ASSOCIATION INTERNATIONALE DE GEODESIE

BUREAU GRAVIMETRIQUE INTERNATIONAL

BULLETIN D'INFORMATION

N° 67

Décembre 1990

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 a margin. Bars cannot be set over superscripts or extended over more than one character. Therefore angle brackets are preferable to accents over characters. Care should be taken to distinguish between the letter 0 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.

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

References. A complete and accurate list of references is of major importance in review papers. All listed references should be cited in text. A complete reference to a periodical gives author (s), title of article, name of journal, volume number, initial and final page numbers (or statement "in press"), and year published. A reference to an article in a book, pages cited, publisher' 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 arranged to that their relation to the data is clear.

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 :

(33) 61.33.28.89
(33) 61.33.29.80

Telex :

530776 F OBSTLSE

or

7400298

Fax :

(33) 61.25.30.98

BUREAU GRAVIMETRIQUE INTERNATIONAL

Toulouse

BULLETIN D'INFORMATION

Décembre 1990

N° 67

Publié pour le Conseil International des
Unions Scientifiques avec l'aide financière
de l'UNESCO
Subvention UNESCO 1990 DG/2.1/414/50

Table of Contents

Bull. d'Inf. n° 67

Part I

INTERNAL MATTER

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 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 meeting, 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 (67 have been issued as December 1, 1990, 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 :

- 65 French Francs without map,

- 75 French Francs with map.

2. HOW TO REQUEST DATA

2.1. Stations 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

70 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 mean density of 2.67 - N_o terrain correction*
44-45	*Estimation standard deviation Bouguer anomaly (mgal)*
46	*System of numbering for the reference station* *1 = IGNS 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.*
61	*Validity* *0 = no validation* *1 = good* *2 = doubtful* *3 = lapsed*
62-70	*Station number in the data base.*

(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 observations 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 nation 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 above 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* *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, Eötvös 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 of 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 of 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 worldwide
56 = Cak
57 = Canadian gravity meter, sharpe
58 = GAG-2
6.. Gravimeters for under water 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	*Eötvös 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	*Validity*
150-154	*Original source number (ex. DMA 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 :

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

where ϕ is the geographic latitude.

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

Formulas used in computing free-air and Bouguer anomalies

Symbols used :

g	:	*observed value of gravity*
γ	:	*theoretical value of gravity (on the ellipsoid)*
Γ	:	*vertical gradient of gravity (approximated by 0.3086 mgal/meter)*
H	:	*elevation of the physical surface of the land, lake or glacier (H = o at sea surface), positive upward*
D_1	:	*depth of water, or ice, positive downward*
D_2	:	*depth of a gravimeter measuring in a mine, in a lake, or in an ocean, counted from the surface, positive downward*
G	:	*gravitational constant* $(667.2\ 10^{-13}\ m^3\ kg^{-1}\ s^{-2}) \Rightarrow k = 2\pi G$
ρ_c	:	*mean density of the Earth's crust (taken as 2670 kg* m^{-3}*)*
ρ_w^f	:	*density of fresh water (1000 kg* m^{-3}*)*
ρ_w^s	:	*density of salted water (1027 kg* m^{-3}*)*
ρ_i	:	*density of ice (917 kg* m^{-3}*)*
FA	:	*free-air anomaly*
BO	:	*Bouguer anomaly*

Formulas :

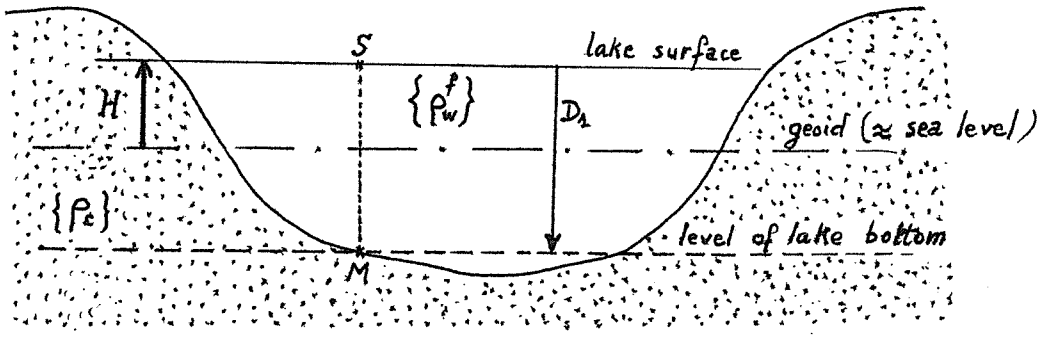
* *FA :* *The principle is to compare the gravity of the Earth at its surface with the normal gravity, which first requires in some cases to derive the surface value from the measured value. Then, and until now, FA is the difference between this Earth's gravity value reduced to the geoid and the normal gravity* γ_o *computed on the reference ellipsoid (classical concept). The more modern concept, in which the gravity anomaly is the difference between the gravity at the surface point and the normal (ellipsoidal) gravity on the telluroid corresponding point* [*] *may be adopted in the future depending on other major changes in the BGI data base and data management system.*

* *BO :* *The basic principle is to remove from the surface gravity the gravitational attraction of one (or several) infinite plate (s) with density depending on where the plate is with respect to the geoid. The conventional computation of BO assumes that parts below the geoid are to be filled with crustal material of density* ρ_c *and that the parts above the geoid have the density of the existing material (which is removed).*

---

*cf. "On the definition and numerical computation of free air gravity anomalies", by H.G. Wenzel. Bulletin d'Information, BGI, n° 64, pp. 23-40, June 1989.

For example, if a measurement g_M is taken at the bottom of a lake, with the bottom being below sea level, we have :



$$g_S = g_M + 2k\rho_w^f D_1 - \Gamma D_1$$

$$\Rightarrow \quad FA = g_s + \Gamma H - \gamma_o$$

Removing the (actual or virtual) topographic masses as said above, we find :

$$\delta g_s = g_s - k\rho_w^f D_1 + k\rho_c(D_1 - H)$$

$$= g_s - k\rho_w^f[H + (D_1 - H)] + k\rho_c(D_1 - H)$$

$$= g_s - k\rho_w^f H + k(\rho_c - \rho_w^f)(D_1 - H)$$

$$\Rightarrow \quad BO = \delta g_s + \Gamma H - \gamma_o$$

The table below covers most frequent cases. It is an update of the list of formulas published so far, which had four typing errors (for cases 2, 4, 5, 8).

It may be noted that, although some formulas look different, they give the same results. For instance BO (C) and BO (D) are identical since :

$$-k\rho_i H + k(\rho_c - \rho_i)(D_1 - H) \equiv -k\rho_i(H - D_1 + D_1) - k(\rho_c - \rho_i)(H - D_1)$$

$$\equiv -k\rho_i D_1 - k\rho_c(H - D_1)$$

Similarly, BO (6), BO (7) and BO (8) are identical.

Elev Type	Situation	Formulas
1	Land Observation-surface	$FA = g + \Gamma H - \gamma_o$ $BO = FA - k\rho_c H$
2	Land Observation-subsurface	$FA = g + 2k\rho_c D_2 + \Gamma(H - D_2)$ $BO = FA - k\rho_c H$
3	Ocean surface	$FA = g - \gamma_o$ $BO = FA + k(\rho_c - \rho_w^s)D_1$
4	Ocean submerged	$FA = g + (2k\rho_w^s - \Gamma)D_2 - \gamma_o$ $BO = FA + k(\rho_c - \rho_w^s)D_1$
5	Ocean bottom	$FA = g + (2k\rho_w^s - \Gamma)D_1 - \gamma_o$ $BO = FA + k(\rho_c - \rho_w^s)D_1$
6	Lake surface above sea level with bottom above sea level	$FA = g + \Gamma H - \gamma_o$ $BO = FA - k\rho_w^f D_1 - k\rho_c(H - D_1)$
7	Lake bottom, above sea level	$FA = g + 2k\rho_w^f D_1 + \Gamma(H - D_1) - \gamma_o$ $BO = FA - k\rho_w^f D_1 - k\rho_c(H - D_1)$
8	Lake bottom, below sea level	$FA = g + 2k\rho_w^f D_1 + \Gamma(H - D_1) - \gamma_o$ $BO = FA - k\rho_w^f H + k(\rho_c - \rho_w^f)(D_1 - H)$
9	Lake surface above sea level with bottom below sea level	$FA = g + \Gamma H - \gamma_o$ $BO = FA - k\rho_w^f H + k(\rho_c - \rho_w^f)(D_1 - H)$
A	Lake surface, below sea level (here $H < o$)	$FA = g + \Gamma H - \gamma_o$ $BO = FA - k\rho_c H + k(\rho_c - \rho_w^f)D_1$
B	Lake bottom, with surface below sea level ($H < o$)	$FA = g + (2k\rho_w^f - \Gamma)D_1 + \Gamma H - \gamma_o$ $BO = FA - k\rho_c H + k(\rho_c - \rho_w^f)D_1$
C	Ice cap surface, with bottom below sea level	$FA = g + \Gamma H - \gamma_o$ $BO = FA - k\rho_i H + k(\rho_c - \rho_i)(D_1 - H)$
D	Ice cap surface, with bottom above sea level	$FA = g + \Gamma H - \gamma_o$ $BO = FA - k\rho_i D_1 - k\rho_c(H - D_1)$

2.6. Satellite Altimetry Data

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

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

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

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

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

All requests for data must be sent to :

Mr. Gilles BALMA
Bureau Gravimétrique International
18, Avenue 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 case (massive data retrieval, holidays...) requests are satisfied within one month following the reception of the written confirmation, or information are given concerning the problems encountered.

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

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

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

The costs of the services listed below are a revision of the charging policy established in 1981 (and revised in 1989) in view of the categories of users : (1) contributors of measurements and scientists, (2) other individuals and private companies.

The prices given below are in french francs. They are effective January 1, 1989 and will be revised periodically.

3.1. Charging Policy for Data Contributors and Scientists

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

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

3.1.1. Digital Data Retrieval

. on one of the following media :
** printout..... 2 F/100 lines*
** magnetic tape..... 2 F per 100 records*
+ 100 F per tape - 1600 BPI
(if the tape is not to be returned)

. minimum charge : 100 F.

. maximum number of points : 100 000 ; massive data retrieval (in one or several batches) will be processed and charged on a case by case basis.

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

. 20°x 20° blocks, as shown on the next pages (maps 1 and 2) : 400 F each set.

. For any specified area (rectangular configurations delimited by meridians and parallels) : 1. F per degree square : 100 F minimum charge (at any scales, within a maximum plot size of : 90 cm x 180 cm).

. For area inside polygon : same prices as above, counting the area of the minimum rectangle comprising the polygon.

3.1.3. Data Screening

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

. 5 F/100 points to be screened.

. 100 F minimum charge.

3.1.4. Gridding

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

. 10 F/ΔΔ' per degree square

. minimum charge : 150 F

. maximum area : 40°x 40°

3.1.5. Contour Maps of Bouguer or Free-Air Anomalies

At a specified contour interval Δ (1, 2, 5,... mgal), on a given projection :
10. F/Δ per degree square, plus the cost of gridding (see 3.4) after agreement on grid stepsizes. (at any scale, within a maximum map size for : 90 cm x 180 cm).

. 250 F minimum charge

. maximum area : 40°x 40°

3.1.6. Computation of Mean Gravity Anomalies

(Free-air, Bouguer, isostatic) over ΔxΔ' area : 10 F/ΔΔ' per degree square.

. minimum charge : 150 F

. maximum area : 40°x 40°

3.2. Charging Policy for Other Individuals or Private Companies

3.2.1. Digital Data Retrieval

. 1 F per measurement

. minimum charge : 150 F

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

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

3.2.3. Data Screening

. 1 F per screened point

. 250 F minimum charge

3.2.4. Gridding

Same as 2.1.4.

3.2.5. Contour Maps of Bouguer or Free-Air Anomalies

Same as 2.1.5.

3.2.6. Computation of Mean Gravity Anomalies

Same as 2.1.6.

3.3. Gravity Maps

The pricing policy is the same for all categories of users.

3.3.1. Catalogue of all Gravity Maps

printout : 200 F

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

3.3.2. Maps

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

. Special maps :

Mean Altitude Maps

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

Maps of Gravity Anomalies

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

World Maps of Anomalies (with text)

PARIS-AMSTERDAM, Bouguer anomalies
(1: 1 000 000) 1959-60 65 FF
BERLIN-VIENNA, Bouguer anomalies
(1: 1 000 000) 1962-63 55 FF
BUDAPEST-OSLO, Bouguer anomalies
(1: 1 000 000) 1964-65 65 FF
LAGHOUAT-RABAT, Bouguer anomalies
(1: 1 000 000) 1970 65 FF
EUROPE-AFRICA, Bouguer Anomalies
(1:10 000 000) 1975 180 FF with text
120 FF without text
EUROPE-AFRICA, Bouguer anomalies
Airy 30 (1:10 000 000) 1962 65 FF

Charts of Recent Sea Gravity Tracks and Surveys (1:36 000 000)

CRUISES prior to	*1970*	*65 FF*
CRUISES	*1970-1975*	*65 FF*
CRUISES	*1975-1977*	*65 FF*

Miscellaneous

CATALOGUE OF ALL GRAVITY MAPS
listing *200 FF*
tape *300 FF*

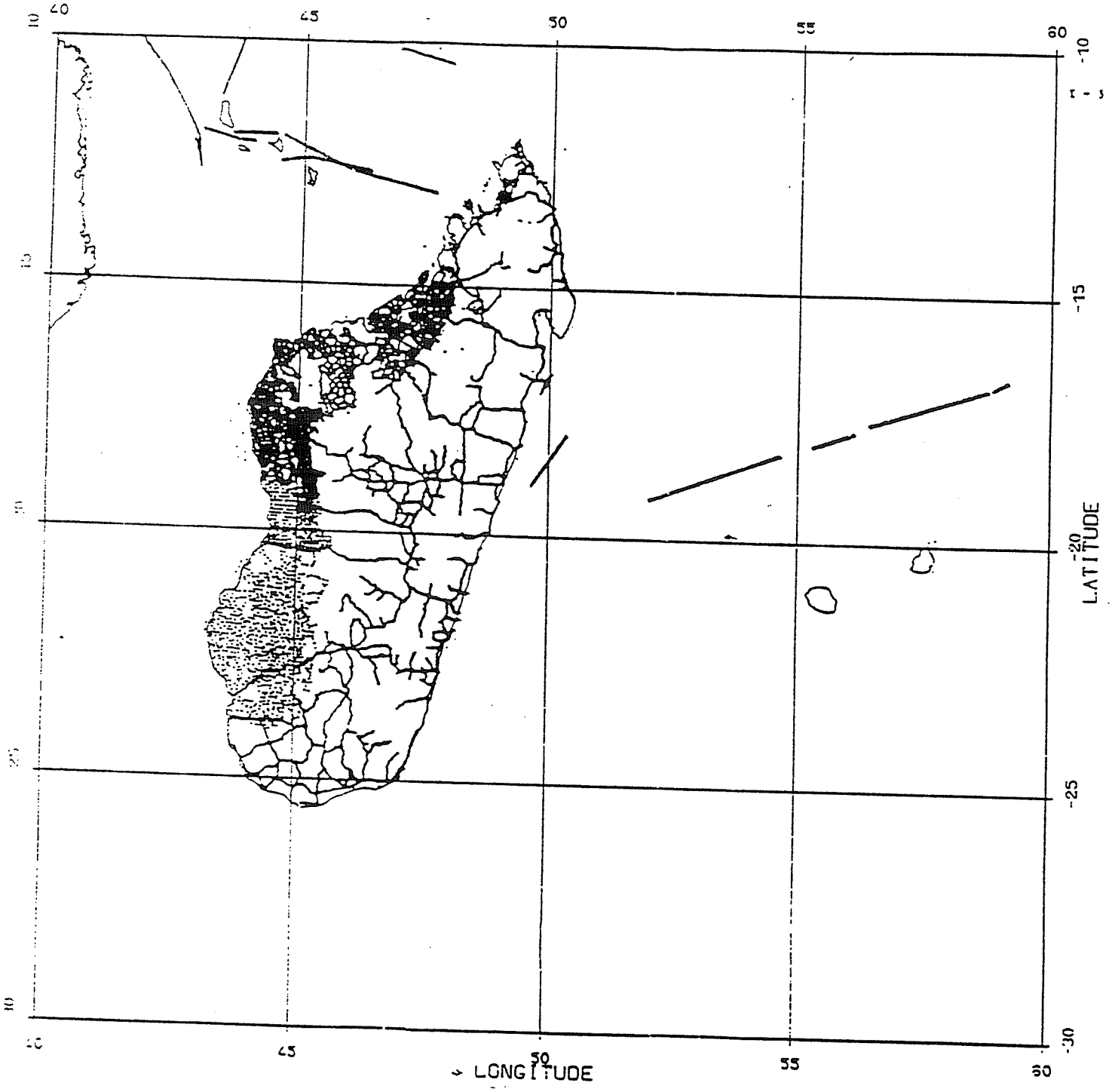
THE UNIFICATION OF THE GRAVITY NETS OF AFRICA (Vol. 1 and 2) 1979 150 FF

