsundstad+

In connection with the construction of an electric power plant in the south-western part of Norway a number of small lakes have been dammed up and connected into one big water reservoir. This lake, called Blåsjø, will be the biggest man-made lake in Norway, see Fig. 1.

When it is completely filled, it will cover an area of 82,2 km^2 and store more than 3.1 10^9 m^3 water. The difference between the highest and lowest regulated water level will be 125 m.

This artificial lake will provide an unique opportunity to study the loading effect on the Earth's crust. Consequently a small steering group was formed to coordinate the research activities in this area. This group consissts of representatives from the Norwegian Water Resources and Electricity Board, Norwegian Seismic Array (NORSAR), the Seismological Observatory in Bergen and The Norwegian Mapping Authority.

The project, comprising repeated gravity measurements and levelling, tiltmeasurements and seismic investigations, started in 1985. Gravimetric tidal recordings are also planned to be included in the project.

1The gravity project which is a cooperation between the Technical University of Darmstadt and The Norwegian Mapping Authority started in 1985 with the establishment and the initial observations of the gravity net. This net covering an area extending about 10 km from the lake, consists of 8 main stations and 20 additional stations. The main stations have been chosen such that the gravity differences between them are very small (less than 0,2 mgal) in order to reduce the calibration problems. The additional stations are established at levelling bench marks and trigonometric stations. A reobservation of the net was carried out in July 1986 and the next resurveys are planned to be carried out at intervals of two years. Five LaCoste Romberg gravity meters were used simultaneously in both campaigns using car- and helicopter transportation.The duration of the project will continuously be appraised, based on the results obtained.

Two levelling profiles are established to determine geometrical deformations. The main profile following the road crossing the area in NW-SE direction is approximately 25 km long and has normaly a bench mark for each set up of, the rod. A crossing profile extending approximately 8 km in each direction from the main profile is established along road following the northwestern side of the lake. The first levelling and the connection to the Norwegian precise levelling net was carried out in 1985. The main profile was relevelled in 1986 and an entire relevelling will be carried out when the reservoir is completely filled. To monitor the tilt using precise levelling a closed loop consisting of 9 bench marks and with a diameter of 250 m, has been established. The initial observations were carried out this summer and the loop is planned to be relevelled each year during the project.

A detailed digital terrain model with a 25 m-spacing obtained by photogrammetric method is provided by The Norwegian Mapping Authority. Theoretical deformation models based on this terrain model will be compared with the observation results obtained.

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* Institut for Physical Geodesy, TH Darmstadt, FRG

+ Statens Kartverk, Hoenefoss, Norway

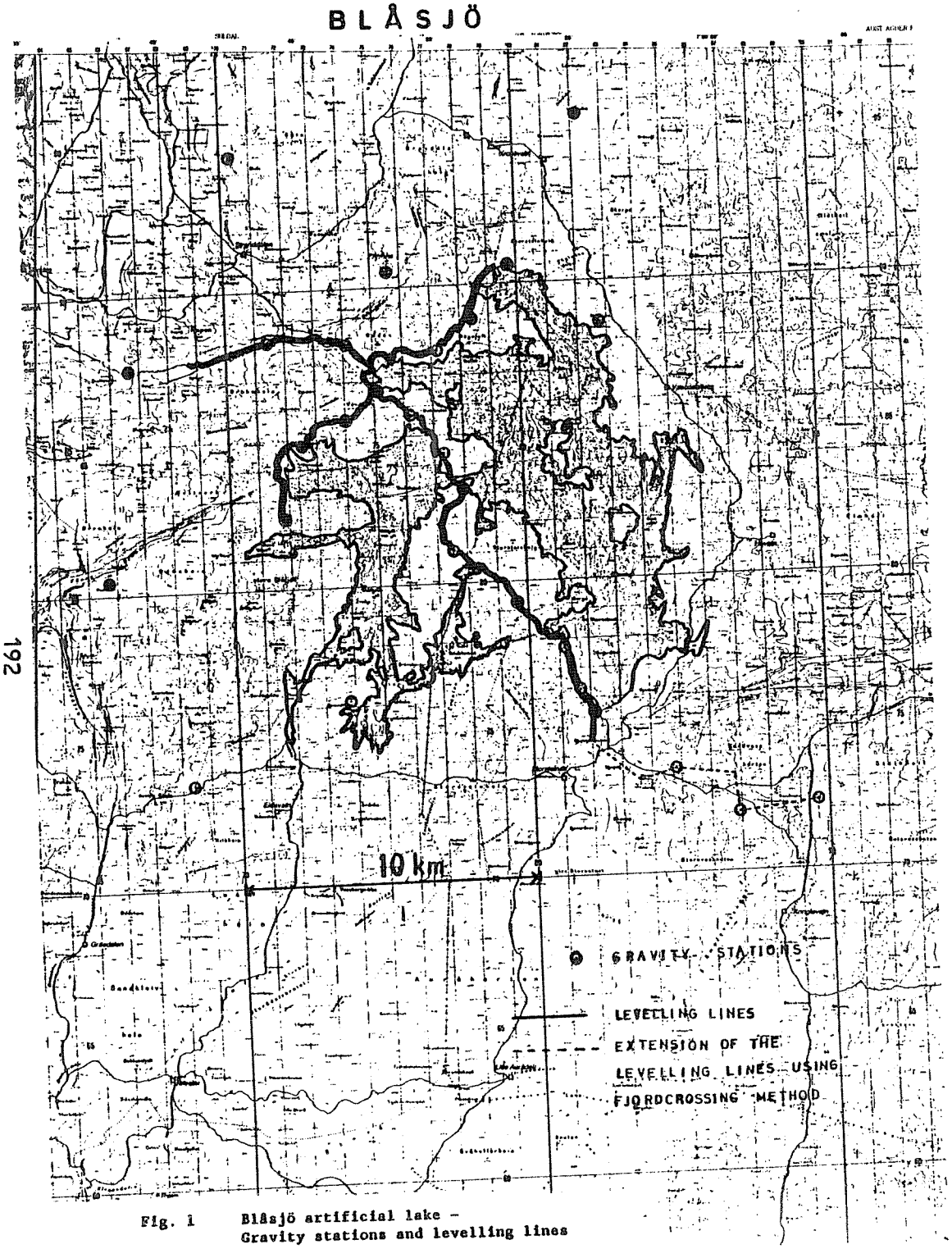

Fig. 1 Blåsjö artificial lake –
Gravity stations and levelling lines

COMPARISON BETWEEN THE THEORETICAL AND OBSERVED TIDAL GRAVIMETRIC FACTORS

DEHANT V.*, DUCARME B.**

* Chargée de Recherche, Fonds National de la Recherche Scientifique,
Institut d'Astronomie et de Géophysique G. Lemaître,
Université Catholique de Louvain,
Chemin du Cyclotron, 2
B-1348 LOUVAIN-LA-NEUVE.

** Chercheur Qualifié, Fonds National de la Recherche Scientifique,
Observatoire Royal de Belgique,
Avenue Circulaire, 3
B-1180 BRUXELLES.

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SUMMARY

According to the conventions used for tidal data analysis, we adopt here the following definition of the gravimetric factor δ : "In the frequency domain, the tidal gravimetric factor is the transfer function between the tidal force exerted along the vertical and the tidal gravity changes measured by a gravimeter". We assume that the local vertical coincides with the normal to the ellipsoid.

This definition differs significantly from what J. Wahr has assumed when he developped his theory. We have thus to recompute the theoretical values of δ. The constant term δ_0 in the representation of δ is only slightly reduced while the latitude dependant term δ_1 is divided by a factor of two (table 1).

Using the data bank of the International Center for Earth Tides we recomputed by linear regression δ_0 and δ_1 from all the available observations. We may conclude that the new value of the latitude dependant coefficient δ_1 fits very well the observations. However the computed constant part δ_0 is still lower than the one deduced from the observations, but the discrepancy has been reduced by a factor of two and reaches now only 0.6 %.

Tidal Gravity factor $\delta = 1 + h - \frac{3}{2} k$

Liquid Core Resonance effects, Coriolis force and flattening effects

Theoretical formulas

Semi diurnal waves $\delta = \delta_0 - \delta_1 \frac{\sqrt{3}}{2} (7 \sin^2 \phi - 1)$

Diurnal waves $\delta(\omega_i) = \delta_0(\omega_i) - \delta_1(\omega_i) \frac{\sqrt{6}}{4} (7 \sin^2 \phi - 3)$

Numerical coefficients

Semi diurnal wave

		Wahr (1)	Dehant (1)	Dehant (2)	Observations
M_2	δ_0	1.1599	1.1629	1.1617	1.1707
	δ_1	-0.0045	-0.0023	-0.0025	-0.0024

Diurnal waves

O_1	δ_0	1.1520	1.1543	1.1534	1.1611
	δ_1	-0.0063	-0.0033	-0.0036	-0.0026
P_1	δ_0	1.1470	1.1493		1.1545
	δ_1	-0.0063	-0.0032		-0.0033
K_1	δ_0	1.1320	1.1344		1.1440
	δ_1	-0.0062	-0.0030		-0.0034

(1) model 1066A

(2) model PREM inelastic (Zschau model for μ, calculated on the basis of PREM - Zschau and Wang 1985).

12TH MEETING OF THE INTERNATIONAL GRAVITY COMMISSION

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M. Blížkovský*, J. Ibrmajor*, S. Olejník***, J. Šefara**

GRAVITY NETWORK AND REFLECTION OF THE GEOLOGICAL STRUCTURE OF CZECHOSLOVAKIA IN GRAVITY MAPS

* Geofyzika n. p. Brno, Ječná 29a, 612 46 Brno, Czechoslovakia

** Geofyzika n. p. Brno, Geologická 18, 825 52 Bratislava, Czechoslovakia

***Geodetický a kartografický podnik, Kostelní 42, 170 30 Praha, Czechoslovakia

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M. Blížkovský*, J. Ibrmajer*, S. Olejník***, J. Šefara**

Abstract. Maintenance and updating of the Czechoslovak gravity network (CGN) and the factors limiting the measurement precision are discussed. The present stage of gravity mapping of Czechoslovakia is outlined. Simplified gravity maps of Central Europe and of Czechoslovakia are enclosed and interpreted in terms of lithospheric structures. Four basic gravity areas are distinguished in the Bohemian Massif and three in the West Carpathians, reflecting the basic differences in lithosphere.

1. Czechoslovak gravity network and its precision

Maintenance and updating of the Czechoslovak gravity network (CGN) are under way to meet the increasing requirements of geodesy and applied geophysics. The present state of the updated CGN ensures high quality of measurements (mean error in absolute level of the network — ± 0.1 μms^{-2}, relative precision of the network between neighbouring points — ± 0.1 to ± 0.2 μms^{-2}).

Updating the CGN includes

- optimization of new measurements utilizing the existing ones,
- automatic data processing and adjustment,
- evaluation of factors limiting the measurement precision,
- study of the non-tidal changes of the Earth's gravitational field.

The areal network consisting of 18 points was based on gravity measurements by a group of gravimeters of the SHARPE and WORDEN type. The network was tied to 8 points at which absolute measurements were made by the laser ballistic gravimeter.

The Helmert method was used of polygroup adjustment. The task consisted of 9216 equations of corrections and of 2910 unknowns (57 gravity values, 39 dimension coefficients and 2814 parameters of the gravimeter drift).

An original method was developed of determining the dynamic constants of the gravimeter measuring system (the attenuation constant and self-vibration period of the balance beam) from the system response to the harmonic motion of the vibration table. For each gravimeter the ranges of frequencies were established at which the index (i. e. the balance beam) is stable, but deflected from the zero position by several units of μms^{-2}, which may be the cause of systematic errors.

The response of gravimeters to natural frequencies of a high frequency range (e. g. at airports) was also studied. Deflections of the balance beam can in such cases reach a magnitude from tenths of units to several units of μms^{-2} A deflection of the balance beam can even be due to an acoustic wave (e. g. deep voice) of a considerable intensity and of a frequency approaching natural frequency. The most important results of these experiments are given in (1, 2, 3, 4).

The tests proved a correlation between gravimeter readings and changes in pressure. Experiments in the pressure chamber for the first time proved the existence of the pressure hysteresis for all ten tested gravimeters. For the pressure differences of 20 to 40 kPa the hysteresis can reach magnitudes of up to 3 μms^{-2}. This phenomenon makes the introduction of precise pressure corrections difficult (5, 6, 7).

* Geofyzika n. p. Brno, Ječná 29a, 612 46 Brno, Czechoslovakia
** Geofyzika n. p. Brno, Geologická 18, 825 52 Bratislava, Czechoslovakia
*** Geodetický a kartografický podnik, Kostelní 42, 170 30 Praha, Czechoslovakia

The existence of local non-tidal changes and of systematic errors of instruments was proved in the course of measurements of gravity differences of the order of 100 μms^{-2}, but it will have to be verified by repeated absolute measurements. The effect of a systematic error on the standardization of an instrument was convincingly proved (for the gravity difference of 500 μms^{-2} the estimation is 0.2–0.3 μms^{-2}). The estimate of the mean random error is ± 0.2 μms^{-2}. From the above analysis it follows that systematic errors can be eliminated when simultaneous measurements by a group of gravimeters are combined with absolute measurements.