. Black and white copy of maps : 150 F per copy

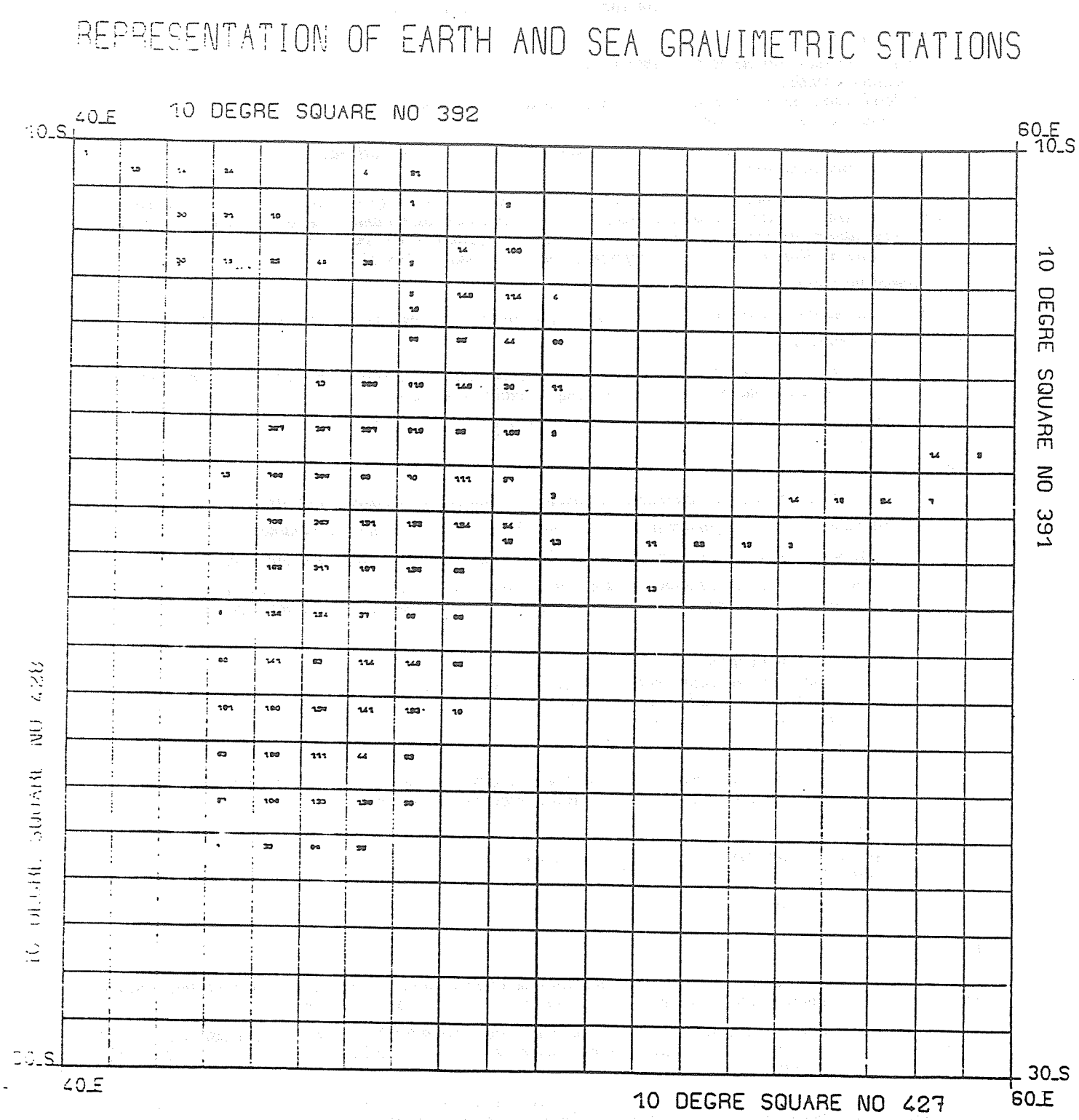
. Colour copy : price according to specifications of request.

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

Map 1. Example of data coverage plot



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



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.*

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 determining 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 bpi 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.

**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 wheter 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.

Part II

13th INTERNATIONAL GRAVITY COMMISSION

Toulouse, September 11-14, 1990

DIRECTING BOARD
OF THE BUREAU GRAVIMETRIQUE INTERNATIONAL

Toulouse, September 10, 1990
9.30 a.m. to 5.00 p.m.

AGENDA

1. Welcome and Opening Remarks ..... Tanner
2. Discussion and Acceptance of Agenda ..... All
3. Reports
   (a) International Gravity Commission ..... Tanner
   (b) Report of the Director of BGI ..... Balmino
   (c) Working Group 1 ..... McConnell
   (d) Working Group 2 ..... Boedecker
   (e) Working Group 5 ..... Poitevin
   (f) Working Group 6 ..... Boulanger
   (g) Working Group 7 ..... Wenzel
4. Status of Data Bases at BGI and Status of Software ..... Balma, Sarrailh, Toustou
   (a) Anomaly Data Base
   (b) Absolute Gravity
   (c) Others
5. Status of Software ..... Balmino
6. Services of the International Gravity Bureau ..... Balmino, Balma
7. Formal and Informal Links with Geoid Commission ..... Tscherning, Tanner
8. Membership of the Directing Board ..... Tanner, all
9. Discussion of Program of Quadrennial Meeting of International Gravity Commission ..... All
10. Officers of the International Gravity Commission ..... All
11. Membership of Working Groups - should there be limits ? ..... All
    Terms of Reference of WG 7 ..... Wenzel
12. General Assembly in Vienna ..... Tanner
    (a) Resolutions
    (b) Reports
    (c) Technical Papers
13. Other Business
14. Date and Time of Next Meeting
15. Adjourn

INTERNATIONAL ASSOCIATION OF GEODESY

COMMISSION III
INTERNATIONAL GRAVITY COMMISSION

1990 MEETING OF THE
INTERNATIONAL GRAVITY COMMISSION

TOULOUSE
SEPTEMBER 11-14, 1990

Introduction

As we get ready for this meeting of the International Gravity Commission we can look back over the last fifty years or so and can see a remarkable record of achievement by those involved in the international gravity community: a record of achievement that has been accompanied by enormous changes in terms of the standards of measurements and the impact of the computer on all aspects of processing, analyzing, interpreting and storing and retrieving gravity data. Who in the days when George Woollard and his colleagues were struggling to put together even the most rudimentary of international gravity networks would have believed that in the 1990's we could routinely think of world absolute standards with a precision of microgals (and probably an accuracy of 10 μgal or better to judge from the recent comparison of absolute gravimeters in Sèvres). Who a few decades ago would have believed that large files of gravity data within a particular region and from various sources could be brought to a common standard in a matter of hours or days, depending upon the complexity. Who would further have believed that we could produce a gravity map of a continent or a world in a matter of months and that the most difficult problems would likely be choice of colour intervals and credits. Yet these and other major advances will be a commonly accepted standard throughout the discussions that take place during this week of discussions.

Commensurate with these technical advances have been a number of changes in the way in which the Commission and its related agencies operate. For example, we now have a vastly improved International Gravity Bureau supported by five working groups responsible for assisting the Bureau in meeting the standards required of its services. These working groups in effect bring the talents and skills of individuals and institutions throughout the world to the aid of the Gravity Bureau in meeting an increasingly complex set of needs within the international gravity community. Perhaps one of the most far reaching changes in this respect is the creation of an international commission for the geoid. This commission was created in response for the need for knowledge of the geoid to an accuracy of centimetres. This leap in accuracy is a manifestation of the need for better and more detailed knowledge of the geoid both for local surveying needs and geodetic and geophysical research. Provision of the gravity data to the standards required by our sister commission will be a daunting task for both the

International Gravity Commission and the International Gravity Bureau.

The International Gravity Commission tries to keep its members in touch with developments within our field of interest through various publications, meetings and working groups. The contributions of the Chairmen of these working groups will give a synopsis of the technical priorities of the Commission and members are urged to take the opportunity to discuss problems with them and the members of their respective working groups regarding problems of common interest.

Regional Subcommissions

At the time of the last General Assembly in Vancouver questions were raised within the Commission regarding the advantages of regional sub-commissions and whether they should be retained. At the request of the Directing Board the International Gravity Commission canvassed the regional sub-commissions to obtain an expression of interest in their continuing. The response seemed mixed, some believing that there were no problems of sufficient interest regionally to warrant duplicating the activities of the central organization, others in regions where considerable activity exists suggested that sub-commissions were very helpful in dealing with regional co-ordination among the various groups. There can be no question that active regional sub-commissions allow for greater input for local organizations and in principal provide a vehicle for adapting global concerns to individual regions or national needs.

The operation (or lack thereof) is no small consideration where the activities of the working groups are concerned. Nowhere is this more evident than in the case of Working Group # 2 responsible for the implementation of the International Absolute Gravity Base Network (IAGBN). Planning for the observing campaigns could be made much simpler if a regional sub-commission could assist with the logistics and other support needed for a series of measurements. Such contributions as connections to IGSN 71 stations is a critical aspect that could be organized by the regional sub-commissions!

The ambivalent response and the undoubted advantages of sub-commissions led the Directing Board to recommend their continuation at least until the next General Assembly at which time the new executive may choose to consider this issue again.

The International Gravity Standardization Net (1971)

For some time the Directing Board has been concerned with the status of IGSN 71 as the primary world gravity standard. Shortly after its formal acceptance at Moscow, Working Group 2 made a

recommendation that, the new absolute instruments considered, there should be no new international campaigns to re-observe all or parts of the network and that no effort should be made to re-adjust this network. Instead the working group recommended that the network in effect be allowed to "grow old gracefully", gradually being replaced as a standard by new absolute measurements as national agencies developed new or re-adjusted old national networks. However, reports of the rapid destruction of sites in this network caused concern within the Directing Board with regard to the network's status within regions of developing countries. After a number of discussions within the Directing Board, a full scale review of the situation with respect to the network was held in conjunction with the General Meeting of the Association in Edinburgh.

The discussion in Edinburgh generally confirmed the earlier recommendation of Working Group 2 (then chaired by Prof. Uotila), but did emphasize the need for the regional sub-commissions to carry out an assessment of IGSN to provide the information needed to monitor the situation. Connections from new absolute stations to IGSN sites clearly are paramount if we are to avoid a situation where no absolute standards are available in some part(s) of the world. Where necessary, regional sub-commissions or other institution might be able to carry out some additional connections by asking individuals travelling to and from some area lacking an absolute gravity reference to make some additional measurements. Creative use of this latter situation could be very effective in maintaining absolute gravity standards, but carries with it the requirement for good communications. In summary, the situation is never so desperate as to be devoid of possibilities for concerted international action if the will is there.

The Edinburgh meeting took place in the context of perhaps as many as half of the stations in IGSN having been destroyed. An examination of the report of the president of the Regional Sub-Commission for North America suggests that, for North America at least, the percentage of sites destroyed is about thirty per cent - much less than the assumption of the Edinburgh meeting. If this figure holds true for the rest of the world, the situation with respect to numbers of stations destroyed may not be as bad as feared. However, the report also notes that the there are cities in which all IGSN sites have been destroyed or otherwise rendered inaccessible. If the numbers of such cities are significant, some of our worst fears about the future usefulness of IGSN in areas of rapid development may come to pass.

Instrumentation

In the past ten years enormous strides have been made with absolute instrumentation. The impressive array of such instruments that took part in the Sèvres experiment last year is testimony to the health and interest in absolute gravity instrumentation.

Particularly impressive among the absolute instruments is that designed and built by Dr. Faller at the JILA laboratory in Boulder, Colo.. Potentially capable of carrying out a precise measurement in a matter of hours this instrument is truly among the first of a new generation of transportable absolute instruments that will be a mainstay of gravity network development, the application of precise gravity to geodynamics, etc. for the foreseeable future. Recent results with this instrument suggest that it is capable of repeating measurements to a few microgals (precision) and that, if the Sèvres experiment is representative, gives results that are accurate to 10 μgal or better. As there are six such instruments being operated by institutions throughout the world, we can expect it to be a major factor in the observation of IAGBN, as indeed it has already demonstrated.

Among the relative instruments the LaCoste and Romberg continues to be the standard. Many of the LaCoste instruments that have featured prominently in recent applications in the field of precise gravity have been on the scene for a number of years (hence their performance is well understood) and have given reliable results in the range of microgals. The question for the future is whether this instrument will continue to be completely predominant in the field of relative gravimetry or will some successor come along. For example, will there be more portable versions of the cryogenic gravimeter that will compete with or even exceed the performance of the LaCoste gravimeter (as presently configured)? Will the newly developed and currently being tested Scintrex instrument find its way into the geodetic field as one of the mainstays of modern gravimetry? There can be no doubt that the cryogenic instrument can record gravity changes in the range of nm/s^2 and better. Early results from the Scintrex instrument suggest a performance that could equal or better that of presently available LaCoste instruments (should this performance be confirmed the ease of operating this instrument and its ruggedness would make it attractive to the geodetic community). Only time and experience will provide the answers to these questions, but again we can conclude that the field of relative gravimetry is indeed healthy and active and that the microgal is no longer an elusive quantity.

Regional Gravity Coverage

As we can see from the report of the Director of the International Gravity Bureau excellent progress has been made in acquiring recently observed regional gravity data sets. At the same time software developed in the last two years by the staff of the IGB has provided the Bureau with a capability of being able to process quickly regional gravity data sets: in the process adjusting them to a common datum and removing or correcting individual observations that differ significantly from those around them. An impressive demonstration of this software was given last year by the staff of the Bureau at a workshop in Toulouse - the gravity

data set from Belgium with observations numbering in the thousands was completely normalized to the IGSN standard in a matter of a few hours. This software places the Bureau at the forefront of institutions engaged in the process of normalizing ("homogenizing") regional gravity data sets.

With regard to regional mapping there seems little doubt that the pace has slowed considerably from former years. There would seem to be at least three reasons for this. First many countries have completed regional coverage with the result that their gravity mapping programs have been greatly reduced or even suspended. Second many of the areas remaining in countries still active in gravity mapping present operational problems that require more time consuming and usually far more expensive procedures. Third, stagnant budgets of surveying agencies have been eroded by inflation thus significantly reducing the resources available to carry out gravity surveys. There may be little that can be done about stepping up the pace of gravity mapping until the financial climate improves to the point where governments can feel comfortable with increasing budgets of surveying agencies. Airborne and satellite techniques clearly offer an alternative to the traditional ground and shipborne techniques, but even these developments are suffering delays due to shortage of funds.

Contemporaneous with this apparent slowing down of gravity mapping activities is the seemingly relentless advance of technology which in the case of geodesy has propelled us into the era of the centimetre geoid. Unquestionably our colleagues in the International Commission for the Geoid will require not only more closely spaced but also more accurate gravity data for their geoid calculations. Just how the national agencies associated with the International Gravity Commission will provide these data is not clear. However, we can be sure that if the need becomes critical, a way to provide the data will have to be found.

Activities of the Working Groups

The reports from the working groups at this meeting are ample testimony to the activities that have been taking place within their respective areas of responsibility. Undoubtedly the working groups are a major source of technical support to the IGB in its efforts to provide gravity data to the international community in a timely and flexible manner.

At the meeting held in Paris a complete review of the terms of reference produced an updated set of objectives for each of the working groups. The results of this review have been published in the Bulletin d'Information and the membership of the IGC will be asked to approve these at this meeting.

Summary

Changing needs, changing technology and changing times have had their effects on the international gravity community. However, one look at the technical program of the meeting can not but convince those present that this historic field of endeavour is in a healthy state. Young scientists continue to enter the field, the focus of research is adjusting to meet the needs of the user community and the breadth of research is impressive. These ingredients will in themselves almost guarantee a heathy and stimulating environment in which all of us engaged in gravity-related research can look forward to a continuing productive career in a field that is as fascinating as it is complex.