2. Gravity mapping of Czechoslovakia

When the gravity mapping of the territory of Czechoslovakia was commenced in 1956, earlier measurements covering an area of 36 000 km^2 were utilized. The mapping on the remaining 102 000 km^2 was accomplished in the years 1957–1960. The density of gravity points was 1 point per 5 km^2. The gravity system in the network of the 1st and 2nd order was tied to the Postupim observatory. The normal gravitational field was then calculated using Helmert's formula (1901–1909).

The elevations of the points were determined with the mean error of ± 0.5 m. The mean error of gravity measurements was ± 5 μms^{-2}. Topographic corrections were made to the radial distance of 166.7 km. Bouguer anomalies were calculated for the uniform density of 2.67 gcm^{-3} at 56 166 points.

Maps of Bouguer anomalies were edited on a uniform topographical background on the scale of 1 : 200 000 in the Gauss-Krüger projection, system 1952. The point gravity values were interpolated with the contour interval of 20 μms^{-2}. The maps were issued under the editorship of Jaroslav Ibrmajer (8). The regional and residual gravitational field maps were derived as well as maps of second vertical derivatives for the square grids of 2 and 4 km. The geological interpretation of the main features of these maps is given in (9, 10).

The second stage of the gravity mapping of Czechoslovakia was commenced in 1958 and is expected to be completed in the 1990's. The considerably higher precision achieved for all parameters necessary for the calculation of Bouguer anomalies enables construction of resulting maps of isanomals on the scale of 1 : 25 000 with the contour interval of 5 μms^{-2}. Up to the present time two thirds of the Czechoslovak territory have been covered by new gravity measurements, in Slovakia itself it is more than 90% (Fig. 1.).

3. Gravitational field of Central Europe

An outstanding megastructure of the gravitational field of Central Europe (Fig. 2.) extends in the Alps and Carpathians. It consists of several negative zones in the West and East Alps, West and East Carpathians and the West Ukraine and continues to the South Carpathians in Romania (10). While in the Alps and West Ukraine the negative anomalies are mostly due to an increased thickness of the Earth's crust (double) at the contact of the African and European lithospheric plates, in the West Carpathians the negative gravity anomaly is assumed to be mainly due to a supracrustal source (11).

The gravitational field of the Bohemian Massif is characterized by a zonal pattern of positive and negative areas of the NE–SW direction.

The gravitational field does not correlate with the Moho discontinuity. It can be explained by the presence of density inhomogeneities in the upper part of the Earth's crust whose gravity effect is often compensated by the inhomogeneities in the lower part of the Earth's crust or in the upper mantle.

The anomalous zones of the Polish platform are oriented predominantly from NW to SE and are generally more extensive and more elevated than the zones in the Bohemian Massif.

An increased level of the gravitational field can also be observed in the Saxothuringicum and Rhenohercynicum, but the anomaly pattern in those regions is more complex. The similarity of the levels of gravitational field on one

hand and the difference in the crust thickness (25 to 30 km in the Saxothuringicum, 30 to 50 km in the Polish platform) on the other lead to an assumption that the structures differ in the lower stages of lithosphere. These conclusions hold for the Pannonian basin as well.

More advanced analyses of the gravitational field must exploit all known geological data as well as results of other geophysical methods. The data were used in two ways:

a) The bulk density values from defined geological structures are used to calculate geological corrections of the gravitational field. The result are stripped gravity maps (12, 13) – figs.3 and 4. They can be interpreted in a common way.

b) The known data (results of the DSS) are used in modelling density cross-sections and in 3D density modelling (14). Thus the solution of the inverse gravity problem can yield more reliable results.

4. Lithospheric structures of the Bohemian Massif derived from gravity data

On the basis of Fig. 4. prominent gravity areas (Fig. 5.) were defined (10, 15, 16).

O – The Lusatian positive area of the Bohemian Massif on the territory of GDR (Lindner 1972)
I – The extensive gravity low of the Krušné hory Mts. and the Krkonoše Mts.
II – The Barrandian – Železné hory Mts. – Broumov positive gravity area
III – The Moldanubicum – Kłodzko negative gravity area
IV – The Moravia – Silesia gravity high

The negative gravity areas are characteristic for granitic magmatism and uplifting tendency. As a rule, the Early Paleozoic cover is not preserved. In the positive areas, on the other hand, basic massifs and abundant volcanites occur. They have a long-lasting subsiding tendency and the Early Paleozoic cover is preserved.

Quantitative interpretations by various authors have shown the predominant effects of density inhomogeneities in the upper part of the Earth's crust on the pattern of Bouguer isanomals. The effect of the Moho relief is almost negligible.

The pattern of vertical density distribution in the Earth's crust changes in the Ohře fault zone (Fig. 5.) and in the western margin of the Carpathians (the Peripieninian lineament). NW of the Ohře fault zone a deep-seated granitic body is present at the depth of 18 km (area I). Within the core of the Bohemian Massif and between the Ohře fault and the Peripieninian lineament the thickness of the upper part of the lower crust (with presumed densities of rocks of 2.8 gcm^{-3} /increases. The boundary between the lower and upper crust is uplifted in regard to adjacent areas. The Ohře fault zone as well as the Peripieninian lineament are considered to be deep fault zones extending beneath the crust.

5. Lithospheric structures of the West Carpathians derived from gravity data

The gravity effects of the Tertiary sediments of the West Carpathians in places exceed 400 μms^{-2}. Therefore, the stripped gravity map differs considerably from the map of Bouguer anomalies. On the basis of Fig. 4. three gravity areas can be distinguished:

I – The Carpathian negative area
II – The transition area of the northern slope of the Pannonian positive area
III – The northern extensions of the Pannonian positive gravity area

Area I has an uplifting tendency, while area III clearly subsides. Area II is characterized by changes of trends of movements over short distances. In result of intensive dynamic movements narrow and deep intramontane depressions originated there. There is disagreement among authors over the cause of the extended part of the gravity low in the High and Low Tatra Mts. (I, Ia). It is considered to be due to light porous sediments covered by the massif of the Inner Carpathians (11) or to a large accumulation of Alpine granitoid plutons (17, 18).

The transition area is, besides the intramontane depressions, characterized by linear gravity depressions above granitoids of different age (IIa).

The northern slope of the Pannonian positive area is characterized by a large accumulation of low density Tertiary sediments and by a reduced Earth's crust thickness.

In eastern Slovakia a gravity high extends to the flysch unit, which is difficult to explain by the present models of the Moho relief. The character of the gravity field suggests that this region belongs to the East Carpathians. Density modelling and interpretation of the deep geological structure of Czechoslovakia based on gravity data are summarized in (14) where the geophysical models of the lithospheric structures based on results of other geophysical methods are presented as well.

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1 – territory surveyed by the end of 1985

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2 – negative isolines, interval of 200 μms^{-2}

Fig. 3. Areas where the gravity effect was calculated of
1 – Neogene
2 – Paleogene
3 – Cretaceous
4 – Neogene and Paleogene
5 – Neogene and Cretaceous sediments

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(M. Blížkovský, J. Šefara et al., 1985)
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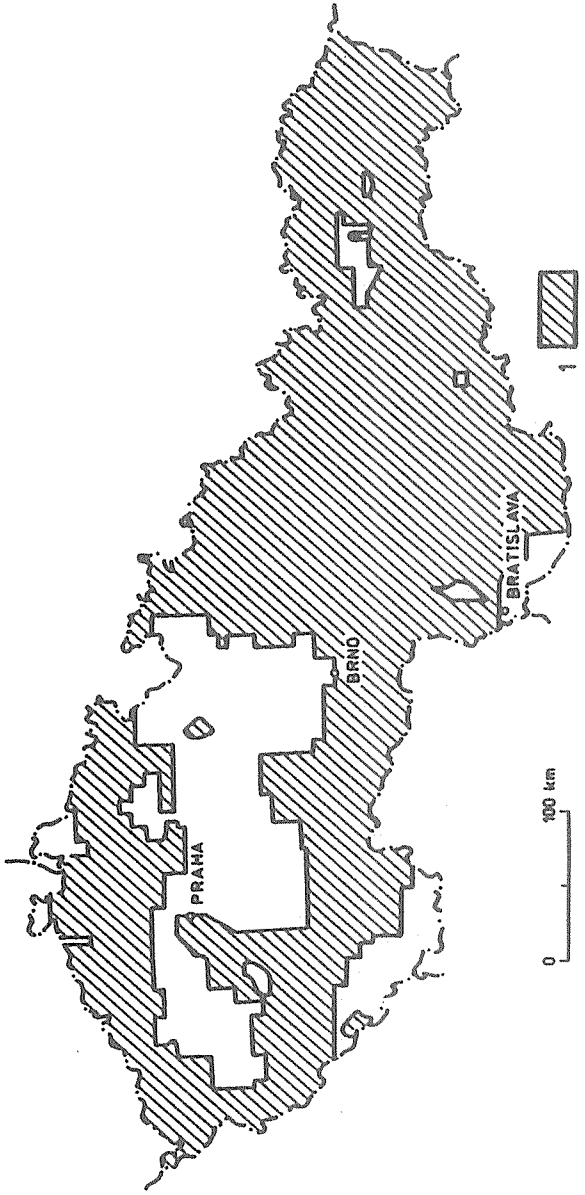
3 – thickness of the lithosphere
(V. Babuška et al., 1985)

Fig. 1.



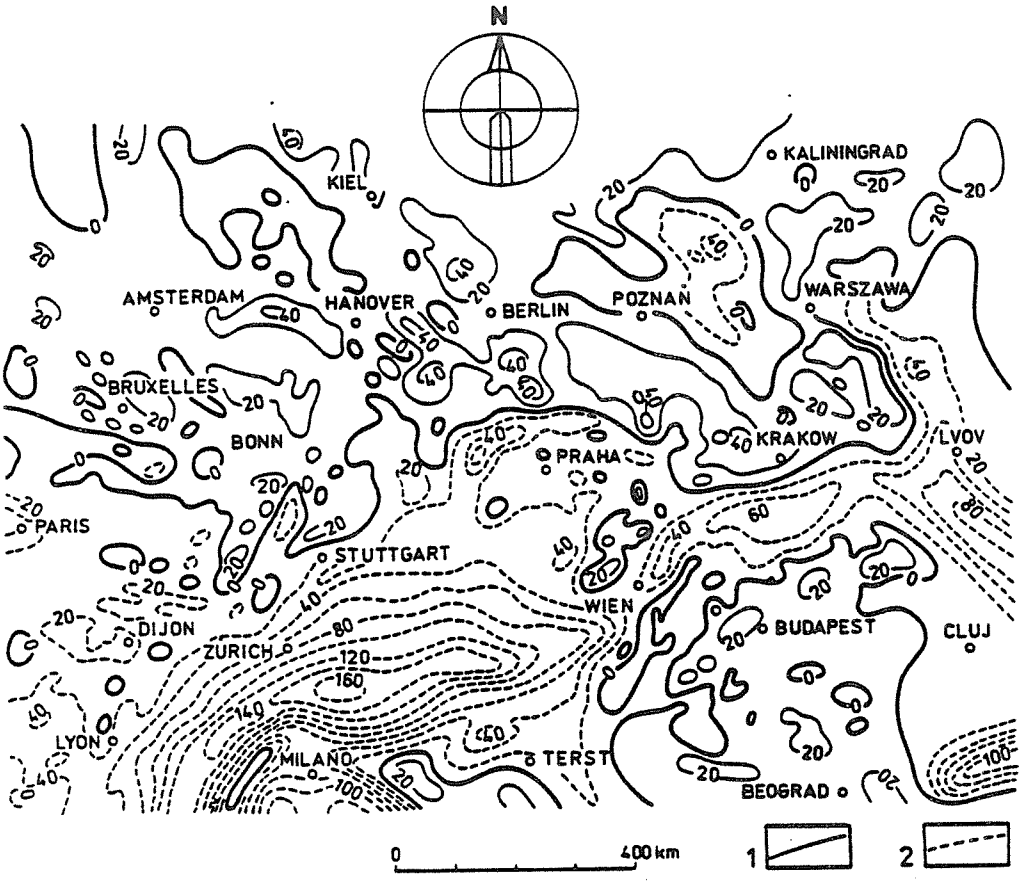

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Fig. 2.

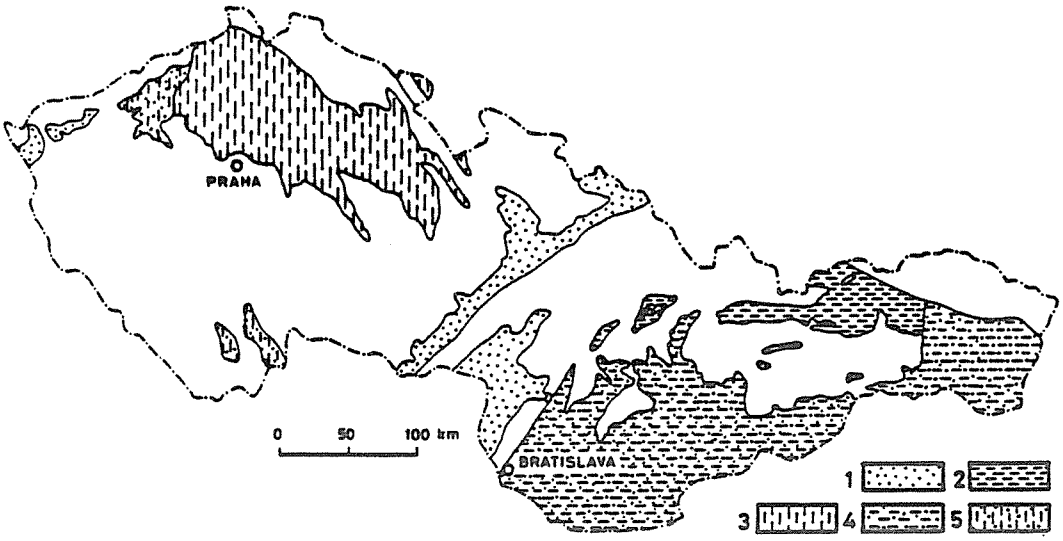
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Fig. 3.

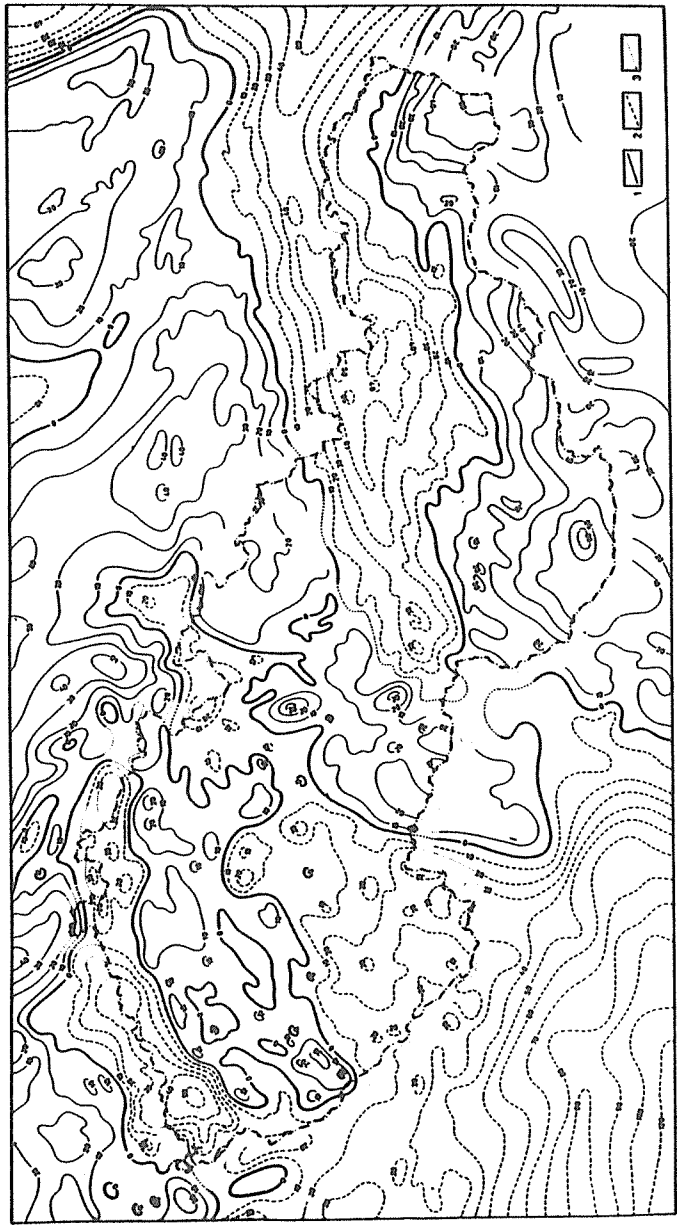

Fig. 4.

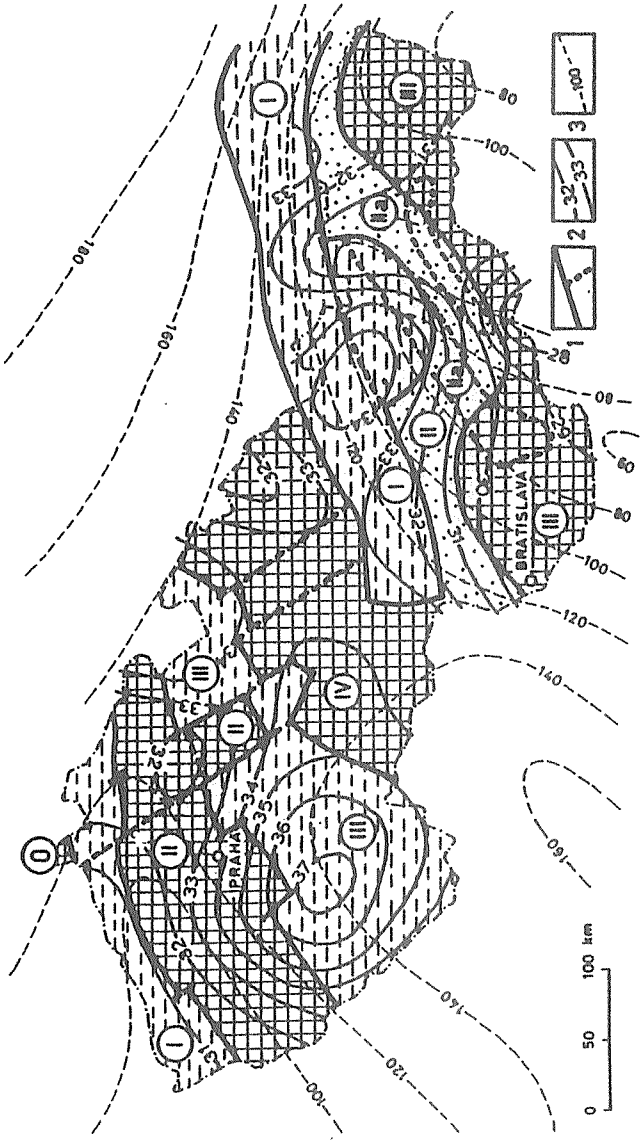

Fig. 5.

GRAVITY FIELD OF XIANG PLATEAU AND ITS RECENT UPLIFT

Jiang Fuzhen, Hsu Houtze

Xizang Plateau is a well known tectonic region in the world. We have calculated and investigated Airy-Heiskanen isostatic anomalies field, the experimental isostatic anomalies field, the thickness of the crust, the undulation of the geoid and other data in the region by using the data of gravity, astronomical-geodesic and satellite measurements and the data of topography. These results have been analysed and compared with non-tide gravity variation, the repeated levelling and the geological results. The conclusions obtained from the above results are :

1. The Xizang Plateau is a whole uplift.

2. The variational zone of the geoid height, the depth of Moho and the field of the isostatic anomalies fit very well. It is also the activity zone of the geologic structure, as well as just coincides with several fault zone.

3. The lowest points of the depression of the mantle are not in the Himalaya mountains where the highest of topography and the thickest of the crust are. It seems contrary to the traditional concept of isostatics.

4. From the observed results of the non-tide gravity variation for four years in succession, it can be seen that the Xizang Plateau uplifts continuously. It is in agreement with the results of the geological research and the repeated levelling survey in this region.

ISOSTACY IN NORTHERN BRITAIN

R.G. Hipkin

The isostatic response function has been computed from some 200 000 gravity observations in Northern Britain, a highland terrain dominated by structures older than 350 Ma. The data show definitively that (i) compensation is local, not regional, and (ii) compensation is entirely within the upper crust. Further analysis of the gravity anomaly spectrum demonstrates a further source in the lower crust but there is no evidence for a source at the known depth of the Moho. These data are consistent with a double layer lithosphere, reflecting the change from quartz-dominated rheology in the crust to olivine-dominated rheology in the mantle.

EXPLORATION GRAVIMETRIQUE DE LA BRANCHE OCCIDENTALE DU RIFT EST-AFRICAIN : LE PERIMETRE DES GRANDS LACS (BURUNDI, RWANDA, SUD-OUEST UGANDAIS, EST DU ZAIRE)

BYAMUNGU B.R[1,2] et LOUIS P.[1]

1. Centre géologique et géophysique - Place E.Bataillon - 34060 MONTPELLIER (FRANCE)
2. Faculté des sciences - UNILU - B.P. 1825 LUBUMBASHI (ZAIRE)

INTRODUCTION

La gravimétrie a joué un rôle important dans la mise en évidence des structures associées à la branche orientale du rift est-africain (SEARLE, 1970 ; SOWERBUTTS, 1971 ; FAIRHEAD, 1976 ; MAKRIS et GINZBURG, Tectonophysics à paraître...). L'étude gravimétrique que nous avons entreprise dans le périmètre de grands lacs (fig 1) et qui a comme cible la branche occidentale du rift est-africain, s'inscrit dans la même préoccupation. Elle intéresse également l'environnement du rift qui s'étend sur le Burundi, le Rwanda et l'Est de la région zairoise du Kivu.

ACQUISITION ET TRAITEMENT DES DONNEES

Pour les mesures du champ de la pesanteur, nous avons disposé d'un gravimètre Lacoste et Romberg (modèle G) et 503 nouvelles stations ont été implantées préférentiellement selon des profils transverses par rapport au rift, en s'appuyant sur le réseau des bases ORSTOM (DUCLAUX et al. 1954) que nous avons convertis dans le nouveau système IGSN71. Les altitudes des stations ont été déterminées en utilisant un nivellement barométrique calé sur les réseaux nationaux de nivellement général. Ceci a été réalisé avec 2 microbaromètres Wallace-Tiernan et les équipements des postes météorologiques des aéroports de Goma (Zaire), Bujumbura (Burundi), Kigali et Kamembe (Rwanda). Les points de mesure ont été

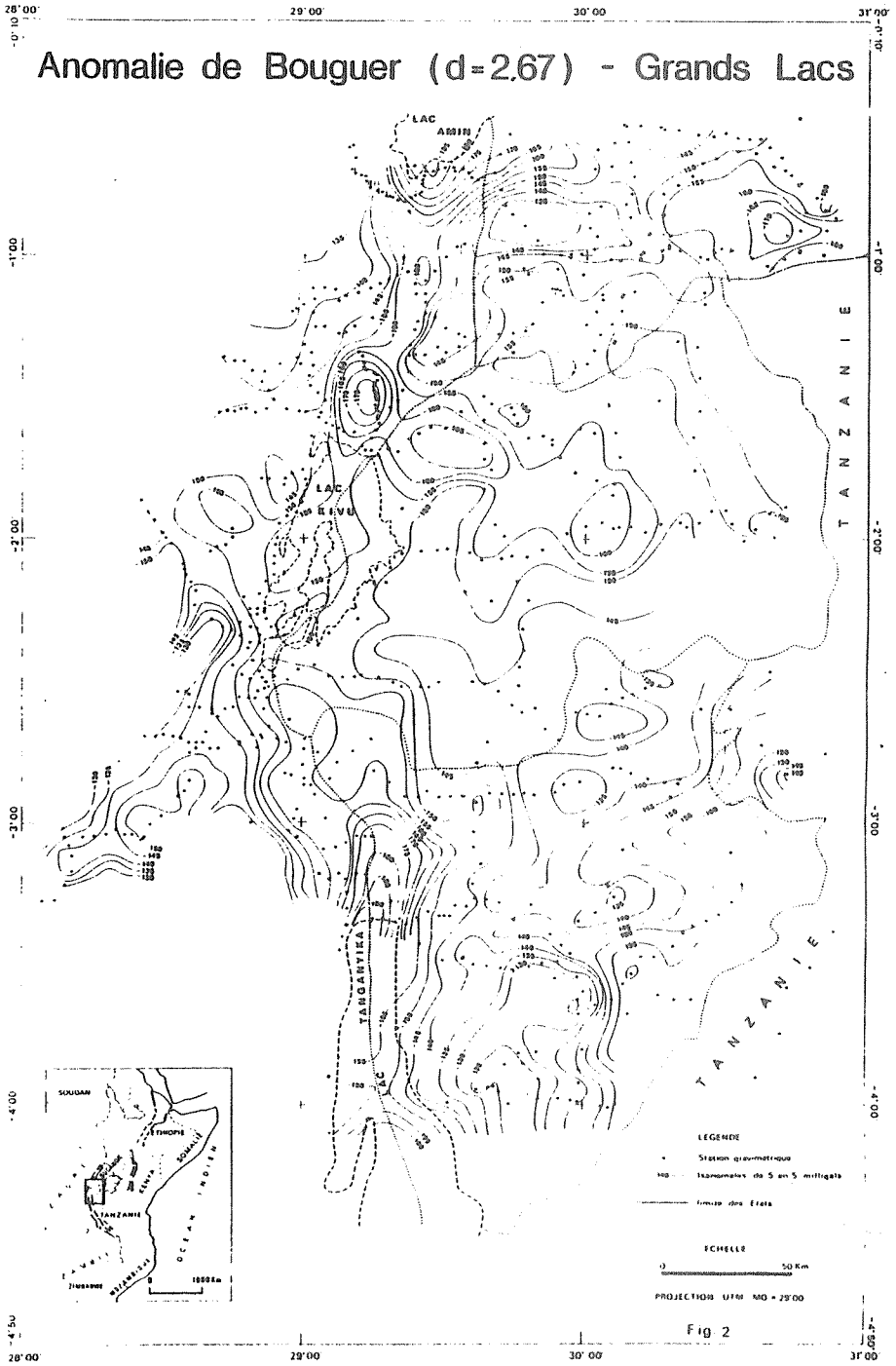

Fig 2

portés respectivement sur des coupures régulières du Kivu au 1/200000 et sur les fonds planimétriques du Rwanda et du Burundi au 1/250000 en utilisant les tracés routiers et le compteur hectométrique, préalablement étalonné, du véhicule. Ceci a permis de déterminer à posteriori les coordonnées de chaque station avec une précision suffisante.