J.G. Tanner

Minutes
of the Annual Meeting of the Directing Board of the Bureau Gravimetrique International held in Toulouse, France on September 10, 1990

Present :

J.G. Tanner, Chairperson
G. Balmino
I. Nakagawa
C. Morelli
C.C. Tscherning
J.E. Faller
D. Toustou
G. Balma
M. Sarrailh
G. Boedecker
C. Poitevin
Y. Boulanger
H-G. Wenzel
R.K. McConnell

1. Dr. Tanner opened the meeting with a brief commentary on the activities of the BGI and the Directing Board over the past year.
   He noted that his term of office as President of the Commission and Chairperson of the Directing Board would expire in 1991. He recommended that the Directing Board make a recommendation to the nominating committee for the next president of the Commission. He also stressed the need for the Directing Board to give careful consideration to the framing of resolutions for presentation at the IUGG General Assembly meeting in Vienna in 1991.
2. There was a wide-ranging discussion of a number of concerns and issues affecting the BGI. The main points are summarized below.
   (a) The Working Groups have been generally effective in mobilizing resources in the scientific community to assist BGI, particularly with respect to the acquisition of new software.
   (b) Acquisition of regional gravity anomaly data seems to have slowed throughout the world in recent years largely due to a decrease in the availability of resources for mineral exploration.
   (c) The main objective of the BGI should be to deliver quality data quickly.
   (d) It is important to advertise the services of BGI to the geophysical community as well as to its traditional clientele in the geodetic community.
   (e) The role, function and activities (or lack thereof) of the Regional Sub-commissions continues to be a source of concern for BGI since their potential to coordinate the acquisition of information related to gravity is in many cases not being realized. Discussion of this issue was deferred to the General Assembly meetings later in the week.
3. The Director of BGI presented a report of activities since the 1990 Edinburgh meeting. The main points were:
   (a) BGI has implement new data management software with better merging capability.
   (b) About 400,000 new observations (mostly marine) have been added to the data base.
   (c) A new data index was released in September 1990.
   (d) Data validation capability has improved markedly with the implementation of the PFATES and GEOGRID software received through C.C.Tscherning and H-G.Wenzel and through further development of the in-house interactive graphics package known as VERSET.
   (e) BGI has had poor response to its requests for absolute g measurement data.
   (f) There has been a response from some of the Regional Sub-commissions to the BGI request for information on the status of IGSN71 stations throughout the world.
   (g) BGI participation in the GEBCO project was discontinued 1.5 years ago when IGN withdrew its one support staff.
   (h) BGI has had significant involvement in many new regional map compilation projects in Africa, North and South America, Europe and Asia and has recently supplied a validated data set for the South American Gravity Project of the University of Leeds.
   (i) The number of suscribers to the Bulletin is now 350 (up from 250 two years ago).
4. In the ensuing discussion of the Director's report the following points were raised:
   (a) Tscherning expressed the opinion that the content of the Bulletin had improved in recent years and that it was now a very useful document for gravimetrists.

(b) In response to a question from Tanner concerning the priorities of the BGI the Director replied that the first priority was to provide good service to the clients and the second to carry out data validation activities.

(c) Wenzell noted that the gravity bibliography produced on diskette by the BGI appears to have been well received by the scientific community.

(d) With respect to wider distribution of the Bulletin Balmino agreed to contact the presidents of Society of Exploration Geophysicists (SEG), American Geophysical Union (AGU), and the European Association of Exploration Geophysicists (EAEG), as well as national metrological agencies, to obtain mailing lists. McConnell agreed to send some Geological Survey of Canada mailing lists.

(e) Tscherning proposed that a Resolution be drafted for the General Assembly thanking various agencies in France for their continued support of the BGI

5. Reports were presented by Chairpersons of the Working Groups. They are not summarized here but appear in their entirety elswhere in this issue of the Bulletin. A summary of the discussion following each of the reports follows.

(a) WG1-Data Processing-(R.K.McConnell)

The Directing Board reviewed the draft Bouguer Anomaly Map of the World and urged that it be published as soon as possible. McConnell agreed to ask the Geological Survey of Canada to print the map and deliver it to BGI by May 15, 1991 so that its release could be announced in the June issue of the Bulletin. He also agreed to find someone at the GSC to write notes for the map which could be distributed as an accompanying handout.

The Board also suggested that WG1 and BGI host a workshop onmarine gravity data validation at the earliest possible opportunity. Balmino agreed to follow up.

(b) WG2-World Gravity Standards-(G.Boedecker)

Boulanger noted that the absolute gravity network of the USSR would be completed in 1991 and that the data would be made available for the IAGBN Project.

Boedecker noted that Prof Biro has proposed, for discussion in Vienna, that the gravity unit be changed from m/s2 to nt.kg.

Faller suggested that BGI publish a map of world-wide absolute measurements in each issue of the Bulletin.

There was a discussion of the need for absolute measurements in parts of the world where IGSN71 has been largely destroyed and few absolute measurements have been done.

(c) WG5-Non-tidal Gravity Variations-C.Poitevin

The Directing Board asked that WG5 collect data from sites where colocated superconducting and absolute gravimeter measurements have been made and to take appropriate actions to ensure that these data are preserved in a central location for posterity.

(d) WG7-Computation of Mean Gravity Anomalies-H-G.Wenzel

Wenzel noted that errors in some areas of the ETOPO5 DTM are so large that the data set must be used with caution in creating Bouguer anomaly grids from Free-air anomaly data.

New mean value software will be available from the Working Group by December 1990.

(e) WG6-Absolute gravity measurements (Y.Boulanger)

6. There was a discussion of the status of the BGI data base and associated procedures. The main points were:

(a) The new data management software developed in-house works well but is fairly complex and dependent on the expertise of certain personnel. BGI is currently looking at ORACLE as a possible replacement.

(b) Tscherning questioned why BGI offers gravity anomalies calculated with only one gravity formula. Balmino replied that in future BGI will offer the client a choice of gravity formula or simply the observed gravity values and other parameters from which the client can calculate anomalies as desired.

(c) D.Toustou of BGI described his VERSET data validation software including the modifications suggested by participants at the 1989 Data Validation Workshop, and circulated examples of output. Tscherning asked if data contributors regularly received feedback from BGI on the results of validation done on their data. Toustou replied that this is not done now but is planned for the future.

(d) The Board encouraged BGI to explore the use of optical disk for data storage and eventually for data distribution.

7. Balma of BGI presented statistics on requests processed during the past year. These are published elsewhere in this issue of the Bulletin. He also presented a summary of new control station information received by BGI.

8. In the discussion of future links with the Geoid Commission Tscherning, acting as spokesperson for Rapp, said that there would be no duplication of effort with the Gravity Commission. The Geoid Commission feels that the work of BGI in collecting and validating data is complementary to its own work.

9. In discussing membership of the Directing Board it was agreed to recommend to the Gravity Commission that the president of the Geoid Commission be an ex-officio member of the Directing Board.
Dr. Medvedev (USSR) and Pr. Groten (RFA) were proposed to replace Pr. Boulanger and Pr. J. Krynski in the Directing Board. These, as well as other nomination proposals, were discussed and approved by the IGC assembly on Sept. 13.

10. With respect to the format for future IGC meetings it was agreed that the meeting period be reduced to three days by having reports on gravity campaigns and map compilations presented as posters. It was further agreed to recommend to the Commission that the venue for the IGC General Assembly be changed to Paris. (*Discussion of this issue at the general assembly meeting concluded that the location should not be changed. Therefore, next IGC will be held in Toulouse in 1994*).

11. It was decided to limit Working Group membership to 20. The terms of reference for WG7 were approved.

R.K.McConnell
Rapporteur

BUREAU GRAVIMETRIQUE INTERNATIONAL
Activity Report
for the period : August 5, 1989 - September 14, 1990

1. SERVICE ACTIVITIES

This is an update of the report of activities presented at the August 1989 meeting of the IGC, in Edinburgh.

1.1. Data Base Software Development

New Cyber 990 was installed at CNES at the end of 1987. Changeover from NOS/BE to NOS/VE operating system required major softwares to be rewritten. This work was completed at the end of 1988. The data base and its system were again re-installed on a newer CYBER 992 in December 1988. The graphic language change requires to rewrite many pieces of software, which has been completed for most of it.

The Bureau has developed a new simple software for the data base management of regional data sets, for instance in the framework of the AGP and SAGP projects (cf. § 2.2 and 2.3). This might allow a faster merging of new sources and ensure better protection against loss of operational continuity.

In addition, the existing software has been upgraded by M. Sarrailh and its performances improved when adding new sources. Subsequently, it will be made more user friendly, as well as better protected against misusage.

1.2. Data Collection

The data base to-day contains about four million point gravity values in 3000 sources. The main new land sources acquired can be found in the Edinburgh report (B.I. n° 65, Dec. 1989). Large marine data sets (e.g. from Lamont Doherty Lab.) have since been merged. It remains more than a quarter million points to be added ; as said above, this has been a very slow process due to the characteristics of the software (until it was upgraded).

New catalogues have been produced (last update : Sept. 4, 1990) and are available on request :

- General coverage of gravity data per 20 x 20 degrees area
- Index catalogue of data distribution : statistics per degree square, mean value, standard deviation.

1.3. Data Validation

Two automated software, PFATES and GEOGRID, were received from Prof. Wenzell (Univ. of Karlsruhe - previously at IFE, Hannover) and from Pr. Tscherning (Univ of Copenhagen) respectively, which allow a fast first stage editing. An automatic validation tool (SYSTEVAL) was developed from them.

A sophisticated new system (VERSET/DIVA) for finer data validation using statistical techniques and interactive graphics has been developed by Denis Toustou.

The Workshop organised by BGI in the fall focused on discussing methodology, algorithms, software hints... used in different centers, and demonstrations of BGI capabilities were performed successfully in real time. The full report appeared in the Bulletin d'Information n° 65.

All land data were validated on a one by one source basis by means of the SYSTEVAL software. Data over South America, Spain, Belgium benefited from a finer validation by VERSET (it is much more man-power consuming) ; VERSET will be used on request on other data sets in the future. It also remains to intercompare overlapping sources. Plans are made to install similar software for the validation of marine data especially to solve for cross-over minimization parameters ; a workshop on this topic could be held in the fall of 1991.

1.4. Requests

The bureau has received 58 requests for data and services in 1989 and 82 requests for the first 8 months in 1990. This corresponds to an increase of ≈ 150 % in five years, with a real jump this year. This activity presently employs one person more than half-time.

1.5. Bibliography

Compilation of the gravity bibliography continues. The digitization of the old bibliography, prior to 1980, has also been undertaken ; this is a huge work which is performed by the BGI secretary and which very likely will continue in 1991 and 1992. A file is now available on floppy disk.

This data base is resident on hard disk on a P.C. and managed by means of the ORACLE software (new version installed in August 1990).

1.6 Miscellaneous

- training of students and visitors : data validation procedures, graphics
- compilation of absolute measurements : difficult (agencies do not answer to our request for data and facts).
- status of IGSN 71 stations : partially established, from reports of European and North-Pacific Sub-commissions, presented in Edinburgh.
- Update of map file and new catalogue : 100 maps added.
- Update of reference station file : 1042 stations added (microfiching in progress).

2. SPECIAL PROJECTS OR EVENTS

2.1. GEBCO Project

One person had been assigned in 1987 by the Institut Géographique National (I.G.N.) to work on the GEBCO hydrographic project. In addition to the Northern Europe sheet (5-01) published in 1987, BGI has produced the North Atlantic sheet (5-04), the Central Atlantic sheet (5-08), the North Polar sheet (5-17).
The course of this effort is (again) frozen due to a decision by IGN to reduce the BGI staff by one person. The work will very likely be terminated at the IGN St Mandé premises.

2.2. African Gravity Project

With respect to the African Gravity Project of the University of Leeds, to which BGI contributed, a 5'x5' grid was produced and will be made publicly available (sold) at the end of 1990. Point values will not be released for 10 years but BGI will have access to them for use in validating future acquisitions of data from Africa.

2.3. South American Gravity Project

BGI is also involved with the University of Leeds in their South American gravity compilation project on the same basis as the African project. BGI validated with its new validation software (see below) about 60 000 gravity observations over this continent and provided them to the project (to end in spring 1991).

2.4. Other Regional Gravity Projects

ULIS (Leeds) has recently made plans for projects similar to the ones above mentioned, in South-East Asia (SEAGP) and in Europe, including the Eastern countries and USSR, up to Ural (WEEGP). BGI will also be involved in these projects. Of special interest is WEEGP since it could benefit to (be coordinated with ?) the efforts of the Subcommission for the Geoid in Europe (of the International Commission for the Geoid).

2.5. Participation in ICL/CC5 Activities

The draft of the compilation of data bases and data centers, established by the Institute of Physics of the Earth (Moscow) with the help of BGI, was updated.

Balmino represents the International Gravity Commission on CC5.

3. SPECIFIC ACCOMPLISHMENTS

5' x 5' Gravity Map of the World

The Bureau and WG1 members (at GSC) are preparing a 5' x 5' gravity map of the whole world. BGI produced the part of the basic grid over land areas (Bouguer anomalies) while GSC prepared the oceanic part (free-air). It should be published at the end of 1990.

4. MEETINGS AND CONFERENCES ORGANIZED

Special meeting of IGC in Edinburgh (U.K.) : August 5, 1989

BGI Directing Board meeting in Edinburgh : August 8, 1989

Workshop on validation of gravity data : Toulouse (France), October 17-19, 1989.

BGI Directing Board meeting in Toulouse : September 10, 1990.

13th Meeting of I.G.C. in Toulouse : September 11-14, 1990.

5. PUBLICATIONS

Bulletin d'Information : Dec. 1989 (n° 65)
Bulletin d'Information : June 1990 (n° 66)

BGI holdings, Data Base Coverage, Aug. 5, 1989
BGI holdings, Data Base Coverage, Sept. 4, 1990
BGI holdings, 1° x 1° statistics of gravity measurements, Aug. 5, 1989
BGI holdings, 1° x 1° statistics of gravity measurements, Sept. 4, 1990
BGI catalogue of Maps, Sept. 4, 1990.

Appendix 1

BGI STAFF

Due to a big reorganization of the Centre National d'Etudes Spatiales (French Space Center) in 1989 - one of the major institutes in France which support BGI, the Bureau has become a service of the newly extended Observatoire de Midi-Pyrénées (OMP), (previously Observatoire du Pic du Midi Toulouse). BGI still benefits from substantial support of the Space Center as well as from the other institutions, in particular as concerned the staff. As a consequence, BGI is no more a department of the Space Center, and activities in the field of Earth and Planetary Geodesy, which were in the past done in the same department (this is why some Technical Notes dealt with matters outside the concern of the Bureau...), are now clearly separated.

The staff of the Bureau is now composed of the following :

Position	Supporting Institute	Percentage of time spent in BGI activities (%)	Name (Jan. 1, 1990)
Director	CNES	30	G. Balmino
Secretary	CNRS	70	N. Rommens
Engineer	CNES	100	M. Sarrailh
Engineer	CNES	20	B. Moynot
Analyst/Prog.	IGN	100	D. Toustou
Technician	IGN	100	G. Balma

Acronyms :
CNES : Centre National d'Etudes Spatiales
CNRS : Centre National de la Recherche Scientifique
IGN : Institut Géographique National

Toulouse, September 10, 1990
G. BALMINO
Director, BGI

Appendix 2

BGI-FAGS Account, 1989

Statement of Income and Expenditure
for the Year Ended 31 December 1989

I - INCOME	
Allocation from UNESCO Subvention to ICSU	8 000,00 $
Publications	1 810,08 $
Others	5,83 $
	9 815,91 $
II - EXPENDITURE	
a. Scientific Activities	
Symposia/colloquia/Working Group	701,51 $
Data Gathering/Processing	310,50 $
Grants to Individuals	560,49 $
d. Administrative Expenses	
General Office Expenses	4 581,49 $
Office Equipment	172,60 $
	6 326,59 $
Excess of Income over Expenditure	3 489,32 $
Accumulated Balance at January 1, 1989	153,53 $
Accumulated Balance at December 31, 1989	3 642,85 $

REPORT OF

BGI WORKING GROUP 1 (DATA PROCESSING)

To the 13th Meeting of the International Gravity Commission

September 11-14, 1990, Toulouse, France

Two main activities have taken place over the last year within the framework of WG. 1.

1. Workshop on Gravity Data Validation, October 17-19, 1989, Toulouse, France

The workshop was organized by the Director and staff of BGI and took place on BGI premises. The primary objectives were :

a) to ensure that BGI staff were aware of the state-of-the-art in gravity data validation in various institutions around the world who are heavily involved in this type of activity and

b) to provide a forum to interchange knowledge, expertise and software among the participating agencies.

The workshop consisted of one day of technical presentations, one day of software demonstrations and a final day of technical round-table discussions.

For various technical reasons, some participants were not able to install and demonstrate their software. C.C. Tscherning of KMS, Denmark successfully demonstrated the prediction-based validation system called GEOGRID and BGI staff demonstrated their version of the prediction-based validation system known as PFATES, developed at the University of Hannover by H.G. Wenzel. BGI also demonstrated their interactive graphic system known as VERSET developed by D. Toustou.

A summary of the technical presentations at the workshop is given in the BGI Bulletin d'Information n° 65 (December, 1989), pp. 90-142.

BGI has judged the workshop to be a success. The Working Group encourages feedback from other participants on the value of such meetings.

2. Gravity Map of the World

Members of the Working Group at the Geological Survey of Canada have completed the compilation of a Bouguer Gravity Anomaly Map of the World at a scale of 1:50.000.000. The map is based on gravity data sets compiled at BGI and is intended primarily as a vehicule to advertise the availability of BGI gravity data to the world-wide user community.