En ce qui concerne le calcul de la correction de plateau, nous avons utilisé la densité 2.67 gcm^{-3} et l'anomalie de Bouguer a été évalué avec un champ théorique donné par le système de reférence géodésique de 1967. L'absence des cartes hypsométriques pour une grande partie du périmètre exploré n'a pas permis le calcul de la correction topographique. C'est donc l'imprécision sur la détermination del'altitude qui réglera l'importance de l'erreur sur l'anomalie de Bouguer. Or l'altitude a été déterminée avec une précision de ±4 mètres, ce qui correspond à une erreur de ±0.8 mgal environ sur un point de mesure.

Pour définir au mieux le champ de la pesanteur dans la région, nous avons complété la couverture récente par 200 points de levers antérieurs, aimablement communiqués par le Bureau Gravimétrique International et portant respectivement sur le pourtour Sud du lac Amin, le Sud-Ouest Ugandais et une petite portion de la Tanzanie. Ceci a permis le tracé de la carte de l'anomalie de Bouguer,de 5 en 5 mgals (fig 2).

QUELQUES ASPECTS DE L'INTERPRETATION

Comme pour l'ensemble des environnements extensifs de l'Est-africain, les anomalies du champ de la pesanteur observées dans le périmètre de grands lacs peuvent être rattachées à des sources de profondeurs distinctes : les sources superficielles, les sources situées à la base de la croûte et celles correspondant aux hétérogénéités du manteau supérieur.

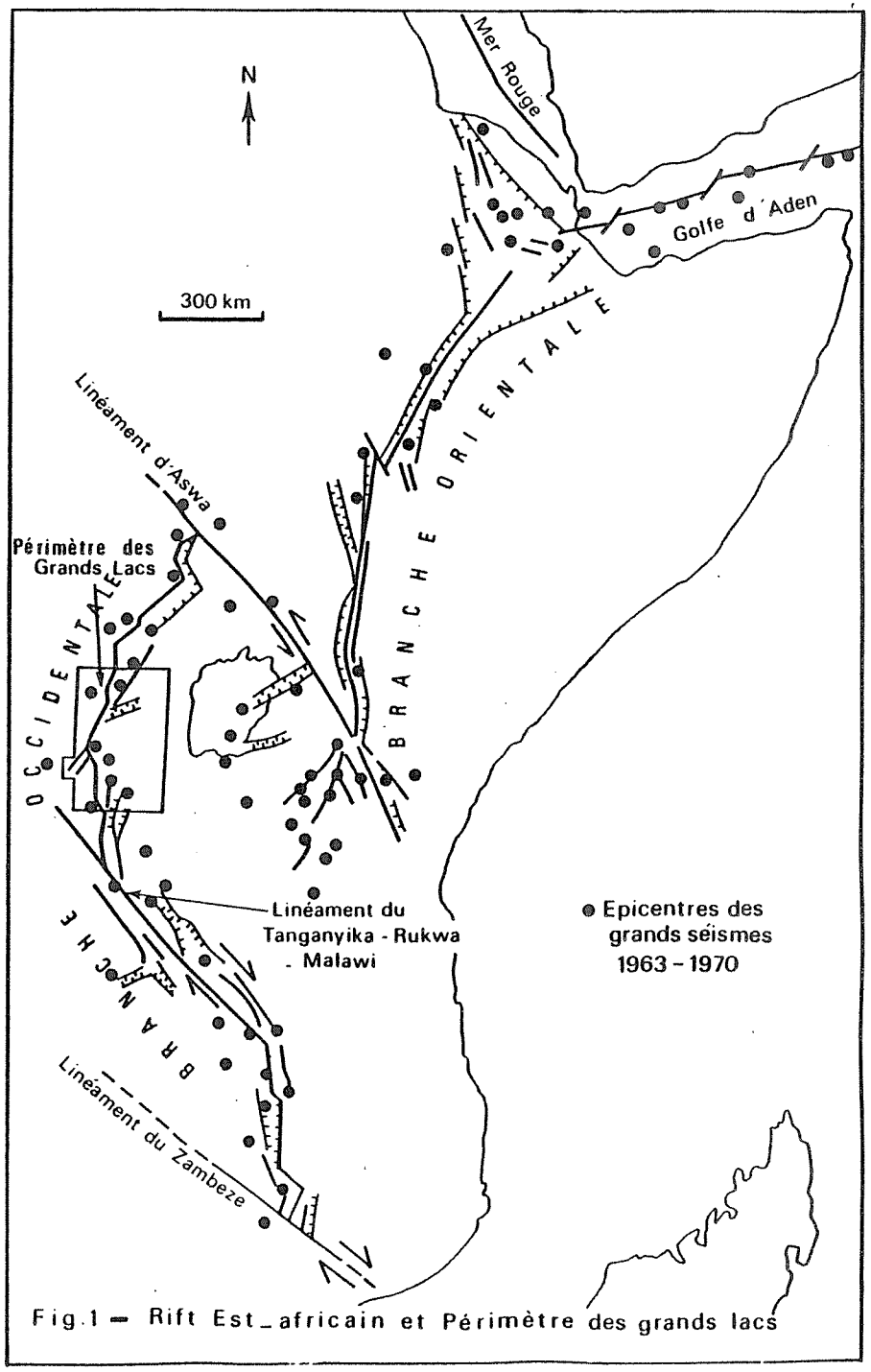

Fig.1 — Rift Est_africain et Périmètre des grands lacs

Les sources superficielles

Il s'agit de celles qui sont directement en rapport avec les structures géologiques locales ; aussi sont-elles marquées par des anomalies tout aussi localisées. A titre d'exemple d'interprétation de celles-ci, nous pouvons noter :

- Une bonne concordance, à faible distance, entre l'allure des isanomales et la configuration générale du rift en relation avec les grands accidents géologiques du périmètre des grands lacs. On notera cependant l'existence d'une différence marquée entre les anomalies de la bordure Est du rift et celles incomplètement cartographiées de sa marge Ouest. Ceci témoignerait d'une complexité géologique et structurale liée vraisemblablement au développement même du rift.

- Des anomalies positives importantes de tendance NE sur les plateaux du Burundi méridional et central. Dans l'ensemble, ces anomalies lourdes sont en relation avec un important système magmatique basique et ultrabasique, vraisemblablement controlé par la tectonique kibarienne (Précambrien moyen) et mis en évidence aussi bien par la couverture aéromagnétique (HUNTING GEOLOGY and GEOPHYSICS, 1974 ; SENGPIEL, 1981) que par la géologie de surface (RADULESCU, 1981). Si la géologie distingue divers massifs basiques et ultrabasiques isolés en affleurement dans les sédiments précambriens, ceux-ci ne correspondent pas toujours à des signatures gravimétriques distinctes. Seule l'importance des anomalies de la pesanteur qui couvre ce domaine fortement densifié par de nombreuses enclaves basiques permet de supposer l'existence à faible profondeur d'énormes masses lourdes dont seules les manifestations de surface sont connues par la géologie. La structure lourde correspondante et qui rend compte des anomalies observées aurait pour un contraste de densité de + 0.2 gcm^{-3} , une largeur de 45 km et une épaisseur maximale de 2.1 km.

- D'importantes anomalies négatives de la zone axiale marquant non seulement les laves superficielles du Virunga occidental mais aussi les structures sédimentaires de la Rwindi (pourtour Sud du lac Amin) et de la Basse-Ruzizi (pourtour Nord du lac Tanganyika). L'anomalie observée dans le Virunga occidental fait partie d'une structure gravimétrique transverse par rapport au tracé du rift et qui se poursuit jusqu'au Rwanda où elle est associée aux granitoides qui affleurent largement au Nord-Est du lac Kivu (MRAC et SGR, 1981). Il serait donc logique d'envisager l'interprétation de l'anomalie de la zone volcanique du Virunga occidental non pas uniquement par une structure des laves superficielles de faible densité (MISHINA, 1983) mais aussi par l'existence sous celles-ci de sources granitiques de plus grande extension. Une importante contribution de ces dernières au champ mesuré est d'autant plus justifié qu'il n'existe pas de relation apparente entre les épanchements volcaniques, certes moins épais, du Virunga oriental, et les anomalies du champ de la pesanteur. Aussi la structure gravimétrique qui couvre le Virunga occidental correspondrait à un effet conjugué d'un empilement de laves superficielles sur 1.5 km d'épaisseur pour un contraste de - 0.2 gcm^{-3} et d'un massif granitique sous-jacent de 3.5 km d'épaisseur avec un contraste moyen de - 0.1 gcm^{-3}. Quant aux structures sédimentaires de la Rwindi et de la Basse-Ruzizi, la gravimétrie permet de leur attribuer respectivement des épaisseurs maximum de 2500 et 3100 m pour un contraste moyen estimé à - 0.5 gcm^{-3} entre le sédimentaire et l'encaissant précambrien.

Les hétérogénéités profondes

Pour la modélisation gravimétrique des sources situées à la base de la croûte et celles plus profondes correspondant aux hétérogénéités du manteau supérieur, nous nous en sommes tenus à des modèles simples en admettant des valeurs raisonnables pour les contrastes de densité. De toutes manières, le manque d'information sur les valeurs réelles des densités et surtout sur leurs variations en profondeur rend illusoire la recherche de modèles plus compliqués qui ne seraient d'ailleurs pas forcément plus proches de la réalité.

En dehors des abords du lac Tanganyika, il n'existe pas de signature évidente qui puisse correspondre aux ondulations du Moho. On notera cependant qu'avec une épaisseur crustale que les informations

sismologiques permettent actuellement d'estimer à 35 km (MUELLER et NOLET, 1982), la remontée du Moho à l'aplomb du rift des grands lacs se situerait pour l'ensemble autour de 5 km, valeur d'ailleurs proposée par des approches sismologiques (BRAM, 1975), pour un contraste de + 0.3 gcm^{-3} entre la croûte et le manteau.

Quant aux hétérogénéités du manteau supérieur et plus précisement l'existence en son sein d'un diapir asthénosphérique, elles intéressent la totalité de la vaste anomalie négative qui couvre l'ensemble de l'Est-africain, depuis le bassin du Zaïre jusqu'à l'océan Indien. La profondeur de la surface de compensation qui parait la mieux convenir en fonction des hypothèses de densité calées sur les données sismologiques et gravimétriques (BRAM, 1975 ; WOHLEMBERG, 1975) est de l'ordre de 125 km. Les modèles de densité calculés avec cette profondeur de compensation et admettant un contraste de - 0.1 gcm^{-3} entre le manteau et le diapir asthénosphérique, situent le toit de ce dernier, à l'aplomb du rift des grands lacs, dans une fourchette de 49 à 60 km de profondeur suivant le secteur considéré. Ce résultat n'est d'ailleurs pas en désaccord avec les lois de vitesse qui situent les zones d'atténuation des ondes S respectivement à 60 km (BRAM, 1975) et 55 km (MUELLER et NOLET, 1982) de profondeur.

Une nouvelle approche ayant trait à la simulation de l'évolution thermique du rift par un modèle numérique d'éléments finis à deux dimensions a été conduite sur une coupe passant par la Basse-Ruzizi. Dans ce modèle de type Mckenzie (MCKENZIE, 1978) nous avons considéré un coefficient d'amincissement de 1.4 pour l'ensemble de la lithosphère en admettant succéssivement 125 km d'épaisseur pour la lithosphère initiale et 35 km pour la croûte initiale, les densités étant respectivement de 2.8 gcm^{-3} pour la croûte et 3.35 gcm^{-3} pour le manteau supérieur. En plus des états thermiques successifs de la lithosphère au niveau de la région, ceci nous a permis non seulement d'évaluer le flux de chaleur et la subsidence en tant que fonction du temps dans une évolution géodynamique, mais aussi d'obtenir pour l'état actuel du modèle des anomalies de Bouguer (calculées) comparables aux valeurs mesurées sur le terrain.