The map is compiled from a 5' x 5' mean Bouguer anomaly data set for land areas, computed at BGI, combined with a Bouguer anomaly data set over the oceans computed at the GSC from the Balmino 15' x 15' GEOS 3 and SEASAT satellite Free-Air data set and the ETOPO5 5' x 5' bathymetry data set provided by the National Geophysical Data Centre in Boulder, USA.

The draft map with a mock-up of the surround is on display at the IGC meeting. Comments from delegates are invited.

After review by the Working Group the map will be amended appropriately and printed by the Geological Survey of Canada. The primary distribution of the map will be from the BGI.

R.K. McCONNELL

Geophysics Division
Geological Survey of Canada
1 Observatory Crescent
OTTAWA, Ontario K1A OY3
CANADA

Tel. 613-995-5307
Fax. 613-952-8987
Telex 0533117 EMAR OTT

13th Meeting of the International Gravity Commission

Working Group II - "World Gravity Standards"
(Chairman: G. Boedecker)

Activity Report 1986 - 1990

The work of WGII was particularly supported by:

D. E. AJAKAIYE, YU. D. BOULANGER, J. E. FALLER, H. HANADA, I. MARSON, K. MCKONNELL, G. PETER, G. BALMINO, A. KIVINIEMI, H. ROEDER, H.-G. WENZEL.

Activities

Standardization:

A first step with respect to the standardization of global gravity reference networks and particularly the IAGBN had been done by SSG 3.87, resulting in station selection criteria on a global and local scale (cf. BOEDECKER/FRITZER, 1986).

Next, "International Absolute Gravity Basestation Network - Absolute Gravity Observation Data Processing Standards and Station Documentation" were thoroughly discussed and revised within WGII and published 1988 (WGII 1988).

To complete the set, "Absolute Gravity Observation Stations Data Documentation Standards" were drafted, distributed and discussed by correspondance and during the IGC Meeting Edinburg 1989. A final agreement was not possible so far, thus this will be a topic at the IGC meeting Toulouse 1990.

The guidelines try not to interfere with purely instrumental problems, because this is outside the scope of this WGII. Once the data documentation standards are ready, the major needs in this direction appear to be satisfied.

Advancement of IAGBN/regional networks:

As of August 1989, 17 IAGBN stations were documented and nearly all of them observed. These include stations from North- and South America, China, Madagascar and Europe. This subset was published in a status report for the special meeting of the IGC in Edinburgh 1989, included also in the BGI-*Bulletin d'Information* in 1989 (WGII 1989). In the meantime, also the documentation of Orroral (cf. appendix) is available. Additional stations have been observed.

Besides a few proposed (BOEDECKER/FRITZER 1986) remote station locations such as Antarctica and remote parts of Siberia, it is particularly Australia and Africa where IAGBN work needs further encouragement and support. Attempts to initiate acitivities in Arabia and India remained unsuccessful.

Consequently, the Australian problem was pursued by correspondance and talks to the University of New South Wales (W. KEARSLEY), Bureau of Mineral Resources (BMR - R. W. R. RUTLAND, D. DENHAM, P. WELLMAN), Australian Surveying and Land Information Group (AUSLIG - J. MCLUCK), Australian National University (ANU - K. LAMBECK). In a local reconnaissance at the station locations Alice Springs, Perth, Yaragadee the preparatory steps necessary were identified, the resulting report communicated to the Australian institutions involved. Also, a few absolute instrument owners were informed and invited to start activities. The assistance of

the Australian colleagues, particularly of J. McLuck of AUSLIG, is very gratefully acknowledged. So far, however, besides the documentation of IAGBN station site Orroral, no activity took place according to recent communication of W. Kearsley and P. Wellman.

In the case of Africa, there is a considerable overlap in the AGSN activities and IAGBN interests, because the IAGBN stations will be a subset (and fundament) of AGSN. Besides the IAGBN-aspect, the AGSN work - as a major regional network - is a primary objective of the work of WGII, (cf. terms of reference, item 2). Consequently, it was tried to encourage AGSN activities. A Gravity Training Workshop was held on invitation of the African Gravity Network Committee, chairperson D. E. Ajakaiye in Yamoussoukro/Ivory Coast in 1987 with graduate participants from ten African countries. A second workshop was held in Jos/Nigeria in 1990 with participants from six African countries. Both workshops were supported by lectures (funded from outside Africa), instruments, etc. On the occasion of the workshop 1990 the idea developed first to concentrate on AGSN stations in East Africa and to re-vitalize - in a new form - an East African Calibration Line. This project will be pursued particularly by S. Riad. One IAGBN station was established and observed by a Madagassi/Russian collaboration in Antananarivo.
A local reconnaissance was also carried out for Bamako/Mali by B. Ducarme of ICET.

There are a few problems for IAGBN work: The absolute meters comparison campaigns revealed that there still is a gap between the accuracy claimed for of some few Mikrogal and the discrepancies of some tens of microgal. Further, the reduction procedure is corrupted by errors or systematic effects from different standards. Consequently, there is some hesitance to employ these instruments to stations were a few microgal accuracy in the absolute sense is very important. However, observations at IAGBN stations could also be seen as instrumental tests as well - not at one station, but at stations spread over the globe. This viewpoint is repeated here to encourage instrument owners to do comparisons not only in Sévres, but also at other places.

Maintenance of IGSN71

The maintenance of IGSN71 is currently pursued through the revision and update by the regional IGC subcommissions. Because this is not finalized, nothing can be reported by WGII.

Gerd Boedecker

Basis of WGII-work

On the occasion of the 1986 IGC meeting, G. BOEDECKER was asked to suceed U. UOTILA as chairman of WGII.

WGII after reformation, was formally endorsed at the IAG General Assembly Vancouver 1987.

The terms of reference as revised at an IGC-Directing Board Meeting 1988 (BGI) are:

> In collaboration with BGI and under the guidance of the IGC
>
> 1. to provide advice and guidance as requested by the BGI and/or national agencies in activities related to the maintenance of IGSN71;
>
> 2. to provide advice and guidance to the international scientific community with respect to updates and improvements to regional gravity networks in order to ensure homogeneity of reference gravity values required to satisfy geodetic, geophysical and metrological needs;
>
> 3. to coordinate the establishment of the IAGBN with a design accuracy better than 10 microgals for the purpose of contributing to global geodynamics investigations,
>
> 4. to encourage and provide advice for activities related to IAGBN such as precise positioning of IAGBN stations and the measurement of gravity differences between stations.

The work of WGII is also based on e. g. the

Resolution # 4, IGC-Meeting 1986:

> Recognizing that
> there is a need for a global network of absolute gravity base stations of 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.

The work of WGII was also supported by

Resolution # 5, IAG General Assembly Vancouver 1987:

> *The International Association of Geodesy*
>
> *recognizing* the urgent need for a global absolute gravity reference network of high accuracy, particularly for monitoring variations with time and maintaining gravity standards, and
>
> *considering* the proposal of IAG SSG 3.87 for an International Absolute Gravity Base station Network (IAGBN) an appropiate basis
>
> *recommends* this should be put in hand now, coordinated by the International Gravity Commission,

requests

1. relevant agencies to give active support to station installation and gravity connections to existing base networks such as IGSN71,

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

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

Intermediate activity reports can be found in the "WGII activity report", BGI-*Bulletin d'Information*, # 63, 1988, and a paper "Status Report 'IAGBN'", IGC Meeting 1989.

References

BGI	Terms of Reference BGI Working Group II - World Gravity Standards, as revised June 24, 1988 *BGI-Bulletin d'Information*, No. 63, p. 29, Toulouse 1988
BOEDECKER/FRITZER	Intern. Association of Geodesy, SSG 3.87, "International Absolute Gravity Basestation Network Status Report March 1986" Veröffentlichungen der Bayer. Kommission f. d. Intern. Erdmessung, Astron.-Geod. Arbeiten Nr. 47, München 1986
WGII 88	International Absolute Gravity Basestation Network (IAGBN) - Absolute Gravity Observations Data Processing Standards & Station Documentation *BGI-Bulletin d'Information*, No. 63, pp. 51-57, Toulouse 1988
WGII 89	Status Report on the "International Absolute Gravity Basestation Network" *BGI-Bulletin d'Information*, No. 65, pp. 50-71, Toulouse 1989

International Absolute Gravity Basestation Network (IAGBN)

Station Location: CANBERRA A.C.T Country: AUSTRALIA

φ = S 35 38' 16".21 λ = E 148 56' 17".09 H = 1322.318 m g =

Overview / Access / Outside View / Topo Map

The Observatory is located on the side of Mount Orroral, 60 kilometres south of Canberra (40 kilometres south of Tharwa the nearest town). This is on the northern perimeter of the Namadgi National Park, over looking the now defunct Orroral Tracking Station.

Travel south of Canberra to Tharwa (various routes) then follow access diagram contained in this summary.

Remarks / Station Identity / Contact

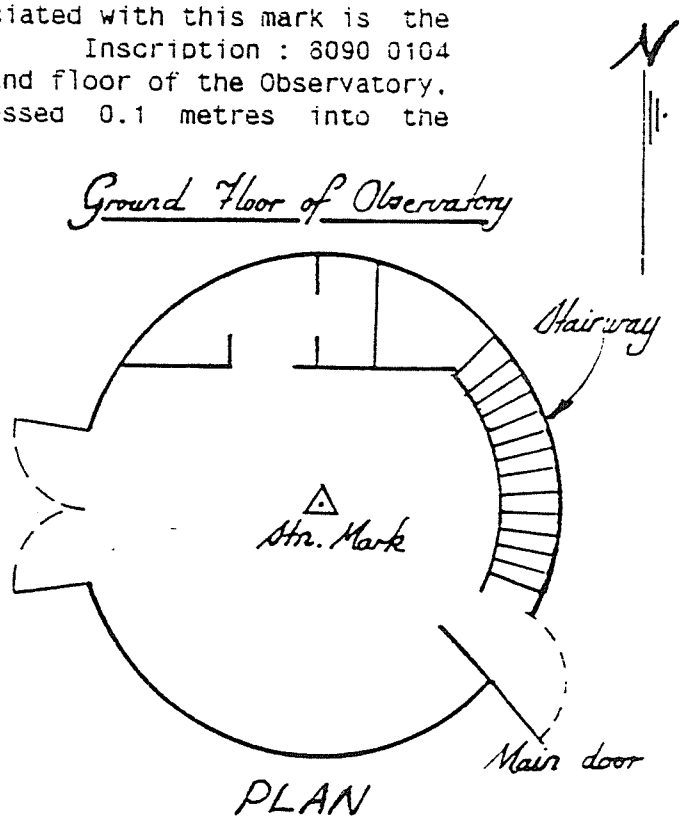
STATION CONTACTS:
DR J.MCK.LUCK
or
MR M.J.ELPHICK

ADDRESS: DAS AUSLIG
ORRORAL OBSERVATORY SECTION
PO BOX 2
BELCONNEN ACT 2616

Phone: 062/357285 Fax: 062/357209

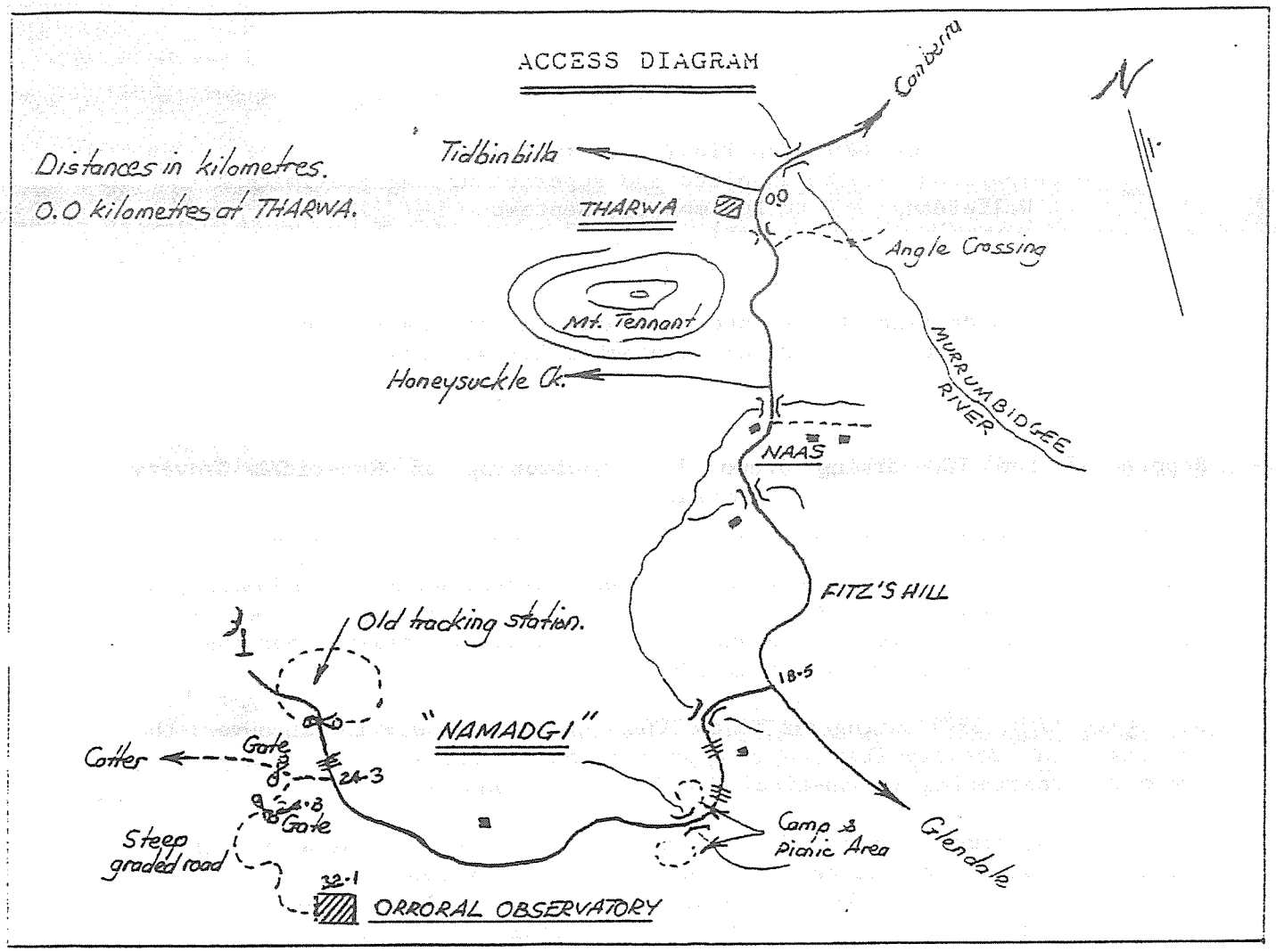
Detailed Sketch (North? Station Marker?) / Photograph

The Station Mark is a centre punched triangular brass plaque. The name associated with this mark is the Orroral Centre Ground Mark. Inscription : 8090 0104 It is located on the ground floor of the Observatory, centrally located and recessed 0.1 metres into the concrete floor.



Date / Author 22 SEPTEMBER 1989 / M.ELPHICK

ACCESS DIAGRAM



PHOTOGRAPH OF OBSERVATORY

WORKSHOP "Non Tidal Gravity Changes:
Intercomparison between absolute and superconducting gravimeters"
Walferdange - G.D. Luxembourg, September 5-7, 1990

&

13th Meeting of the International Gravity Commission
Toulouse - France, September 11-14, 1990

Report of the IGC-Working Group V : Monitoring of Non-tidal Gravity Variations.

This report is an updated version of the report distributed at the IGC Special Meeting of August 5th, 1989 during the General Meeting of the IAG in Edinburgh, U.K. A complete quadrennial report will be prepared for the XXth IUGG General Assembly in Vienna in 1991.

On August 20th, 1987 during the XIXth IUGG General Assembly in Vancouver, the International Gravity Commission approved the creation of the IGC-Working Group V: "Monitoring of Non-tidal Gravity Variations".

A resolution, first discussed by the present WG-members during a preliminary meeting in Vancouver, has been adopted by the IAG as Resolution n° 4 (Bul. Geod. Vol. 62,n° 3, p. 278). It supports the work of IGC-W5. According to the IAG rules, the resolution has been sent officially at that time to all the concerned institutions.

The Terms of Reference of IGC-WG5 are :
"to link together the existing and future superconducting gravimeters in a network monitored by absolute gravimeters in order to study residuals, after removal of the tides, for geophysical interpretation, leading to the monitoring of non-tidal gravity variations at a global scale".

A list of possible actions was suggested. It is :

A) coordination of regular intercomparisons between absolute and superconducting gravimeters in order to modelize <u>instrumental effects</u> (drift monitoring, calibration, ... ; evaluation of instrumental capabilities ...).

B) <u>exchange of "know how"</u> between participants at different levels : technical, data processing, standardization ...

C) <u>multidisciplinary approach of environmental effects</u> such as :
- removal of the "complete" tide;
- loading effects such as oceanic, atmospheric ... loadings;
- geohydrological effects, etc. ...

D) stimulation of instrumental developments
such as :
- improvement of absolute gravimeters
- development of a nitrogenic superconducting gravimeter ...

The basic ideas underlying the creation of IGC-WG5 are based on the fact that there exists now two kinds of high precision gravimeters :

- the absolute gravimeters which now reach a precision of 10^{-9} and are transportable.
- the superconducting relative gravimeters which are site fixed, reaching a long term precision of 10-9 and measuring continuously. The main advantage of the superconducting instruments compared to spring gravimeters is a very low and quite regular drift rate allowing namely to detect the induced effect of polar motion (A ~ 8 microgals, T ~ 430 days).

After removal of the tide and environmental effects, it is expected that these instruments produce residue drift curves which can be representative of long term gravity variations at the level of 10^{-9}.

A correlation of such curves coming from instruments located at different sites should allow to detect gravity variations on a large scale.

Regular absolute measurements, once or twice a year, are needed to refer the residues curves to an absolute value and to separate instrumental effects from the signal.

Measuring at the maximum and minimum of the largest tidal amplitude, absolute gravimeters could contribute to the calibration of superconducting gravimeters too.

At the level of precision of 10^{-9}, environmental effects are very critical. The IGC-W5 is the adequate platform for the exchange of informations and experiences between "absolute and superconductive gravimetrists" in view of a better modelization of these effects.

Obviously, the activity program of WG 5 is a long term program depending essentially on the willingness of the members to participate in the activities of the group.

The membership to IGC-WG5 is widely accessible to owners/responsibles of absolute and superconducting gravimeters and also to persons on the way to purchase such equipment to participate in the network. Some scientists deeply involved with research in the field of interest of the WG are welcome too.

Besides the members, some IAG officials and a number of geodesists and geophysicists receive informations about the activities of the WG5. Their advices are deeply appreciated as they can contribute with "other eyes" to the activities of the WG. An updated list of members and informed persons is given in annex to this report.

The principal communication way of WG5 is by means of circular letters. These are generally coupled with a questionnaire for maximum efficiency.The answers are then synthesized and serve as a starting point for another circular letter.

It resulted from this exchange of informations that the organization of a work-
shop was highly appreciated by almost all members of the WG. Most of the answers were in favour of the proposal to held a 3 days - workshop the week before the International Gravity Commission in 1990. The meeting place has been chosen in Walferdange - Grand Duchy of Luxemburg. In this way, the European Centre for Geodynamics and Seismology (ECGS) can provide supports for travel expenses in Europe and the cost of the Proceedings to be published in "Les Cahiers de l'ECGS" (n° 3).

An informal meeting (17 participants) of WG5 already took place in Walferdange in December 1987. The report of this meeting was attached to the circular letter n°2. Copies of it are available on request to the chairman of the WG.

Circular letters also carry other informations as paper abstracts,reports of other working groups (when available),etc...

One of the most important activities of WG5 is to encourage and coordinate absolute measurements at the sites of superconducting gravimeters. Until now, as far as we are informed, such experiences have been performed in :

- Belgium	Bruxelles	June 1976	IMGC
- Belgium	Bruxelles	June 1987	JILAG-3
- Belgium	Bruxelles	Apr 1989	JILAG-5
- France	Strasbourg	May 1989	JILAG-5

the two last measurements have been performed during a campaign (Finland, F.R.Germany, Belgium, France, Spain) organized by B. Ducarme thanks to the participation of the Finnish Geodetic Institute.

- France	Strasbourg	Nov 1989	JILAG-5
- Belgium	Bruxelles	Dec 1989	JILAG-5
- Belgium	Bruxelles	Dec 1989	JILAG-3

on the way back from the intercomparison of absolute gravimeters at BIPM -Sèvres.

- USA	Richmond	JILAG-4
- Canada	Cantley	JILAG-2

Other measurements are running now in :

- Belgium	Bruxelles	Sept 1990	JILAG-5
- Belgium	Membach	Sept 1990	JILAG-5

Similar measurements are planned in Japan (Mizusawa) and China (Wuhan) but have not yet been performed up to now.

The agreement between the absolute values in a same site has to be taken with caution as the measurements are not necessarily processed in the same way everytime.

The formatting, processing and archiving of absolute gravity measurements are very important questions to debate with the BGI and the IGC-WG2 and WG5.

A clear and precise definition of all the corrections to apply to gravity observations should be decided and published. The original data sets should be stored in a convenient way to allow a fast reprocessing if necessary.

For the gravity tides correction a standard procedure was already proposed by the working group on "Theoretical Tidal Models" during the meeting of the Permanent Commission on Earth Tides at Helsinki in August 1989.
A decision should be taken during the IUGG General Assembly in Vienna in 1991.
However, due to oceanic loading corrections, in situ tidal parameters are generally requested to guarantee a precision better than 5 μgal.

For the atmospheric pressure correction, responsible people from superconducting side have to determine experimentally the impulse response of the instruments while a theoretical correction is applied to absolute gravity observations.

The behaviour of the residue curve of the superconducting gravimeters is not completely elucidated. However, attention was focused on two points of importance :

- the need to measure the water-table variations with a precision of about 10 cm depending of the geological conditions of the site;
- the existence of an annual term with an amplitude of few microgals. An instrumental origin of this periodic term is not excluded at all.

To promote exchanges of superconducting data, the list of existing instruments and available time series should be known and disseminated. Provisional time-tables of absolute gravity measurements should be available too and disseminated in order to offer the opportunity to organize measurements at the "right time" at the superconducting sites.
These informations should be included in the next circular letters of IGC-WG5 thanks to the cooperation of the members of the WG. Please, be so kind as to send these informations to C.Poitevin who will synthesize them.

For the time being, 35 participants from 16 countries are officially registered for the Workshop "Non Tidal Gravity Changes". The number of abstracts received until now is 17. Three open technical discussions are scheduled during the meeting. The proceedings of the Workshop will be published in volume n° 3 of "Les Cahiers de l'ECGS". If you are interested by this publication, please send your name and address to C.Poitevin as soon as possible in order that the number of supplementary copies to be printed can be evaluated.

C. POITEVIN
Chairman IGC-WG5

Centre de Géophysique Interne
Observatoire Royal de Belgique
Avenue circulaire, 3
B-1180 Bruxelles
BELGIUM

Tel : (32/2) 3730 294 or 211
Fax : (32/2) 374 98 22
Tlx : 21565 OBSBEL B

ANNEX I

LIST OF WG 5 MEMBERS

AAA WG5 MEMBERS
INSTITUTION
ADDRESS
ZIP CITY
COUNTRY
TELEPHONE TELEX FAX
INFMAIL
FUNCTION
SUPRA ABSOLUTE

Boulanger Yu. D.
Soviet Geophysical Committee
Molodezhnaya 3
SU-D117296Moscou
U.R.S.S.
1375687 411196
IGC WG6
ABS.USSR

Crossley David
Dept. Geol. Sc.-McGill Univ.
3450 University Street
H3A 2A7 Montreal
Canada
514/398-4886
BITNET EYID MCGILLA
GWR TT70

Ducarme Bernard
Observatoire Royal de Belgique
Av.Circulaire 3
B-1180 Bruxelles
Belgique
32-2/3730211 (248) 21565 32-2/3749822
GWR TT30 SN122

Faller James
JILA
Campus Box 440 Univ.Colorado
80309 Boulder, Co
USA
1-303/492-8509 755842 1-303/492-5235
DB BGI
JILAG N°

Guo You-Guang
National Inst. of Metrology
7, District 11, HePing Str.
100013 Beijing
Chine
421/1631-301 210028 NIM CN
NIM-II free fall

Higashi Toshihiro
Geophysical Inst.-Kyoto Univ.
Sakyo-ku
606 Kyoto
Japon
75/7512111 5422693
GWR TT70 n°8 & 9

Hinderer Jacques
Institut Physique du Globe
5 Rue Rene Descartes
F-67084 Strasbourg
France
33-88605063 33-88616747
BITNET A75101@FRCCSC21
GWR TT70 n°

Hsu H.T.
Inst.Geod.& Geoph.-Acad.Sc.
54 Xu Dong Road
Wuchang,Hubei
Chine
813805 5112 86-1/8011095
Vice President IGC
GWR TT

Lambert Anthony
Geolog. Survey of Canada
Observatory Crescent 3
K1A OY3 Ottawa, Ontario
Canada
1-613/9955446 1-613/9529088
GWR TT70 N° JILAG N°2

Makinen Jaakko
Finnish Geodetic Institute
Ilmalankatu 1A
SF-00240 Helsinki
Finlande
358-0/410433 358-0/414946
GEODEET@FINFUN
JILAG N°5

Marson Iginio
Ist.Miniere e Geof.Appl.
Via Valerio 10 Univ.Trieste
I-34127 Trieste
Italie
39-40/568201 460014 39-40/5603176
SYM.FREE-FALL IMGC

Peter George
Geod.Res. Develop. Lab.
N/CG114 Rockwall Bldg R.4260B
MD 20852 Rockville
U.S.A.
1-301443-0594 RCA 7401071 1-301443-8328
JILAG n°4

Poitevin Christian
CGl-Observ.Royal de Belgique
Avenue Circulaire 3
B-1180 Bruxelles
Belgique
32-2/3730211 (294) 21565 32-2/374 98 22
IGC WG5

Richter Bernd
Institut fur Angewandte Geod.
Richard Strauss Allee 1
D-6000 Frankfurt/Main 70
RFA
49-69/6333225 413592 49-69/6333425
GWR TT40 & TT60

Roeder R.H.
Institut fur Erdmessung
Nienburgerstrasse 6
D-3000 Hannover 1
RFA
49-511/7622794 923868 49-511/7624008
JILAG N°3

Sakuma Akihiko
Bureau Int. Poids & Mesures
Pavillon de Breteuil
F-92312 Sevres Cedex
France
33-1/45340051 201067
ABS.BIPM TYPE N°2

Sato Tadahiro
International Latitude Observ.
Iwate-Ken
023 Mizusawa
Japon
197/24 7111 837628
GWR TT70 N°7

Segawa Jiro
Ocean Res. Inst.-Univ. Tokyo
15-1 1-chome Minamidai
Nakano-ku Tokyo 164
Japon
03-376-1251 25607
OMNET: J. SEGAWA
GWR TT70 n°10

Steinhauser Peter
Institute Meteor.& Geophysics
Hohe Warte 38
A-1190 Vienna
Autriche
222/364453 (209) 131837
JILAG N°

Tsubokawa Tsuneya
National Astronomical Obs.
2-12 Hoshigaoka
023 Iwate Mizusawa-Shi
Japon
81-197/247111 837628 81-197/235156
ABS.ILOM

Warburton Richard
GWR Instruments
11404 Sorrento Valley Road
92121 San Diego CA
USA
1-619/452-7655 4994623 1-619/4526965
GWR TT

Wenzel H. Georg
Geodaet.Inst.-Univ.Karlsruhe
Englerstr.7
D-7500 Karlsruhe-1
RFA
49-721/6082307 721166 49-721/694552
Secretary IAG Sec III/DB BGI

Zurn Walter
Black Forest Observatory
Heubach 206
D-7620 Wolfach
RFA
07836-2151 725625

Goodkind John M.
Univ. of California, San Diego
Dept. of Physics, B-019
CA 92093 La Jolla
U.S.A.
1-619/5342716 9103371271 1-619/5340173

ANNEX II

LIST OF INFORMED PERSONS

WG5
INSTITUTION
ADDRESS
ZIP CITY
COUNTRY
TELEPHONE TELEX FAX
INFMAIL
FUNCTION
SUPRA ABSOLUTE

Achilli Vladimiro
Dipt.Ing.Civ.-II Univ.
"Tor Vergata" Via E.Carnevale
I-00173 Roma
Italie
39-6/24990575 611462 39-6/24990586

Ajakaiye Deborah
Department of Physics
Ahmadu Bello University
Zaria
Nigeria
73/52910 81350
Secretary IAG Sec III

Baldi Paolo
Ist. di Sc.Terra-Univ.Udine
V. Ungheria 43
I-Udine
Italie
39-51/243586 39-51/250106

Balmino Georges
CNES-GRGS-BGI
Av.Edouard Belin 18
F-31055 Toulouse Cedex
France
33-61/332889 531081 33-61/253098
BITNETBALMINO@FRCICT81
Dir.Bureau Grav.Int./DB BGI

Boedecker Gerd
Bayerische Akad.Wissenschaften
Marstallplatz 8
D-8000 Munchen 22
RFA
49-89/23031212 5213550
EARN DMOLRZ01 id A2101AB
IGC WG2

Courtier Nicholas
Geophys. Div., GSC
Observatory Crescent 3
K1A OY3 Ottawa, Ontario
Canada
1-613/9924842 1-613/9529088

De Meyer Frans
Institut Royal Meteorologique
Avenue Circulaire 3
B-1180 Bruxelles
Belgique
32-2/3730620 21305 32-2/3755062
1259

Dehant Veronique
Observatoire Royal de Belgique
Avenue Circulaire 3
B-1180 Bruxelles
Belgique
32-2/3730211 (246) 21565 32-2/3749822

Groten Erwin
IPG, THD
Petersenstrasse 13
D-6100 Darmstadt
RFA
49-6151/163900 419579 49-6151/165485
XBR2D25B DDATHD21

Krynski S.
Inst. Geod. i Kartografii
Ul. Jasna 2/4
00950 Warszawa
Pologne
Vice President IGC/DB BGI

Legros Hilaire
Institut Physique du Globe
5 Rue Rene Descartes
F-67084 Strasbourg Cedex
France
33-88605063 33-88616747

Louis Michel
140 Rue de Grenelle
F-75700 Paris
France
33-1/45503495 204989 33-1/45550785
General Secretary IAG

Mansinha Lalu
Dept. of Geophysics
Univ.of Western Ontario
N6A 5B7 London ONT
Canada
1-519/6613141 0647134 1-519/6613292
BITNET LALU@UWOVAX.UWO.CA

McConnell R.K.
Geophysics Div. G.S.C.
1 Observatory Crescent
K1A OY3 Ottawa
Canada
1-613/9955307 533117 1-613/
Secretary IGC/IGC WG1

Melchior Paul
Observatoire Royal de Belgique
Avenue Circulaire 3
B-1180 Bruxelles
Belgique
32-2/3730211 (249) 21565 32-2/3749822

Morelli Carlo
Universita-Ist.Miniere
1 Piazzale Europa
I-34127 Trieste
Italie
39-40/52465 460014
Secretary IGC/DB BGI

Mueller Ivan
Dept.Geod.Sc.-Ohio State Univ.
1958 Neil Avenue
43210-1247Columbus Ohio
USA
1-614/2922269 245 334 1-614/2922957
President IAG

Nakagawa Ichiro
Geoph.Inst.-Kyoto University
Sakyo-ku
606 Kyoto
Japon
81-75/7512111(3911) 5422693
President IAG Sec III/DB BGI

Neuberg J.
c/o Dept.physics-Univ.Colorado
Campus Box 390
Boulder, CO.80309
USA

Paquet Paul
Observatoire Royal de Belgique
Avenue Circulaire 3
B-1180 Bruxelles
Belgique
32-2/3730211 (266) 21565 32-2/3749822

Tanner Jim
R.R. NL1
Union
NOL 2LO Ontario
Canada
1-519/6313190 533447 1-519/6334997
President IGC/DB BGI

Torge Wolfgang
Inst.Erdmessung-Univ.Hannover
6 Nienburgerstrasse
D-3000 Hannover 1
RFA
49-511/7622795 923868 49-511/7624006
Vice-President IAG

Tscherning C. Christian
Geoph.Inst.-Univ.Copenhagen
Haraldsgade 6
DK-2200 Copenhagen N
Danemark
45-1/810447 16469 45-1/822565
EARN/BITNET GDIIMAGE at NEUVM1
DB BGI

You are deeply involved in the activities of IGC-WG 5. You are not yet on the mailing list (see IGC-WG5 report) and you want to be "in", then fill in this form and return it to :

C. POITEVIN
IGC-WG5
Centre de Geophysique Interne
Observatoire Royal de Belgique
Avenue circulaire, 3
B-1180 BRUXELLES

Tel: 32/2 37 30 211 FAX: 32/2 374 98 22 Telex : 21565 OBSBEL-B

IGC-WG 5 Mailing List

Name : ..... Surname .....

Organisation : .....

Address : .....

Zip Code : ..... City : ..... Country : .....

Tel : ..... Fax :..... Telex : .....

Electronic Mailing : .....

I would like to be registred as :

- an informed person ☐
- a member of the IGC-WG5 ☐ , I am responsible/ouwner

  of : - absolute gravimeter : *.....