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THE PRESENT STATE OF THE EUROPEAN GEOID

Report presented in Toulouse, Sept. 25, 1986

G. Birardi

1. The setting up of the European geoid is a big enterprise. It commenced in 1975, at the Grenoble IAG General Assembly, when Levallois presented the first European geoid ; it was exclusively based on astro-geodetic levelling, and had an accuracy of 2-3 m in the heights, which was then a very good result.

Since then, there has been a wonderful progress of the geodetic techniques and devices : we have now geoidal heights with an accuracy of 20-30 cm, and we hope that in the next future they may descend to 2-3 cm. This is the goal which we would reach in the whole European and Mediterranean area ; no doubt that it is an ambitious goal, which will yet require a tremendous common effort.

2. This problem, and the related questions, were examined and discussed in the recent "Symposium on the Definition of the Geoid" which was held in May 1986 in Florence, under the patronage of the IAG. Somebody of you attended it, but the large majority was absent ; therefore I shall try to summarize here the contents and the results of this Symposium.

It was attended by the best specialists of this matter, altogether 63 scientists and technicians from 22 countries of the whole world ; there was a full presence of the 5 SSGs interested in the definition of the geoid, i.e. n° 3.88, chairman : Birardi, "Determination of the Geoid in Europe" ; n° 3.90, chairman : Tscherning, "Evaluation of Local Gravity Field Determination" ; n° 4.91, chairman : Sünkel, "Local Gravity Field Approximation" ; n° 4.92, chairman : Sjöberg, "Global Gravity Field Approximation" ; n° 5.97, chairman : Khale, "Gravity Anomalies and Geodynamics of Mountain Belts".

3. Six working sessions took place, in which the different aspects of the study of the geoid were touched.

a) The **First Session** : *Potential Models, State, Accuracies* was chaired by Sünkel. Here Rapp proposed an important new solution to degree 180 of his preceding models of the gravity field, obtained using an improved terrestrial anomaly field and the GEM L2 potential coefficients, merged with oceanic data derived from GEOS 3 and SEASAT altimetry. Papers by Bosch-Schwintzer, Sideris-Schwarz, Forsberg, all concerning the treatment of potential models, were also presented.

b) In the **Second Session**, chaired by Sjöberg, the *Computational Aspects of Geoid Determinations* were examined. In an invited paper Kearsley described the algorithms to adapt the ring integration method to find the inner zone contribution to geoid heights, and presented the results of numeric tests. Papers by Sjöberg, Denker, Wenzel, Dufour, Nagy, Groten on interesting aspects of geoid computation were presented by their authors, excepted the last two ones, which were presented by Benciolini and Kling.

c) The **Third Session**, chaired by Tscherning, was devoted to the *Present State of the European and Mediterranean Geoid* ; we shall see it later.

d) From an operative point of view the most important Session was probably the **Fourth** one *The Role of the GPS, Satellite Altimetry and Gradiometry*. Here Schwarz presented an invited paper on the possibility of obtaining relative geoid determinations from an integration of GPS-satellite and inertial data along the path of the inertial vehicle, and gave some first numerical results. Other important papers on the GPS were presented by Hein, Seeber, and Andersen ; while Knudsen and Vassiliou presented interesting reports on the combination of satellite altimetry and airborne gradiometry for the determination of the geoid.

e) The **Fifth Session** *Geophysical Aspects of Geoid Determination* was chaired by Hein. An invited paper by Sünkel presented an original spherical harmonic analysis of the topographic-isostatic potential for a generalized Vening-Meinesz model. Several important problems, based on elevated physical-mathematical developments, were presented by Barzaghi-Sanso (on the inverse gravimetric problem), by Colic-Petrovic-Alijnovic (on the Yugoslavian geoid with Moho information), by Lelgemann (geotectonic structures in the European geoid), by Peng-Fang (geophysical implications in the geoid of Northern Scandinavia), by Erker (geoid in the mountains), by Zavoti (geoid and DTM).

f) A very interesting Session was the Last one *Future Trends and Developments*, chaired by Sanso. Here the German school presented two important papers on the future of the European geoid ; the first one, by Denker-Torge-Lelgemann-Wenzel, examines the consequences of the new extremely accurate GPS data on the geoid definition, and proposes the strategies and the requirements for a new European high precision geoid ; the second one, by Torge-Wenzel, reports on the state of the GPS European traverse, and its contribution to the validation of the European geoid. Several other papers - by Heck, Carlson, Vanicek-Kleusberg, Twigg, Tscherning, Hofman-Wellenhof - present very interesting studies on the influence of geodynamic phenomena, on the combination and integration of heterogeneous geoid information, on the merging and mutual influence of data in neighbouring areas, on the opportunity of better unifying the European data and data treatment.

All the papers, and the related comments and discussions, will be collected in the Symposium Proceedings, which will be probably publicated within this year.

4. In the closure Session the following Recommendations of the Symposium were discussed and carried :

I - The Symposium, **recognizing** the significant work and contributions of many Study Groups, particularly of SSG n° 3.88, for the determination of the geoid ; and **considering** the increasing importance of the high-resolution determination of the geoid ; and **recognizing** that such determination is needed both on a global and regional scale,

suggests

that the IAG form a "Commission on the Geoid Determination" that would consider :

a) the theoretical and numerical aspects of the geoid estimation,
b) the actual determination and evaluation of the geoid based on national efforts and international cooperation.

II - The Symposium, **recognizing** the availability of high precision relative coordinate information coming from GPS observations,

recommends

the use of these data for the verification and the improvement of geoid determinations.

III - The Symposium, **recognizing** the progress which has been obtained in performing the North-South European GPS traverse in Central and North Europe, proposed by Recommendation n° 7 and 10 in the 1984 Paris meeting

recommends

that extension of the work be continued to South Europe as soon as possible.

IV - The Symposium, **recognizing** the importance of high-resolution digital terrain models, appropriate for the precise determination of the geoid,

recommends

that responsible Agencies estimate and make available such models for scientific purposes.

Particularly important is the first Recommendation ; it should be taken into serious account, yet more considering that with the Vancouver General Assembly the main SSGs interested in the definition of the geoid will close their life.

Here in Toulouse I was informed by Pr. Torge that the setting up of this Commission will probably meet some difficulties in the high spheres of the IAG. This is well comprehensible, a Commission is a big job ; however, the only important thing is that the works for the definition of the geoid go on, and I am sure that the IAG will find the right solution for this problem.

5. In these 11 years, since Grenoble, the work for the European geoid has gone on in a very effective way, due to the efforts of many distinguished Colleagues, who have set up local and regional geoids in the largest part of the Western Europe. Also in the Eastern Europe, and in the Mediterranean Eastern and African Countries a lot of good work has been done ; unfortunately we have very scarce information on it. We sincerely hope that in a peaceful future we may better cooperate.

In Florence someones of these regional geoid determinations were presented ; by Tscherning (Nordic Countries), Sünkel (Austria), Benciolini et a. (Italy), Livieratos et a. (Greece), Yalin (Turkey), Strang Van Hees (North Sea), Bürki (Switzerland). It is remarkable that the most advanced ones are based on the combination of several kinds of data, such as gravity, altimetry, astro-geodesy, satellite ; it is also to be stressed the increasing importance of gravity data in geoid determination, and this is one more reason for a closer contact between the gravity people and the geoid people.

Now the problem is to merge all these regional geoids into an unique European context. Several colleagues - I remember Boucher, Lelgemann, Sanso, Torge, Tscherning - are working on it. A good dorsal bone of this context will be given by the North-South European GPS traverse, which runs from northern Norway to Sicily. The northern and central part of it - up to the Austrian border - has already been observed under the direction of Torge ; the southern part, that is Italy, will probably be completed within next year.

6. I hope that in Vancouver I may give you more complete and exhaustive information on the European geoid. Before Xmas I shall send a circular letter with my final call for news on the European geoid ; I beg the courtesy of the concerned Colleagues for a quick answer.

Thank you.

HIGH RESOLUTION RELATIVE GEOID FOR NORTHERN BRITAIN

R.G. Hipkin

Using Stokes' second method, whereby the geoid is found as a correcting undulation on the Bouguer co-geoid, a very high resolution geoid has been computed for a 100 000 km^2 area of Northern Britain. In regions of rough terrain, this method greatly improves the accuracy and resolution without the need for special densification of gravity observations. A program of geometric observations is about to start to verify the accuracy independently, but a relative accuracy of about a centimetre with a horizontal resolution of 2 km appear probable. The effect of geological and topographic features less than 10 km across can be clearly seen on the geoid map.

*FIRST COMPUTATION OF A GRAVIMETRIC GEOID OVER MADAGASCAR**

J. Rakotoary, G. Balmino

Free-air gravity anomalies computed from gravimetric measurements on land and satellite altimetry derived geoid heights have been used to determine a 15' x 15' geoid over Madagascar. The technique used a combination of Stokes integral and high degree and order (180) spherical harmonic reference model. The results await evaluation from existing astro-geodetic measurements and satellite Doppler point positions (combined with survey).

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STATUS OF AND PROGRESS REPORT ON THE NEW JILA ABSOLUTE GRAVIMETER

J.E. Faller and T.M. Niebauer

The latest results and experiences with the new JILA absolute gravimeter will be discussed. The value of g measured at JILA with our new instrument will be compared with those obtained during the past five years by other absolute instruments.

Improved Relative Gravimetric Techniques for Detecting Recent Crustal Movements in Northern Iceland

by

R.H. Röder and W. Torge

Institut für Erdmessung
Universität Hannover
Nienburger Str.6
D-3000 Hannover 1

12th Meeting of the International Gravity Commission
Toulouse, September 22-26, 1986 *)

ABSTRACT:

Improved techniques for relative gravity measurements and evaluation have been developed at Institut für Erdmessung, Universität Hannover. They include the implementation of an electrostatic feedback system at LaCoste-Romberg gravity meters, and a complete data evaluation in the field using a micro-computer. Together with geometric levelling these techniques have been employed at a repetition survey of a gravity control system established in the neovolcanic zone of northern Iceland (Krafla fissure zone), in order to further investigate the recent rifting process. Accuracy and reliability of the final gravity values could be improved through the new methods. A comparison with the results of the 1980 survey showed in general the same behavior of the vertical movements as between 1975 and 1980, but with smaller amplitudes.

*) Also presented at the 7th International Symposium on Recent Crustal Movements, Tallinn/USSR September 8-13, 1986.

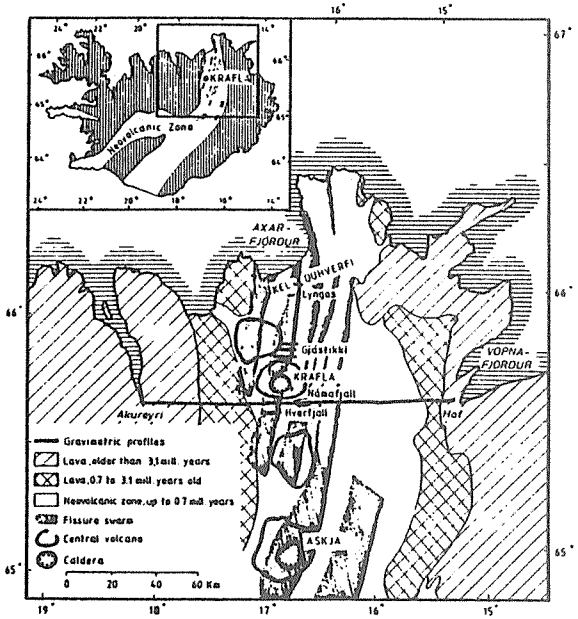


Fig. 1: Location of gravity profiles in northern Iceland

precision techniques have to be used, especially in gravimetry. In order to fulfill the corresponding high accuracy demands at the difficult environmental conditions in Iceland, a number of improvements were made in gravimetric techniques within the past 20 years (TORGE and KANNGIESER 1983). Some new developments, carried out at the Institut für Erdmessung during the last years, have been employed and tested at the 1985 Iceland survey.

3. Improvements in gravimetric instrumentation and evaluation

3.1 Gravimeter calibration

At the 1985 campaign four LaCoste-Romberg (LCR) gravimeters were employed (D-8, D-23, G-298, and G-709). A major problem is the calibration of the gravimeters. LCR gravity meters, both model D and model G, are known to suffer from longwave and shortwave (periodical) calibration errors, which can be determined on suitable calibration lines, as in the gravimeter calibration system Hannover (Table 1) (KANNGIESER et.al. 1983a).