  - superconducting gravimeter : *.....

* Please indicate all available informations

REPORT ON

THE ACTIVITIES OF THE WORKING GROUP 6

"COMPARISON OF ABSOLUTE GRAVIMETERS"

To the 13th Meeting of the International Gravity Commission

September 11-14, 1990, Toulouse, France

As a result of the 2nd International Comparison of Absolute Gravimeters in Sèvres 1985, notable systematic errors were observed in the measured gravity values. Taking into consideration this circumstance, a resolution was adopted at the meeting of the International Gravity Commission during the XIX General Assembly of the International Association of Geodesy (Vancouver, 1987) to the effect that such comparisons should be continued and carried out systematically, if possible every 3-4 years. For this purpose the Working Group 6, IGC, "Comparison of Absolute Gravimeters" was set up with Pr. Yu.D. Boulanger as Convener. It was also suggested to hold the next comparison in the autumn of 1988. The tentative participants were Austria, Canada, China, Finland, Germany, BIPM (Sèvres), Italy, Japan, USA and USSR.

The first WG6 meeting took place in Paris on 22-23 June 1988, where it became apparent that in 1988 in many countries the absolute gravimeters would not be ready as yet for comparison. Pr. P. Giacomo, Director of BIPM at that time, invited the next comparison to Sèvres in the end of 1989, which was accepted with gratitude. Moreover, Pr. E. Groten and Dr. M. Becker have kindly agreed to undertake the accomplishment of the relative measurements necessary for setting up a microgravimetric network and for the determination of vertical gradients over the pillars.

Since BIPM cannot receive simultaneously ten instruments, it was decided to carry out this comparison by two groups : the first group in the last decade of November, and the second group in the first decade of December 1989. In the interval between them, it was recommended to make measurements with relative gravimeters.

The second WG6 meeting, which took place on 23-24 November 1989, in Sèvres just before the beginning of the observations, discussed and finally adopted the observation program for both absolute and relative gravimeters. The order was established of processing of observations and concrete dates of its accomplishment. A wish was expressed to publish a full report on observations in Bull. d'Inf. after their discussion at the XIII IGC meeting in Toulouse in September 1990. The preparation of the materials for publication and their generalisation was entrusted to Yu.D. Boulanger, J. Faller and E. Groten.

However, not a single country presented its results by the fixed deadline (end of February 1990), and the materials were received with great delay and at different dates. I received the last additional corrections to the data in the second half of June, making it necessary to recalculate the summarising Tables and to introduce corrections into the final results of comparison three times.

At the same meeting, three scientific papers were presented by Pr. A. Sakuma (France), Pr. J. Faller (USA), and Dr. L. Vitushkin (USSR) on further prospects of development of absolute gravity determinations concurrently with the determination of vertical gradients, with a subsequent discussion.

As planned previously, ten countries took part in the comparison : Austria, Canada, China, Finland, Germany, BIPM, Italy, Japan, USA and USSR. The observations were successful : the maximal differences was recorded between the BIPM instrument (980 925 963.5 ± 1.5 mcgal) and the instrument from the USSR (980 925 986.9 ± 4.4 mcgal), i.e. 23.4 ± 4.6 mcgal.

For the first time in the history of gravimetry, practically simultaneously, ten absolute gravimeters made 19 independent absolute gravity determinations on six pillars, and observations of 43,964 drops were processed and the results generalized.

By using measurements of relative gravimeters, all these results were reduced to one point A (0.05) located at the height of 5 cm over the metallic disc mounted in the upper surface of pillar A (on the first floor in room 1 of the Laboratory Building of BIPM in Sèvres).

In the reduction of the measured absolute gravity values particular attention was focused on nonlinear dependence of the value of vertical gravity gradients on the height over the pillar. On the basis of comparison of the obtained results the following conclusions can be drawn :

1. The full mean square error of absolute gravity determination with one instrument by convergence of 19 independent measurements amounts to $\sigma = \pm 7.4$ mcgal.

2. Same by convergence of measurements on one and the same pillar with different instruments is $\sigma = \pm 7.9$ mcgal.
3. Same from estimation by the authors of measurements with allowance for all systematic errors known to them reaches $\sigma = \pm 5.0$ mcgal.
4. Same from convergence of measurements of differences of gravity values between pillars carried out by absolute and relative gravimeters is $\sigma = \pm 4.3$ mcgal.
5. The absence of systematic difference is established between the results of measurements made by the JILAG group of gravimeters (eleven measurements) and a group of gravimeters of other types (eight measurements). The difference amounted to 1.4 ± 3.7 mcgal.
6. By convergence of measurements, carried out by groups of three-four absolute gravimeters from observations at five pillars, the error in mean gravity determination is consistently ± 4.3 mcgal (± 0.5 mcgal).
7. The modern level of accuracy of absolute gravimeters allows us to set up a World Gravimetric Network of the First Order with measurements by one instrument at about ± 7 - ± 8 mcgal, and by a group of three-four gravimeters the accuracy can be increased to ± 5 mcgal.

A more detailed description of results of the comparison of absolute gravimeters shall be published by the BGI in Bull. d'Inf. after its discussion at the XIII IGC meeting in Toulouse in September 1990.

In conclusion I would wish to express deep gratitude to Pr. T. Quinn, the new Director of BIPM, for kindly inviting the 3rd International Comparison of Absolute Gravimeters to BIPM in Sèvres and to Pr. A. Sakuma for the excellent preparation and organization of the measurements.

Many cordial thanks are also extended to Dr. M. Louis, General Secretary of IAG, for his valuable assistance in the organization of this international enterprise.

July 1990, Moscow

Yu. D. Boulanger

INTERNATIONAL GRAVITY COMMISSION
WORKING GROUP NO. 7
COMPUTATION OF MEAN GRAVITY ANOMALIES

Chairman: Hans-Georg Wenzel, Geodätisches Institut, Universität Karlsruhe
Englerstr. 7, D-7500 KARLSRUHE 1, Phone : 0721-6082307, Fax : 0721-694552

Terms of Reference:

- the aim is the computation of a world wide set of mean free air gravity anomalies and standard deviations of block size 5' x 5' using current BGI data holdings,
- to test existing software for the prediction of mean gravity anomalies from point data with respect to accuracy and computation time,
- to supply BGI with appropriate software for production computation of mean gravity anomalies,
- to assist BGI in collection and compilation of 5' x 5' mean gravity anomalies from other terrestrial gravity sources (maps, already existing mean values of equivalent block size),
- to establish and supply BGI with procedures for the merging and validation of mean gravity anomalies.

Approved at the meeting of BGI Directing Board, Toulouse September 10, 1990.

INTERNATIONAL GRAVITY COMMISSION
WORKING GROUP NO. 7
COMPUTATION OF MEAN GRAVITY ANOMALIES

Chairman: Hans-Georg Wenzel, Geodätisches Institut, Universität Karlsruhe
Englerstr. 7, D-7500 KARLSRUHE 1, Phone : 0721-6082307, Fax : 0721-694552

Report for the Period July 1989 to August 1990

presented to 13th Meeting of the International Gravity Commission, September 11 to 14, Toulouse 1990.

1 Membership

The current members of the IGC working group 7 are : Dr. Heiner Denker, Institut für Erdmessung, Universität Hannover (FRG); Dr. René Forsberg, Geodetic Institute, Copenhagen (Denmark); Dr. Michel Sarrailh, Bureau Gravimetrique International, Toulouse (France), and Dr. Hans-Georg Wenzel, Geodätisches Institut, Universität Karlsruhe (FRG). The IGC working group 7 is in principle open for new members, but I would like to have the working group as small and efficient as possible.

2 History

The IGC Working group 7 has been created at the meeting of the BGI directing board at June 24th, Paris 1988. The terms of reference defined at that meeting are given in the appendix. A report for the period June 1988 to July 1989 has been presented at the meeting of the International Gravity Commission at August 5th, Edinburgh 1989.

3 Meeting of the WG

During the 1st International Geoid Commission Symposium, June 13th, Milano 1990, a short meeting of IGC working group 7 was held with H. Denker, R. Forsberg, H.-G. Wenzel, and G. Balmino as representative of M. Sarrailh. At the meeting, a number of topics related to working group 7 have been discussed; the main results are summarized in the following.

- The main task for IGC working group no. 7 is to enable BGI to create a world wide 5' x 5' terrestrial free air gravity anomaly data set. This task has to be fullfilled within the next year.
- The second task is to work out procedures for individuals and institutions to create regional 5' x 5' free air gravity anomaly data sets, which can be released to the international community.

- It is adopted to produce 5' x 5' terrestrial mean free air gravity anomalies (as agreed by the executive committee of the International Geoid Commission and the working group 7 members). BGI has already large 5' x 5' terrestrial mean free air gravity anomaly data sets fro Africa and South America by cooperation with the University of Leeds (UK), which unfortunately are not yet freely distributable but can be used for internal comparisons.

- The main procedure should be to use directly digital free air gravity point data bases, as e.g. the BGI data base. For land areas, the BGI data base is already completely screened. For marine areas, the screening of the BGI data base will start at the end of this year (after having implemented and tested the software for track bias adjustment of sea gravity data, which will be started next week).

- For the production of 5' x 5' mean free air gravity anomalies on land, the procedure will be to compute simple point Bouguer anomalies, to average the point Bouguer anomalies within 1' x 1' subblocks, and to predict the mean 5' x 5' Bouguer anomalies using the 1' x 1' averages inside the 5' x 5' block and 2' around the block (see Fig. 1). The final 5' x 5' free air gravity anomalies will be computed from the predicted 5' x 5' Bouguer gravity anomalies and available 5' x 5' world wide mean elevation data set ETOPO5. The quality of the predicted mean free air gravity anomalies will strongly depend on the quality of the mean elevations. But this decision has to be revised because of large errors in the ETOPO5 data set (see section 4). For the direct prediction of mean 5' x 5' gravity anomalies, least squares collocation will be used, and different programs will be prepared (see section 5). For the mean anomaly prediction, a numerically integrated point covariance function will be used.

- For the production of 5' x 5' mean free air gravity anomalies on sea, the procedure will be to predict directly mean free air gravity anomalies from point free air gravity anomalies, the prediction method will be the same as for land areas.

- For the computed 5' x 5' data, the mean free air graity anomaly plus ist standard deviation , the used mean elevation, the mean Bouguer anomaly and its standard deviation will be stored. Additionally, the number of used point gravity data and a key for the applied computation method (to be prepared for future merging with other data sets) will be stored.

4 Mean Elevation Problem

It was initially planned, to use the worldwide 5' by 5' mean elevation data set ETOPO5 for the transformation of predicted mean Bouguer gravity anomalies to mean free air gravity anomalies. At the Milano meeting, Forsberg has already mentioned large errors of the ETOPO5 data set in Scandinavia and Canada. After the Milano meeting, Denker has reported on a comparison of the ETOPO5 data set at different areas of the world and reported large errors of the ETOPO5 data set up to 2 km, given in Tab. 1. Thus, we cannot use the ETOPO5 data set for the mean anomaly computation, and there is no other 5' by 5' world wide data set available. The only decision we can make now for the production of a world wide 5' by 5' mean free air gravity anomaly data set from BGI point gravity data base

is to directly predict mean free air gravity anomalies from point free air gravity anomalies. Naturally, the predicted mean free air gravity anomalies will have large errors especially in areas with rough topography and in areas with sparse point data distribution. Therefore, it is necessary to work out procedures for anomaly production for individuals and institutions, which can use high quality regional mean elevation data sets, and can release their data sets to BGI to be merged with the global data set.

Table 1: Comparison of 5' by 5' mean elevations with ETOPO5 by H. Denker

data set	number	mean [m]	stdv [m]	min [m]	max [m]
E0505BAK63 Netherland from 3' x 5'	377	2.2	9.3	-50	58
E0505FIN83 Finland	10662	2.0	22.6	-253	314
E0505FRG87 FRG from 1 km x 1km	5332	3.3	60.5	-609	555
E0505IFE87 Northsea, Baltic Sea	7311	-0.4	17.6	-175	110
E0505VEN87 Venezuela	2138	-37.4	310.6	-1900	2050
E0505IFE90 Europe from 6' x 10'*	122210	-16.0	129.1	-1817	1785

*large errors at areas with rough topography (Alps, Norway)

5 Software

There has been made available to the working group a small piece of software for mean anomaly computation by Dr. Peter Vaniček, University of New Brunswick (Canada), which unfortunately does not meet the requirements of working groups 7 task. Dr. Hans Sünkel, Technische Universität Graz (Austria), has agreed to release an existing complex software package for mean anomaly prediction to the working group, for which a short description is available. Sünkel's program is currently under investigation whether it fully meets the requirements of the working group. H. Denker, R. Forsberg and H.-G. Wenzel are preparing programs especially for the task of working group 7, by modifying existing programs (Forsberg and Wenzel) or by creating a completely new program (Denker). The most efficient software is expected to be Denker's program, because he is writing a new program especially for the task of working group 7 and he is operating on a CDC computer, the same which is used by BGI. After having released the different programs to BGI, it is planned to test the programs at BGI with respect to computation time and to select the most efficient program.

Hans-Georg Wenzel

Karlsruhe, September 4th 1990.

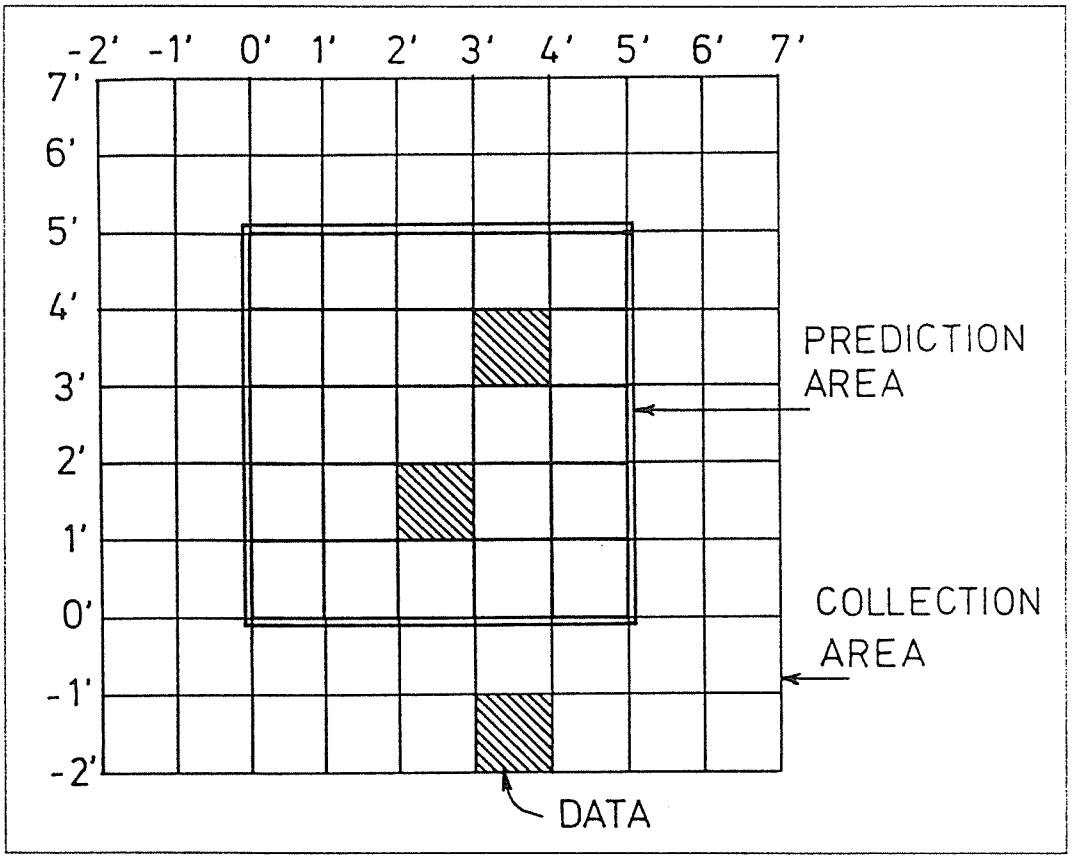


Figure 1: Collection and Prediction Areas

ACTIVITY REPORT ON GRAVIMETRY FOR NORTH PACIFIC REGION DURING THE PERIOD FROM APRIL 1986 TO MARCH 1990

Ichiro NAKAGAWA

The countries belonging to the Sub-Commission for North Pacific Region have positively taken activities in gravimetry. However, the publication of results and the exchange of their information are not always satisfactory, depending on the situation of each country.

Three stations to be included in Subset B of the International Absolute Gravity Basestation Network, which are Kyoto, Tsukuba and Mizusawa, have finished their arrangements. They are available for absolute gravity measurements at any time. At these stations, repeated gravity measurements are planned with an absolute apparatus at proper intervals.

Observers from other countries may use these stations at any time.

As for the report on gravimetry during the period from April 1986 to March 1990, gravimetric activities in Japan for those period are described on "the Report on the Gravimetry in Japan during the Period from April 1986 to March 1990" and submitted to the 13th Meeting of the International Gravity Commission. This report has a list of bibliography.

Absolute and Superconducting Gravimetry in Japan

In Japan, absolute gravimeters have independently been developed at two institutes; National Astronomical Observatory of Mizusawa (NAOM) and Geographical Survey Institute (GSI).

NAOM has four sets of absolute gravimeters in total, at present. One of them is the Sakuma's original stationary type installed at NAOM. Three sets of them are transportable and are employed a simple free-fall method. The first model of the transportable gravimeter has been used since 1978. NAOM has been performed absolute gravity measurements using this gravimeter at nine stations distributed mainly in Tohoku District since 1984. This gravimeter has an advantage of good stability and low scatter (less than 10 microgals) at the gravity value of a single drop measurement. The second model was completed in 1989 and its improvement has been made on a few points. This gravimeter was employed at the Third International Comparison of Absolute Gravimeters (BIPM, 1989). The result obtained by the measurements at BIPM was in good agreement with the mean value of the final data derived from nine participants. The third model is a rotating vacuum-pipe type. This gravimeter has an advantage for performing a large number of consecutive measurements since there is no complicated mechanism inside the vacuum-pipe.

Geographical Survey Institute (GSI, Tsukuba) has been performed absolute gravity measurements at eleven stations since 1982. The main purpose of the measurements is to update and revise the Japan Gravity Standardization Net 1975 (JGSN 75). The fundamental part of the GSI gravity apparatus is a commercial version of the Sakuma's transportable

type (Jaeger), but a number of improvements have been made to the Jaeger apparatus, especially for the data acquisition system. Direct comparisons of this apparatus with the NAOM gravimeter have been made at four stations. Discrepancies between both apparatuses amounted to about 60 microgals. As this value is much larger than an uncertainty of the measurements, it is necessary to investigate a systematic error source. GSI has a plan for performing absolute gravity measurements using this apparatus at Syowa Base, Antarctica in 1991.

As for continuous observations of gravity changes by means of superconducting gravimeters, four gravimeters (GWR, model TT-70) are being operated in Japan; two sets at Kyoto (Kyoto University), one set at Esashi (NAOM) and one set at Kakioka (Tokyo University). Absolute gravity measurements have been carried out at these stations using NAOM and GSI absolute apparatuses. A direct comparison of absolute gravimeter with superconducting one is not carried out, but we have a plan to execute it in the near future. In addition, we have a plan to install another superconducting gravimeter at Syowa Base, Antarctica in 1991.

Gravity Measurements at Syowa Base, Antarctica

At the Syowa Base, one of 36 stations included in Subset A of the International Absolute Gravity Basestation Network, the National Institute of Polar Research is preparing to establish a gravity station, according to the following schedule.

1. The 32nd Japanese Antarctic Research Expedition departing Japan in the autumn of 1990 will construct a gravity observation hut (Size : 6 m x 8.4 m, Height : 3.4 m) as a part of its Earth Science Program, and complete it around January 1991. The hut will be separated from other buildings and it will have three rooms : a front room, a mechanical room and an observation room. The size of the observation room is 5.7 m x 5.7 m, in which two bases for an absolute gravimeter (2.5 m x 1.5 m) and a superconducting gravimeter (1.5 m x 1.0 m) are available.
2. In the autumn of 1991, a gravimetry mission of two specialists will be sent for absolute gravity measurements as members of the 33rd Japanese Antarctic Research Expedition. The gravity measurements will be carried out for about one month with an absolute gravity apparatus belonging to the Geographical Survey Institute.
3. In the autumn of 1992, another mission will be sent for absolute gravity measurements. The measurements will be carried out for about one month with an absolute gravity apparatus belonging to the National Astronomical Observatory of Mizusawa.
4. Comparing with the results obtained by two apparatuses and examining them, gravity measurements will be carried out again with either apparatus after 1993.

The National Institute of Polar Research is expecting to fulfill the above-mentioned schedule. Both the establishment and observation plans are being progress smoothly.

As for another plan at the observation room which will be built in Syowa Base in the autumn of 1990, continuous observations of gravity changes are also planned with a superconducting gravimeter. It will be installed at the observation room of Syowa Base in the autumn of 1991.

Continuous observations for 3 to 5 years are in preparation. Under the present situation, the supply of liquid helium is a difficult problem, but the National Institute of Polar Research may solve this problem.

Development on Gravimetry in China

Jing-Young CHEN

The gravimetry in China is being organized and coordinated by the National Bureau of Surveying and Mapping, the People's Republic of China.

The new generation gravity basic control network "National Basic Gravity Net 1985 (NBGN 85)" was established in 1985, which has much higher accuracy than the old one. On the basis of the NBGN 85, the layout and measurements of the National First-Order Gravity Network were organized and carried out, respectively, in order to form the national gravity fundamental control network with gravity stations of enough densification. All the field works of this project were completed by the end of 1989.

For the National First-Order Gravity Network, gravity measurements were performed by LCR-G gravimeters with the length of each measurement line of about 300 km. The connected measurements were made with the gravimeters transported by van in most cases, and sometimes by train or by small airplane. It was required at least to take two gravimeters and three independent results for each measurement line. The accuracy designed was less than 25 μgals for an average error among the measurement lines and less than 60 μgals for the mean error of point values. The preliminary analysis shows that the practical result is better than the designed accuracy. It is estimated that the data processing and analysis would be completed by 1990 and be submitted for utilization.

In order to meet the need of the establishment of national gravity control network and the requirement of densification of gravity points by various institutes, eight national calibration sites of gravimeter's scale values, scattered all over the country, have been established with unified design, layout and measurements. The calibration sites are mainly used for calibrating the gravimeters utilized for lower than first-order gravity measurements. This project has already been completed and officially used.

After the completion of the National First-Order Gravity Network, the gravity control system in China has systematically been formed.

The gravity standard baseline and the vertical baseline (for differences between short measurement sections) used for calibrating high accuracy gravimeters have been established in general. The baselines will mainly be used for instrumental error analysis and scientific researches.

On the basis of the above-mentioned work, the following work has been done by other economic departments:

1. Putting in order, analyzing and unifying the gravity measurement results of the past years.
2. Inter-regional connected measurements of regional gravity networks.
3. Checking and calibration analysis of gravity instruments, etc.

Furthermore, progress and achievements have been made to a certain

extent on utilization of gravimetry in the refinement of the geoid, on data processing of gravimetry utilized in GPS three dimensional measurements, on building up of gravity data base as well as the compilation of gravity anomaly maps.

On absolute gravimetry, eight absolute gravity stations in China were measured in May to June 1990 jointly by the National Bureau of Surveying and Mapping of China with the Geodetic Institute of Finland. In particular, one absolute gravity station was established and measured in Lhasa City located in the Qinghai-Xizang Plateau which attracts worldwide attention. The results of the absolute gravity measurement campaign will be published in 1991. The absolute gravimeter developed in China was compared at the Third International Comparison of Absolute Gravimeters (BIPM, 1989) with other absolute gravimeters, and the difference of only 6 μgals was found for the total average values.

National Report on Gravimetry in Indonesia

Jacub RAIS

1. Introduction

The geographic position of Indonesia is very unique from the point of geology and geophysics. Three plates; the Indo-Australian plate, the Pacific plate and the Euro-Asian plate, meet each other in the Indonesian Archipelago forming active island arc systems with its high seismicity and volcanism. The active subduction process along the trenches offshore west of Sumatra, south of Java, and in the Banda Sea region indicates that the whole regions are not stable; in other words, movements are still in process.

To have a better understanding of the nature of the regions, gravity surveys are conducted all over the country. Geodetic and levelling networks together with gravity control are being conducted. Systematic gravity mappings with the scales of 1:100,000 and 1:250,000 have also be carried out since 1969. Local gravity surveys for exploration works are carried out with close spacing to localize mineralization sites and hydrocarbon mineralization.

2. Activity

2.1 Establishment of Gravity Base Station Network

A gravity base station network is a distribution of base stations with key values. Indonesia defines three categories of gravity stations; main base stations, base stations of the first order and of the second order. The main base station is obtained by either an absolute or a relative gravity measurement. At present, there is only one main base station known as DG 0 with a GRS 67 value of 977 976.38 mgals (ADKINS *et al.*, 1978). There are no stations with absolute measurements in Indonesia. The first order base stations were established using the main base station as reference.

Since 1978, there are 109 first order base stations in Indonesia. Then, the second order base stations are established by connecting them to the first order base stations. Both the first and second order base

stations are mainly used for detailed surveys, such as for exploration, of minerals and hydrocarbon deposits. The standard error for the first order base station is 15 μgals, that for the second order is 30 μgals and that for common measurement stations is 60 μgals.

2.2 Geodetic Purposes

2.2.1 Geodetic Network

Horizontal geodetic network has covered the whole archipelagoes, consisting of triangulation stations, satellite Doppler stations and GPS stations. The triangulation stations covered mostly Sumatra, Java, Bali and the whole parts of lesser Sunda Islands in 1884-1942, whereas the Doppler stations covered mainly Kalimantan, Maluku, Irian Jaya, Java and lesser Sunda Islands in 1980-1990. Forty GPS stations are mainly located in Sumatra at the old triangulation stations along the Sumatra fault system for the purpose of crustal deformation studies.

Vertical geodetic network or levelling network covers Sumatra, Java, Bali, West Kalimantan and South Sulawesi. The first order network covers mainly Java and Bali, whereas the second order network covers Sumatra, West Kalimantan and South Sulawesi. In order to correct the levelling surveys and to define the height system and vertical datum, gravity profiles are made along the vertical geodetic network.

2.2.2 Gravity Surveys

Gravity surveys for geodetic purposes were carried out in 1986 covering Java, Sumatra and South Sulawesi. There are nine first order gravity base stations established in Sumatra at the main airports. The second order gravity base stations were established in Java, Sumatra and South Sulawesi (see Table 1). Next to the previous calibration line established in 1972 (UNTUNG, 1972), two new calibration ranges are made respectively in Java (Subang - Tangkuban Perahu) with the gravity range of 276 mgals (see Table 2).

3. Systematic Gravity Mapping

3.1 Regional Gravity Mapping

Systematic gravity mappings with the scale of 1:100,000 for Java and that of 1:250,000 for the islands outside Java were carried out since 1969 by the Geological Survey of Indonesia. Topographic base maps with the scale of 1:100,000 for Java and that of 1:250,000 for the islands outside Java are used. There are 50 topographic charts in Java and 181 in outside Java. About 40 % of the whole regions are covered by gravity surveys, 70 % for Java and 30 % for outside Java. A gravity reading is made at about 2-3 km for the scale of 1:100,000 and 10-15 km for that of 1:250,000.

Beside the definition of the gravity field of Indonesia, results of the gravity surveys are used to support an interpretation of geological maps. Structural geological subsurface configurations are mostly derived using gravity data as substitutes.

Bouguer anomaly maps are being produced with the scales of 1:100,000, 1:250,000, 1:1,000,000 and 1:5,000,000. As free-air values are calculated and stored in the computer, a free-air anomaly map could be made

at any time.

3.2 Local Gravity Surveys

Gravity data are widely used for the exploration of hydrocarbon deposits as well as of minerals. Surveys restricted to an exploration work are called "local gravity survey". A station interval mostly varies from a few metres to about five hundred metres. Rock density is determined to aid the geological interpretation and constructing gravity models.

4. National Gravity Committee

Gravity data are spread all over the country. Almost every institute engaged in exploration has a collection of data obtained mostly from field measurements. Such data should be organized in a proper way for easy access and retrieval. They have to be stored in a data bank so that a gravity data base of Indonesia will be established. Having considered problem that may arise in gravity collection and collation, a national gravity committee was established in 1989 by the name of Komite Gayaberat Nasional (or in English, National Gravity Committee). The purpose of this body is to make all gravity data in the country available in a data bank and to coordinate them using a specific format.

5. Conclusion and Recommendation

The followings are conclusion and recommendation.

1. Gravity data in Indonesia are scattered in many institutions engaged with exploration and scientific studies, such as Snellius II Expedition. Because the system of storage is not properly handled, it is not easy to be made available to parties involved with gravity map compilation.
2. Software for gravity net adjustment is hardly needed to help improve the accuracy of the reduction of anomaly.
3. Absolute gravity stations are recommended to be established in Indonesia. Location of such stations will have to be chosen at firm sites preferably in Java, Kalimantan, Sulawesi and Irian Jaya.

References

ADKINS, J. S., SUKARDI, S., SAID, H. and UNTUNG, M., (1978), A Regional Gravity Base Station Network for Indonesia, Direktorat Geologi, Publikasi Teknik Seri Geofisika, 6.

HEINZ, Ilk, (1989), Gravity Network Adjustment, TAT BAKOSURTANAL (publikasi terbatas).

HEINZ, Ilk, (1989), The Gravity Base Network of Indonesia, TAT BAKOSURTANAL (publikasi terbatas).

KOMITE GAYABERAT NASIONAL, (1989), Hasil Lokakarya Pengukuran Gayaberat, Sindangreret II, Cikole, Lembang, October 22-23, 1989 (tidak dipublikasi).

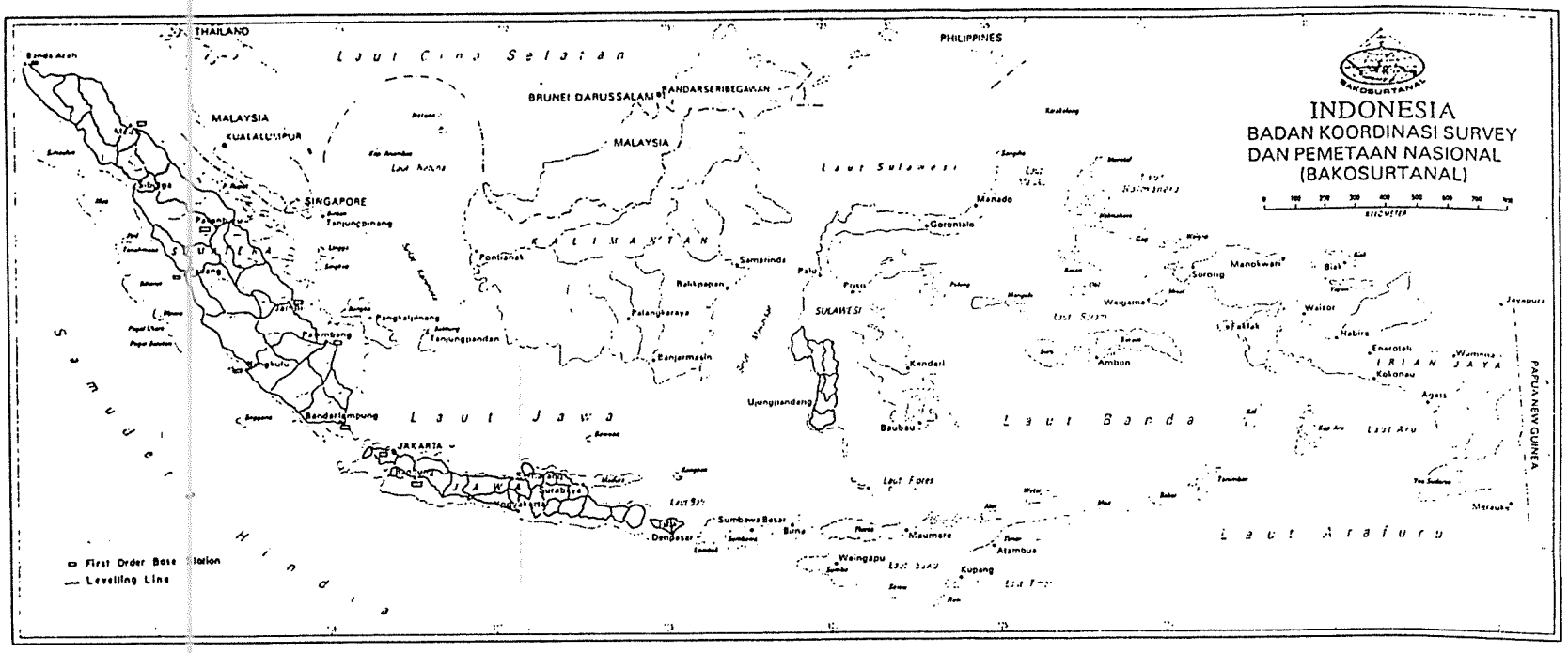
UNTUNG, M., (1972), Brief Information on Gravity Calibration Loop, Newsletter, Geol. Surv., Indonesia, 5.