3.2 SRW-feedback-system

The electronic SRW-feedback system was constructed for the observation of small gravity differences without using the gravimeter's screw, in order to overcome the imperfections of the mechanical system (levers, screw, gear box), but it can also be used for the determination of corresponding corrections (short periodic terms of the calibration function). Basic requirement for the installation of our device in a LCR-gravimeter is, that the instrument is equipped with a Capacitive Position Indicator (CPI). The CPI indicates small deviations of the gravimeter beam from the horizontal zero position, caused by gravity effects not completely compensated by the mechanical system. By the SRW-system the CPI output voltage is used together with a bias voltage to generate an electrostatic force which returns the beam to the zero position and holds it fixed there. The necessary feedback voltage can be made almost perfectly linear with the gravity difference by adjusting the electronics. The two parameters of a function which transforms the SRW-output voltages into gravity units can be easily determined on three stations of a calibration line.

The measuring range of the SRW-systems varies between 4 and 20 mgal, depending on the specific gravity meter. Further advantages of the system, besides of the simple calibration, are the independence of the sensitivity from gravimeter tilt, and a good output filter (damping 65 dB/decade, 30 sec delay time). Especially under the unfavourable environmental conditons for high precision gravity surveys in Iceland, these measures both helped to increase reading accuracy and to reduce the measuring time significantly.

3.3 Program system 'GRAVITY'

For a complete data processing and evaluation of gravity measurements already during fieldwork, the program system 'GRAVITY' was developed for the micro computer Hewlett Packard 9816. Programming language is HP-Basic 3.0. The system contains the routines 'GRAVITY', 'DATAIN', 'PREPRO' and 'ADJUST' and needs several DATAFILES.

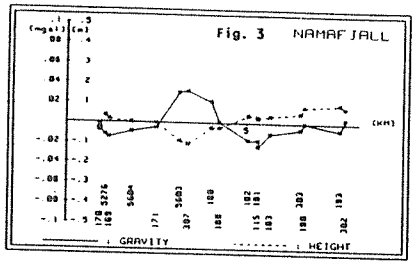
observations also suffer from calibration uncertainties and errors caused by transportation effects (mechanical shocks, temperature variations). The standard deviation for the mean value of a single epoch is assumed to be < ±0.025 mgal. The measurements indicated, that the gravity values of Keflavik and Akureyri did not change significantly between 1965 and 1980. With respect to the measuring accuracy this is also valid for the periode 1980-1985 (Table 2).

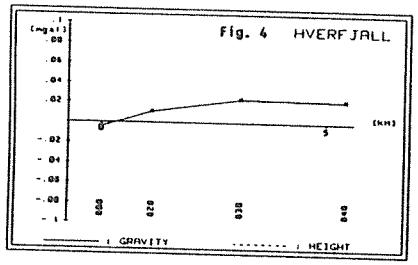
Epoche	Number of gravity meters	Number of connections	Gravity value of Keflavik [gal]	Number of gravity meters	Number of connections	Gravity value of Akureyri [gal]
1965-1980	1 or 2 per epoche	48	982.259392	1 to 4 per epoche	51	982.333382
1981	2	4	982.259373	3	6	982.333405
1985	2	4	982.259381	4	8	982.333413

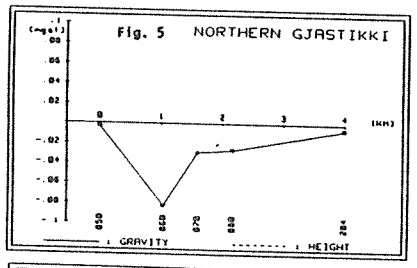
Table 2: Gravity connections Hannover-Keflavik (Hannover fixed 981.262376 mgal) and Keflavik-Akureyri (Keflavik fixed 982.259392 mgal)

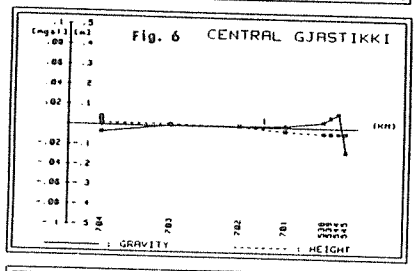
4.2 Measurements in Northern Iceland 1985

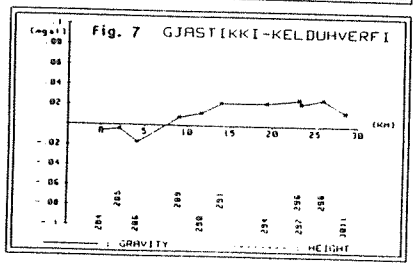
In the 1985 survey gravity and height determinations were repeated in the central part of the main profile (21 gravity stations), the Namafjall profile (20), the Hverfjall profile (4), the western parts of the Gjastikki north (5), and central (8) profile, while in the Gjastikki-Kelduhverfi profile (13) only gravity measurements were carried out. Within the profiles observations between adjacent stations were performed with four gravity meters and three repetitions. Ten stations have been selected to form a base network and were connected through additional observations in order to control error propagation. Two survey groups operated independently, using one LCR model D and one model G instrument. At the G-gravimeters the SRW-systems were used when the gravity difference was within its measuring range (G-709: nearly all measurements, G-298: half of the measurements), whereas the model D gravimeters were read in the conventional manner, but using the SRW-output instead of the CPI-output. Altogether 1400 readings were carried out, resulting in 1136 observed gravity differences. The accuracies of single observed differences have been estimated from a common adjustment. They are given in Table 3.











The stations of the central part form the Namafjall profile (Fig.3). There gravity increased up to 30 microgal accompanied by subsidence in a narrow, 1.5 km wide part. West and east of this area we find gravity decrease with correlated elevation changes. In the Hverfjall profile (Fig.4) gravity increase up to 20 microgal has been observed. In this profile height measurements were performed in 1985 for the first time. This is also true for the northern Gjastikki profile (Fig.5). There a maximum gravity decrease of 80 microgal was found between 1980 and 1985, 60 microgal of which already occured between 1980 and 1981 (TORGE and KANNGIESER 1983). East of this minimum gravity decreased by 30 microgal in two stations. For the central Gjastikki profile (Fig.6) no significant gravity and height changes could be detected between 1980 and 1985 except of a local gravity decrease of 25 microgal in a single station, which also occured already between 1980 and 1981. The Gjastikki-Kelduhverfi profile (Fig.7) is characterized by small gravity decrease in the southern part (northern Gjastikki region) and gravity increase up to 25 microgal in the northern part.

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SECULAR CHANGES OF GRAVITY OBSERVED IN KINKI DISTRICT, JAPAN

Mikio SATOMURA
Institute of Geosciences, Faculty of Liberal Arts, Shizuoka University,
Shizuoka 422, JAPAN

Ichiro NAKAGAWA, Hironori TSUKAMOTO, Toshihiro HIGASHI
Geophysical Institute, Faculty of Science, Kyoto University, Kyoto 606, JAPAN

Yoichi FUKUDA
Department of Earth Sciences, Faculty of Science, Hirosaki University,
Hirosaki 036, JAPAN

and

Kajuro NAKAMURA
Regional Observation Center for Earthquake Prediction, Faculty of Science,
Kyoto University, Takatsuki 569, JAPAN

Abstract

Gravity measurements have repeatedly been carried out in the area around Lake Biwa since 1971 in order to detect the secular change of gravity. Another precise gravity measurement has also been carried out along the levelling route in Kii Peninsula since 1972.

The gravity change obtained there was not in a good correlation with the vertical movement obtained from levelling surveys, but it was with the movements obtained from the observations of water level and oceanic tides. The gravity increase was found at the tip of the Kii Peninsula, and this may be partly explained by the areal contraction caused by the push of the Philippine Sea Plate.

1. Introduction

We started an investigation for detecting the time change of gravity in the area near Kyoto in 1971. Two areas around Lake Biwa and in the Kii Peninsula were chosen in Kinki District to carry out precise gravity measurements.

We were interested in the area around Lake Biwa; first, it is close to Kyoto, and therefore the gravity measurements can be carried out easily, accurately and within a short time; secondly, in Kinki District including this area, gravity measurements had repeatedly been carried out between 1950 and 1962 by using North American and Worden gravimeters, and the results showed that gravity value had increased on the shore of Lake Biwa, but the results obtained by such gravimeters were not so accurate that they could not tell whether the gravity increase was real or not; thirdly, in this area two more precise gravity measurements were carried out in 1964 and 1967 by using LaCoste & Romberg gravimeters, but the methods of precise gravity measurements were not yet refined and such data had some questions on the accuracy to detect the secular change of gravity. We started the precise gravity measurements along the route around Lake Biwa in 1971 with LaCoste & Romberg gravimeter G-196, and they have been carried out almost every year.

Next, we paid attention to the area in the Kii Peninsula. It is not far apart from Kyoto, and in this area there is much possibility to prove that a large gravity change accompanies a large scale of crustal movements. According to geophysical studies made so far, the ground gradually subsides at ordinary times, while an abrupt uplift occurs at the times of great earthquakes, at the tip of the Kii Peninsula. Therefore, it is highly expected to measure the gravity change of a large scale in this area. In general, the southern part of the Kii Peninsula has a high gravity anomaly, while the northern part has a low one. We could, therefore, find many gravity stations with a similar gravity value all over the area. The rectilinear distance between the two

extreme stations was about 200 km in north and south. Along the levelling route of the area covering Lake Biwa and the Kii Peninsula, such first order bench marks were chosen in 1970, as gravity stations, as gravity differences from the Gravity Station of Geophysical Institute of Kyoto University (reference station in the present study and its gravity value is 979.708 gals) are smaller than 1 mgal. Besides them, the first order bench marks with the gravity value of 979.686 gals ± 1 mgal were added to the iso-gravity stations in due consideration of their distribution, in 1973.

The schematic map of the Kinki District, which includes Lake Biwa and the Kii Peninsula, is shown in Fig. 1.

Apparent secular changes of gravity were calculated from the measured data under the assumption that the gravity value at the Gravity Station of Geophysical Institute of Kyoto University has been constant during the whole period concerned. They are shown in Fig. 2 for the area around Lake Biwa and in Fig. 3 for the iso-gravity stations. The accuracy of each gravity difference is 6 - 9 μgals after 1971 for the area around Lake Biwa and it is 5 - 8 μgals for the iso-gravity stations.

2. Gravity Value at the Reference Station

The Gravity Station of Geophysical Institute of Kyoto University was used as reference station which is firmly constructed on a stable bedrock. However, it cannot be said that the gravity value at the reference station has been constant only because the fact.

We can use only the data obtained by the relative gravity measurements themselves in Kinki District in the attempt to prove the assumption that the gravity value at the reference station has been constant. First, we calculated the mean values of gravity differences from the reference station at stations in the area around Lake Biwa; at these stations ten gravity measurements were

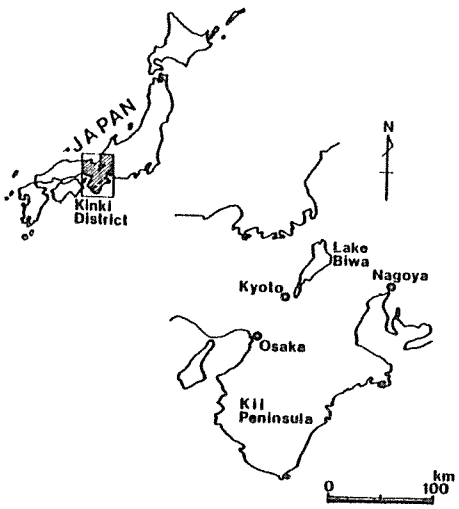

Fig. 1. Schematic map of Kinki District.

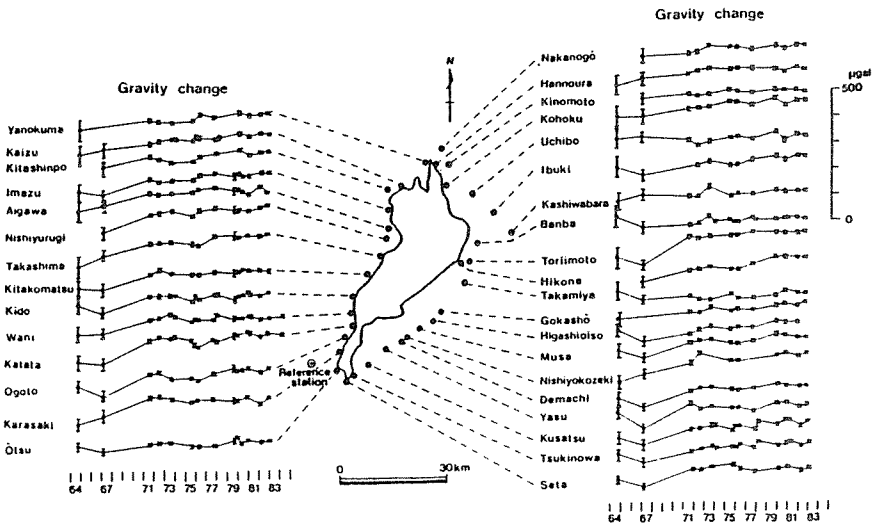

Fig. 2. Apparent secular change of gravity in the area around Lake Biwa under the assumption that the gravity value at the reference station has not changed during the whole period concerned.

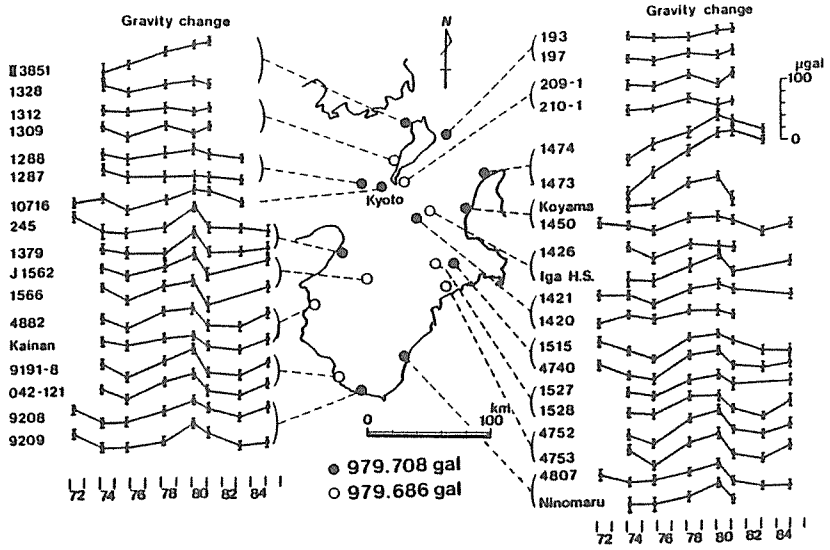

Fig. 3. Apparent secular change of gravity at the iso-gravity stations in Kinki District under the assumption that the gravity value at the reference station (Kyoto) has not changed during the whole period concerned.

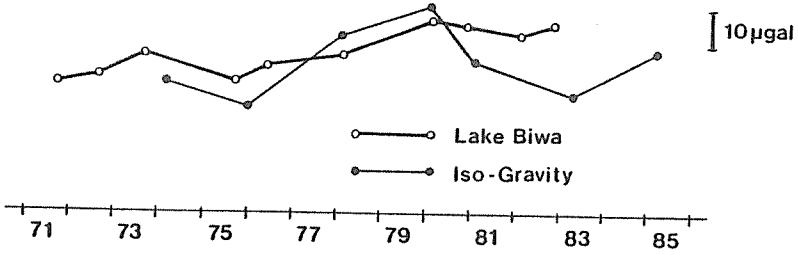

Fig. 4. Changes of the mean values of gravity differences from the reference station in the area around Lake Biwa and those of the iso-gravity measurements.

carried out during the period between 1971 and 1982. Second, we calculated the mean values of gravity difference from the reference station at stations where seven measurements were carried out as iso-gravity measurements by means of two or three gravimeters. These results are shown in Fig. 4. Two results which obtained by independent gravity measurements show the similar tendency, specially before 1981. This fact may show that the gravity values have changed in the same way in the whole area of Kinki District, but it is more probable that the gravity value at the reference station has changed in a contrary way to that given in Fig. 4.

Unfortunately, we did not have an opportunity, up to the present, to carry out precise absolute measurements of gravity in the area concerned, but we have only measured gravity differences. Therefore, we cannot discuss the common change of gravity in the whole area of Kinki District, if it exists, but we may only discuss the residual change without the common change.

We will discuss the residual change of gravity at each measured station, under the assumption that the change of mean values shown in Fig. 4 is due to the change at the reference station. The residual change is shown in Fig. 5 in the area around Lake Biwa and that obtained from the iso-gravity measurements is shown in Fig. 6.

3. Gravity Changes around Lake Biwa

The gravity change after 1971 cannot be found so clearly in Figs. 2 and 5. As the gravity measurements were carried out almost once a year during the period between 1971 and 1982, the mean rates of gravity change were estimated by the least squares method assuming that the gravity change during this period was linear to the lapse of time. Their results are shown in Fig. 7. From Fig. 7, we can briefly find out the pattern that the gravity value increased along the northern shore of the lake and decreased along both the

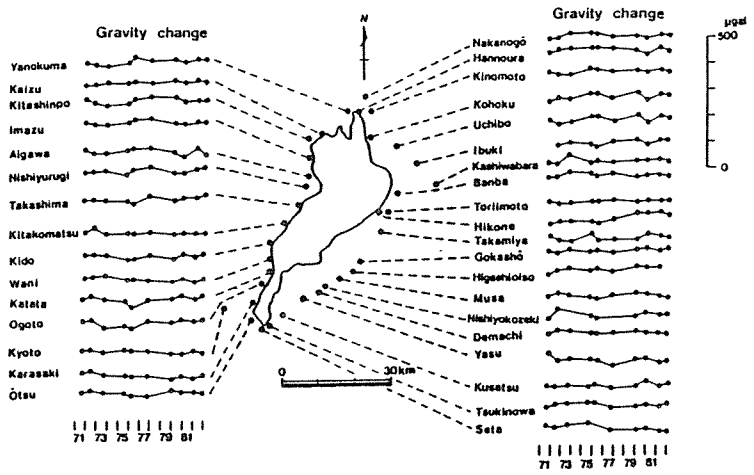

Fig. 5. Residual changes of gravity after eliminating the common change in the area around Lake Biwa.

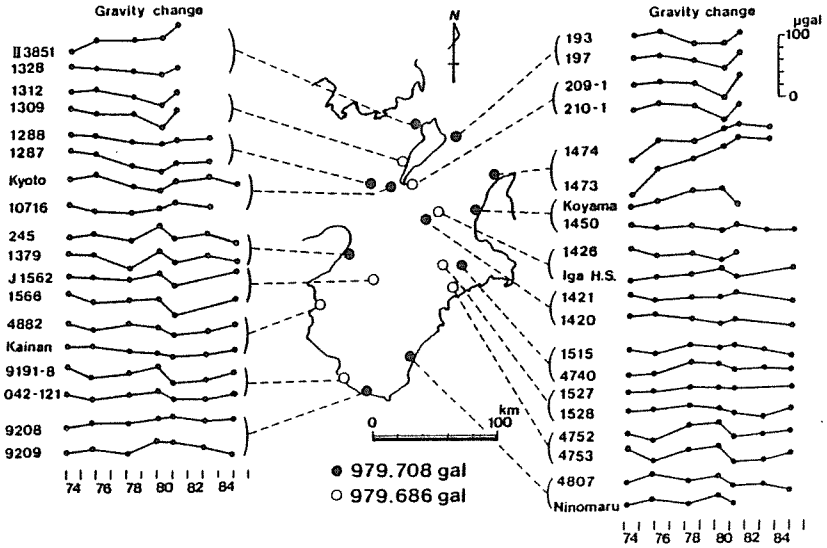

Fig. 6. Residual changes of gravity after eliminating the common change at the iso-gravity stations.

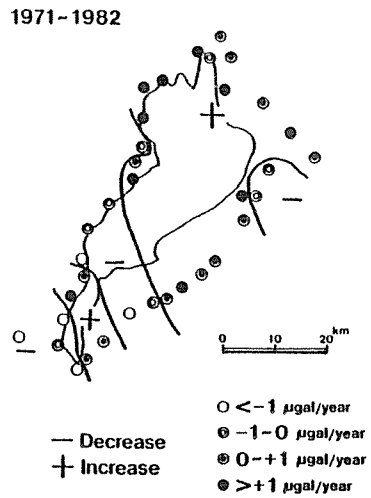

Fig. 7. Mean rates of gravity change assuming that the gravity change was linear to the lapse of time between 1971 and 1982.

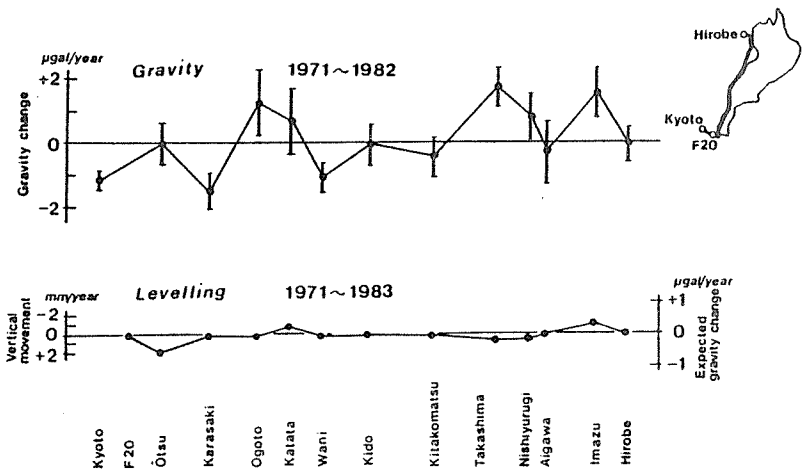

Fig. 8. Comparison of gravity change with vertical movement obtained from levelling surveys at the stations on the western shore of Lake Biwa.

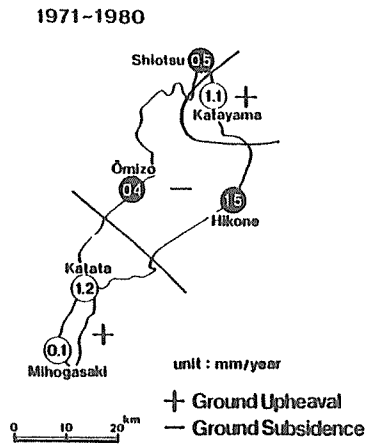

Fig. 9. Locations of water level stations and vertical movements obtained from their data. Open circle shows ground upheaval and closed one shows ground subsidence.

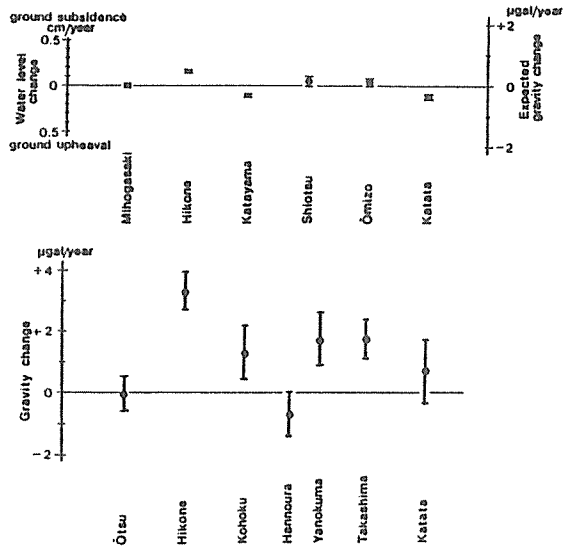

Fig. 10. Comparison of gravity change at the gravity stations near water level stations with vertical movement obtained from the data of water level.

southern and western shores.

Levelling surveys during the period concerned were carried out along the western shore of the lake in 1971, 1975/1976, 1979 and 1983. The comparison between gravity change during the period of 1971 - 1982 and vertical movement during that of 1971 - 1983 is shown in Fig. 8. It shows that the gravity change did not have the same tendency as the vertical movement.

Next, the relation between gravity change and change of water level of Lake Biwa is examined. As for the data on water level of the lake, six stations belonging to the Kinki Regional Construction Bureau of the Ministry of Construction are available. The vertical movement at each station was calculated from the monthly mean data of water level during the period of 1971 - 1980. The results are shown in Fig. 9 as well as locations of the water level stations. It shows that the ground subsided in the north area and it uplifted in the south area around Lake Biwa. It is harmony with the gravity change.

The comparison of gravity change at the gravity stations near water level stations with vertical movement obtained from the data of water level is shown in Fig. 10. The gravity change is more similar to the vertical change obtained from water level data than that obtained from levelling surveys. But the amount of the gravity change is much greater than that expected from the water level change.

4. Gravity Changes in the Kii Peninsula

The mean rates of gravity change at the iso-gravity stations were obtained by the same method as those at the gravity stations around Lake Biwa, and they are shown in Fig. 11. As can be seen from Fig. 11, the gravity increased in the southeastern part of Kinki District and decreased in the northwestern part.

Levelling surveys were carried out by the Geographical Survey Institute

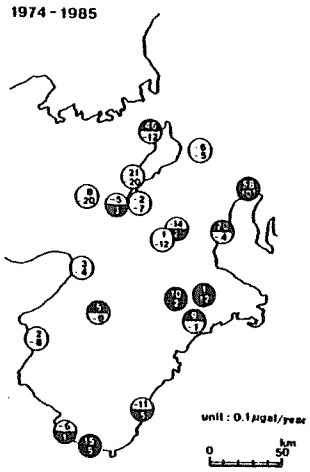

Fig. 11. Mean rates of gravity change at the iso-gravity stations assuming that the gravity change was linear to the lapse of time between 1974 and 1985.

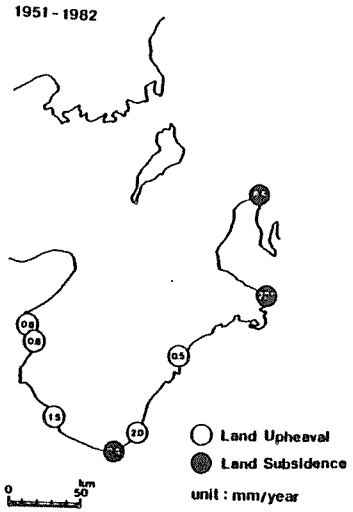

Fig. 13. Vertical displacement obtained from the data of oceanic tidal observations between 1951 and 1982.

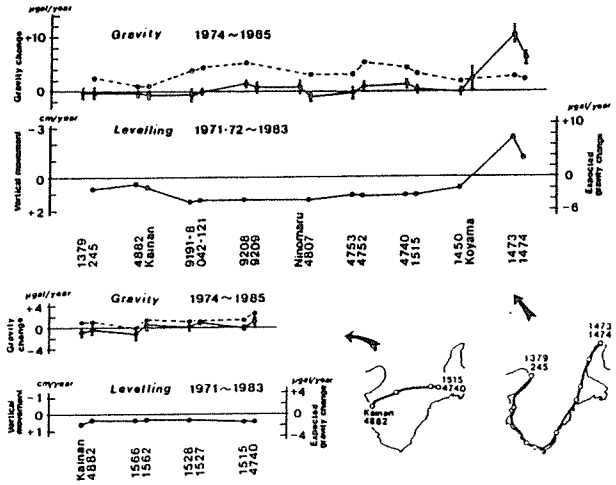

Fig. 12. Comparison of gravity change with vertical movement obtained from levelling surveys at the iso-gravity stations. Broken lines show the gravity change which is reduced the effect of vertical movement.

along the levelling routes of both the coast and inland areas of the Kii Peninsula in 1971/1972, 1979 and 1983. The comparison of gravity change with vertical movement which was obtained by the levelling surveys, is shown in Fig. 12. The gravity change shown in this figure was obtained by applying the least squares method as in the case of Lake Biwa. The correlation between gravity change and vertical movement is not so clear at almost stations. The gravity changes at both B.M. 1473 and B.M. 1474, however, are almost the same as the expected ones from vertical movements. This is the free-air change of gravity due to the ground subsidence by over pumped-up of underground water.

The vertical movement of the crust can be estimated by using the change of mean sea level. Next, we compare the gravity change with such crustal movement as that obtained by oceanic tidal observations. Oceanic tidal observations have been carried out at several stations along the coast of the Kii Peninsula. Kato and Tsumura (1983) analyzed the data between 1951 and 1982, and their results are shown in Fig. 13. They showed that Kushimoto, which is at the tip of the Peninsula, was subsiding at the rate of 0.9 mm/year, but Kainan and Wakayama, which are located at the foot of the Peninsula, were uplifting at the rate of 0.6 mm/year. These results are not similar to the vertical movements obtained from levelling surveys, but similar to the gravity changes. However, the amount of vertical movements derived from oceanic tidal observations is not enough for letting us to explain the gravity change measured.

The gravity change by the vertical movement which was obtained by the levelling surveys was reduced by free-air gradient and the reduced values are plotted with broken lines in Fig. 12. Fig. 12 shows that the gravity increased by a few μgals/year at the southern part of the Kii Peninsula. The geodetic control surveys were repeated and areal contraction of 5×10^{-7} per year was obtained in the southern and eastern parts of the Kii Peninsula. We may think

that such contraction is caused by the push of the Philippine Sea Plate. The direction of the motion of the Philippine Sea Plate is northwest relative to the Eurasian Plate near the area concerned (Seno, 1977), and the Plate subducts with a low angle from the Nankai Trough to the coast of the Kii Peninsula and the depth of its surface is about 30 km beneath the coast. The angle of subduction is steeper beneath the inland area. The leading edge reaches at the foot of the Kii Peninsula, and its depth is about 80 km (Fukao et al., 1983). The northwest - southeast cross sectional view of the Eurasian Plate and the asthenosphere under it just above the subducting Philippine Sea Plate may be assumed as drawn in Fig. 14(b).

We estimated the gravity changes obtained by the density change of 10^{-6} g cm^{-3}/year (Satomura, 1985) in the Eurasian Plate with the cross section shown in Fig. 23(b) by using the formula of Talwani et al.(1959). Their results are indicated in Fig. 14(a), showing that relative gravity increase is expected only about 1 μgal/year when the reference station is located in Kyoto. This amount is smaller than the reduced gravity change at the southern part of the Peninsula, but some parts of gravity changes may be expected to occur by the areal contraction.

The relations between gravity and elevation changes obtained at B.M. 1473 and B.M. 1474 are shown in Fig. 15. Elevation changes were calculated with the net adjustment under the assumption that the elevations at B.M. F39 (Toyoake City, Aichi Prefecture) and B.M. SF191-2 (Tarui Town, Gifu Prefecture) had been unchanged. F, B and W indicate free-air, Bouguer and water-saturated gradients of gravity, respectively. If the amount of the ground subsidence is as same as that of the pumped-up underground water, the gravity might change as the line W. The actual gravity change, however, was smaller than the expected gravity change from the line W till March 1978. Afterwards the amount of the latter was smaller than the former. This means that ground subsidence

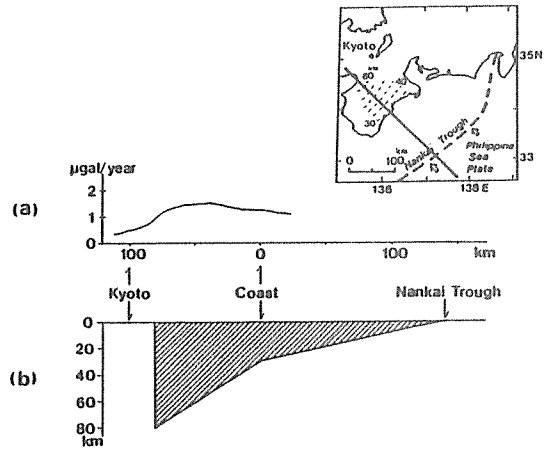

Fig. 14. (a) Gravity change estimated by the density change of 10^{-6} g cm^{-3}/year in the cross section of (b).
(b) The cross sectional view of the northwest-southeast direction of the Eurasian Plate and the asthenosphere just above the subducting Philippine Sea Plate.

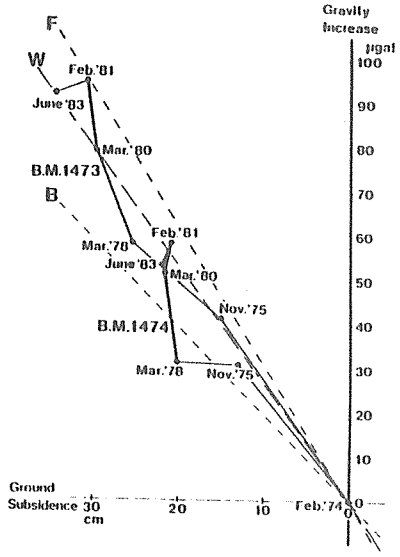

Fig. 15. Relations between gravity and elevation changes obtained at B.M. 1473 and B.M. 1474.

was greater than the amount corresponding to the volume of pumped-up underground water before March 1978. The ground subsidence had already started at about 1960, and then it may conclude that the underground water pumped up until 1974, when the gravity measurements started, caused the ground subsidence with some delay of the phase. As the regulation against pumping underground water has been put in force since January 1976, the volume of the pumped-up underground water has thereafter been getting smaller. Under these circumstances, the ground subsidence practically stopped in 1978, but gravity increase still continued until 1981. This can be explained by recovery of underground water after the regulation against pumping.

Great earthquakes whose magnitudes are greater than 8.0 occur at the interval of about 100 years off Kii Peninsula. The last one occurred in 1946, and the period when we have carried out many precise gravity measurements, was in an inactive stage of the above-mentioned cycle of earthquake occurrence. When such a great earthquake occurs off Kii Peninsula, this area should be one of the most probable areas where a great deal of gravity change is expected to be measured in Japan. The present results shall contribute as fundamental data to detect the gravity change related with seismic activity.

5. Conclusions

We have repeatedly carried out the precise gravity measurements during the period of more than 10 years in Kinki District in order to detect the secular change of gravity. Some bench marks were specially chosen for this purpose as the iso-gravity stations along the levelling routes of the area covering Lake Biwa and the Kii Peninsula.

The results obtained from the present investigations are as follows:

a) The gravity change was not in a good correlation with the vertical movement obtained from levelling surveys, but it was with vertical movement derived from the observations of water level or oceanic tides.

b) The gravity increase was found at the tip of the Kii Peninsula, and it may be partly explained by the horizontal contraction of the crust by the push of the Philippine Sea Plate.

c) The observed gravity change agreed with the expected one from the vertical movement where the ground has severely subsided because of over pumped-up underground water. This proves that the precise gravity measurement is useful for detecting a certain underground change.

It is a very great advantage that the precise gravity measurement can directly connect two stations which are located far apart. The levelling survey cannot realize this advantage, while the oceanic tidal observation and water level one have the same advantage. It may be ascribed to this advantage that, according to the results of the present measurements, the gravity change is nearly the same as the gravity change expected from ocean tidal observation or water level one. When we take such advantage into account, a few stations must be selected carefully in a wide area and the direct measurements must be carried out between the reference and selected stations. This way of using the gravimeters is the most useful to detect the gravity change.

The results of gravity measurements through the present investigations must be the valuable and useful data in order to study the secular change of gravity in the area concerned, because the measurements were carefully performed after active discussions and many examinations about the methods of measurements and the characteristics of gravimeters. We used the same gravimeters, the same measured method and so on. We believe that a more reliable information on the secular change of gravity will be obtained within the next ten years or a little more, by repeating the similar gravity measurements with equal time interval.

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LONG TERM PERIODICAL GRAVITY CHANGES OBSERVED WITH A SUPERCONDUCTING GRAVIMETER

F. DE MEYER*, B. DUCARME**

SUMMARY :

From a four years registration period with a Superconducting gravity meter installed at the Royal Observatory of Belgium we were able to modelize the instrumental drift in order to study long period gravity changes. By instrumental drift we mean apparent gravity changes that we can physically explain by some instrumental properties. The initial drift rate was of the order of 0.15 μgal day^{-1} and is slowly decreasing.

We then introduced the long period tides, the polar motion effects and an annual component and we finally obtain residues exhibiting a white noise structure. The origin of the annual term is not yet clearly understood and could also have an instrumental origin.

* Koninklijke Meteorologische Instituut, Ringlaan 5, Brussel.

** Fonds National de la Recherche Scientifique,
Observatoire Royal de Belgique, Av. Circulaire 3, 1180 Bruxelles.

GRAVITY CHANGES 1981-6 OVER THE ATALANTI FAULT SYSTEM, GREECE

E. Lagios and R.G. Hipkin

A network of precise gravity stations was established in 1981 over the Atalanti Fault System, Greece. It has been remeasured annually, using intercalibrated LaCoste gravity meters. The method of analysis and precision of the data will be briefly discussed. Between 1982 and 1983, a 12 km section of the network bulget, apparently by some 30 cms. This "bulge" was observed by the surveys of 1983 and 1984 but had largely subsided in 1985. Differential movement was concentrated along known faults but no Earthquakes larger than magnitude 2.1 occurred there between 1981 and 1983.

*COMPUTATION OF THE GRAVITY VECTOR FROM TORSION BALANCE DATA IN SOUTHERN OHIO USING COLLOCATION**

D. ARABELOS and C.C. TSCHERNING

The method of least-squares collocation was used for gravity vector estimation from torsion balance observations in Southern Ohio. The results were very dependent on the covariance function used and on the selection of a proper signal to noise ratio. Here standard deviations of the noise of ± 7 E.U. (10^{-9} s^2) gave the best results. They were, expressed in terms of standard deviations of differences observed-predicted, ± 0".4 for deflections of the vertical and ± 2 mgal for gravity anomalies. This compares to signal standard deviation of ± 4" and ± 22 mgal for deflections and gravity anomalies, respectively.

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INTERPOLATION OF GRAVITY ANOMALIES IN SOUTHERN AFRICA

C.L. Merry

Interpolated gravity values can be used to estimate gravity corrections to levelling data, where gravity observations have not been made at benchmarks. In this paper a technique for interpolation is described which uses as a high order reference field a bicubic spline representation of mean gravity anomalies, as a first step. Further steps in the interpolation involve the use of elevation correlations and local collocation. This technique has been applied to southern African gravity data, yielding estimated gravity values at selected benchmarks. This same technique has also been used to predict (with the aid of a DEM) 1/4° x 1/4° mean free air gravity anomalies in the same region.