Table 1. Gravimetric Network Summary made by BAKOSURTANAL (1986-1990)

Order	Location	Station Interval (km)	Number of		Gravimeter Employed	Measurement Method	Measurement Duration
			Station	Line (km)			
1st	Main airports in Sumatra	>200	8	-	3LCR	A-B-A	4 consecutive weeks by plane
	Jakarta and Bandung airports	>200	2	-	3LCR	A-B-A	4 consecutive weeks by plane
2nd	Along main roads in Java	2-10	880	3,250	1LCR	A-B-C-D, D-E-F,,,,	4 duration of weeks a year done by car
	Along main roads in Sumatra	2- 5	2,420	10,620	3LCR	A-B-C-D, D-E-F,,,,	7 consecutive months by car
	Along main roads in South Sulawesi	2- 5	470	2,072	3LCR	A-B-C-D, D-E-F,,,,	2 consecutive months by car

Table 2. Gravity Calibration Line

No.	Location	Number of		Gravity Difference (mgal)	Height Difference (m)	Traveling Time	
		Bench Mark	Line (km)			Without (h)	Using Instrument (h)
1	Subang - Tangkuban Perahu (Java)	6	30	276	1,300	1	6
2	Medan - Brastagi (Sumatra)	4	50	288	1,395	2	6



Gravity Network Map

INTERNATIONAL ASSOCIATION OF GEODESY

13th Meeting
of the
INTERNATIONAL GRAVITY COMMISSION

Subcommission - North America
Report on
Relative Gravity Networks

Toulouse, France September 11-14 1990

CANADA

Relative Gravity

Six relative gravity projects were completed in the last year:

1. 1025 gravity measurements were made on the ice in Peel Sound and Barrow Strait.
2. A co-operative survey with the U.S. Geological Survey collected 5600 kilometers of sea gravity measurements in Lake Huron and Georgian Bay.
3. A regional gravity survey in north-central British Columbia established approximately 850 gravity stations at 10 to 12 km intervals.
4. A geophysical survey in southern British Columbia established 200 gravity stations.
5. 500 gravity observations were made along five seismic profiles in Newfoundland.
6. A co-operative survey with the U.S. Geological Survey collected 4240 km of sea gravity measurements in the Strait of Georgia.

The National Gravity Database currently contains in excess of 600 000 data points.

Status of IGSN-71 Stations

The Canadian Gravity Standardization Net (CGSN) consists of 5585 stations (400 First Order and 5185 Second Order). Of these, 145 are common to IGSN-71. All stations in the CGSN are inspected at least once every 10 years. The current status of IGSN-71 stations in the CGSN is as follows:

No. of IGSN-71 stations	145
Destroyed	42
Obsolete (in existence but difficult to reach)	34
Active	69

Since 1972 there have been several thousand new measurements between CGSN stations of which about 1500 have been made directly between IGSN-71 stations.

Absolute Gravity

Twenty-two sites are proposed for absolute gravity stations (see table 1 and figure 1). All of these absolute stations are tied to the IGSN. The absolute gravity determinations at these stations will be used as datum control for the

readjustment of the Canadian Gravity Standardization Net 1980 (CGSN80) and in support of postglacial crustal rebound and secular change studies.

Figure 2 shows a comparison between IGSN-71 and recent absolute measurements in Canada. The relatively large errors in IGSN-71 at high gravity values are likely due to non-linearities in the LaCoste-Romberg gravimeters used to establish IGSN-71. Errors in IGSN-71 at high latitudes may, as well, be due to the fact that the highest absolute gravity measurement constraining IGSN-71 was at g=982.xxxx. Errors in IGSN-71 at high latitudes were recognized early in the 1970's. Accordingly, many additional ties to Resolute were made with new LCR gravimeters during that period. The results of the newer measurements were incorporated into the adjustment of the Canadian Gravity Standardization Net 1974 (CGSN74) which currently defines the gravity datum for Canada. In the 1974 adjustment, the datum was determined by entering the IGSN-71 gravity values with their appropriate weights. The effect of the error in the IGSN-71 value for Resolute is apparent.

Research

The Canadian Absolute Gravity Site (CAGS) established just north of Ottawa in 1987 is maintained on a continuous basis to provide a national absolute gravity reference value. Research into the effect of environmental influences such as rainfall, air pressure etc. on the absolute gravity instrument is in progress. Paramount in this research are the data from a GWR superconducting gravimeter that was installed at the site last year. This instrument will also be used for monitoring the dynamics of the Earth's core, the long term ground deformations associated with earthquakes and the long period gravity spectrum.

Information contributed by:
R. K. McConnell
Geological Survey, Canada

UNITED STATES

Relative Gravity

There are presently in the U.S. gravity data base 1 million land gravity observations covering the conterminous states and parts of Canada and Mexico and .8 million sea gravity observations covering the continental shelf areas of the Atlantic and Pacific oceans.

Status of IGSN-71 Stations

In the conterminous United States there are 369 IGSN-71 stations in 85 cities. In the last year 44 IGSN-71 stations were recovered bringing the total of recently recovered IGSN-71 stations to 252. The condition of these recovered stations is as follows:

Good condition	130
Poor condition	11
Searched for but not found	33
Destroyed	78

Judging from this 68 percent sampling of the IGSN-71 stations this is 30 percent of the stations either destroyed or not now recoverable since 1971. The IGSN-71 stations are then being lost at the rate of 1.6 percent per year. Of greater concern is the fact that in 15 of the cities visited there is now none or only one IGSN-71 station remaining. This would prorate to 26 cities out of the 85 in the U.S. where there is none or only one IGSN-71 station remaining (31 percent). The stations in the airport environs are being lost 24 percent faster than the stations in the center of the city.

There was no recovery attempted of the 46 IGSN-71 stations in Hawaii and Alaska.

In addition to the IGSN-71 stations discussed above there were 656 other IGB network stations visited. Of these stations:

Good condition	427
Poor condition	43
Searched for but not found	81
Destroyed	105

The only significant difference between the recovery of the IGB network stations and the IGSN-71 stations is that for

the IGB network the percent of stations that were recovered in good condition is twice as large.

Absolute Gravity

In the last four years the NGS has been using a Joint Institute for Laboratory Astrophysics (JILA) absolute gravity instrument to establish a national network of 54 absolute gravity reference stations (see table 2 and figure 3) and to observe gravity at a number of coastal stations as part of the sea level monitoring program. In the conterminous U.S. 39 absolute gravity stations have been established thus far. At 14 of these stations the tie to the IGSN-71 stations is also available at this time. These differences in gravity value (after removal of the Honkasalo term) are given in figure 4. A linear relationship exists for the station residuals along the east coast but the other station residuals show little correlation.

Information contributed by:
Robert E. Moose
National Geodetic Survey, USA

MEXICO

Relative Gravity

In the last ten years the following number of land gravity stations have been observed:

1981	1262	
1982	3054	
1983	4698	
1984	3685	
1985	2017	
1986	2237	
1987	1041	
1988	2726	
1989	2047	
1990	1800	(July)

It is estimated that there are now 200 000 data points in the Mexican Gravity Database.

Status of IGSN-71 Stations

There are 447 IGSN-71 stations in Mexico. Of these 71 percent still exist.

Absolute Gravity

No absolute gravity stations have as yet been established.

Information contributed by:
Antonio Hernandez-Navarro
Geodesia Fisica, Mexico

Table 1

ABSOLUTE GRAVITY SITES IN CANADA

Cantley - Canadian Absolute Gravity Site -(2)
Ottawa-(2)
Alert
Resolute Bay
Inuvik
Yellowknife
Churchill-(3)
Charlevoix
Schefferville-(3)
Kuujjuarapik-(3)
Calgary(Priddis)
Victoria
Myra Falls
Strathcona Dam
Pinawa
Algonquin Park(Algonquin Radio Observatory)-(2)
Whitehorse-(2)
Saskatoon-(2)
Penticton-(3)
Ucluelet
Nanoose Harbour
La Ronge

all stations are tied to IGSN

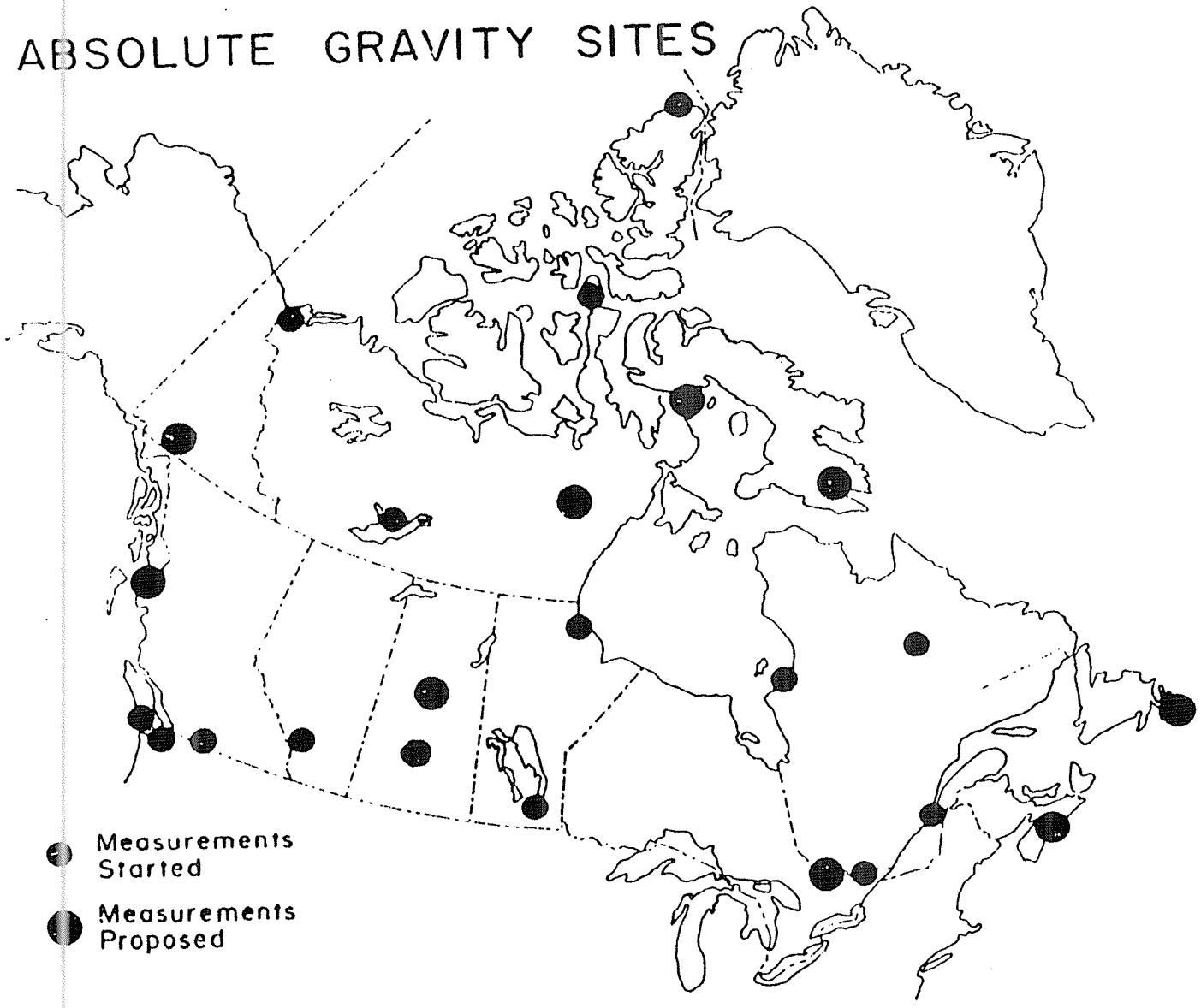

ABSOLUTE GRAVITY SITES
Measurements Started
Measurements Proposed

Figure 1

Table 2

U.S. Absolute Gravity Base Net Stations

Bangor, Maine
Westford, Massachusetts
Scranton, Pennsylvania
Greenbelt, Maryland
Gaithersburg, Maryland
Blacksburg, Virginia
Charlotte, North Carolina
Atlanta, Georgia
Valdosta, Georgia
Orlando, Florida
Miami, Florida
Buffalo, New York
Lansing, Michigan
Columbus, Ohio
Louisville, Kentucky
Memphis, Tennessee
Hattiesburg, Mississippi
Internatl. Falls, Minnesota
St. Cloud, Minnesota
Wausau, Wisconsin
Iowa City, Iowa
Sioux Falls, South Dakota
Rolla, Missouri
Kansas City, Missouri
DeQueen, Arkansas
Minot, North Dakota
Pierre, South Dakota
North Platte, Nebraska
Topeka, Kansas
Leonard, Oklahoma
Wichita Falls, Texas
Austin, Texas
Ft. Davis, Texas
Great Falls, Montana
Miles City, Montana
Sheridan, Wyoming
Casper, Wyoming
Loveland, Colorado
Mt. Evans, Colorado
Trinidad, Colorado
Gallup, New Mexico
Alamogordo, New Mexico
Newport, Washington
Idaho Falls, Idaho
Portland, Oregon
Elko, Nevada
Dutch John, Utah
Springdale, Utah
Quincy, California
Yosemite, California
Mojave, California
Pinyon Flat, California
Mt. Lemmon, Arizona
Tucson, Arizona

Gravity Change Absolute minus IGSN-71
differences in mgals uncertainty < 0.02 mgals

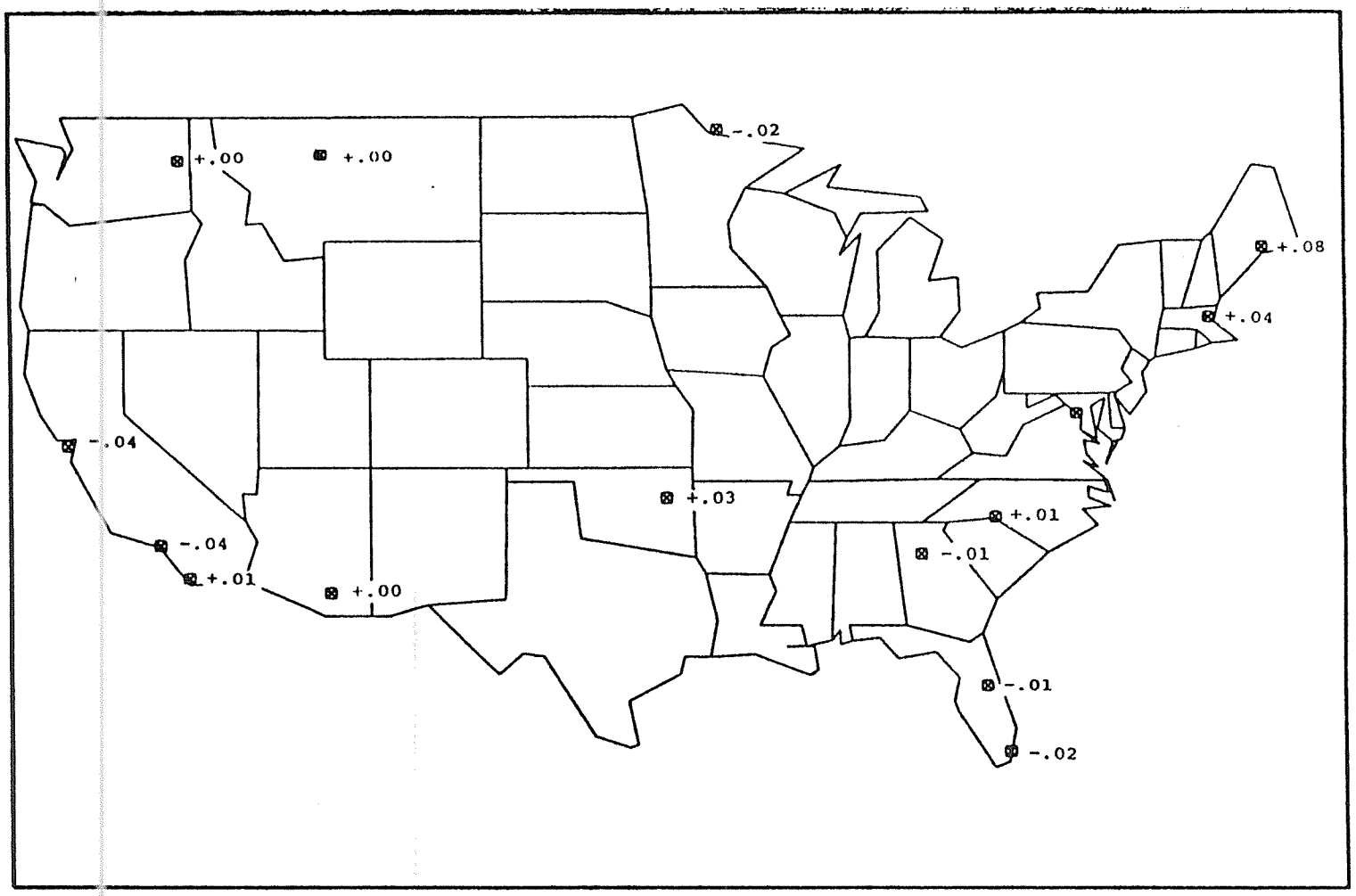
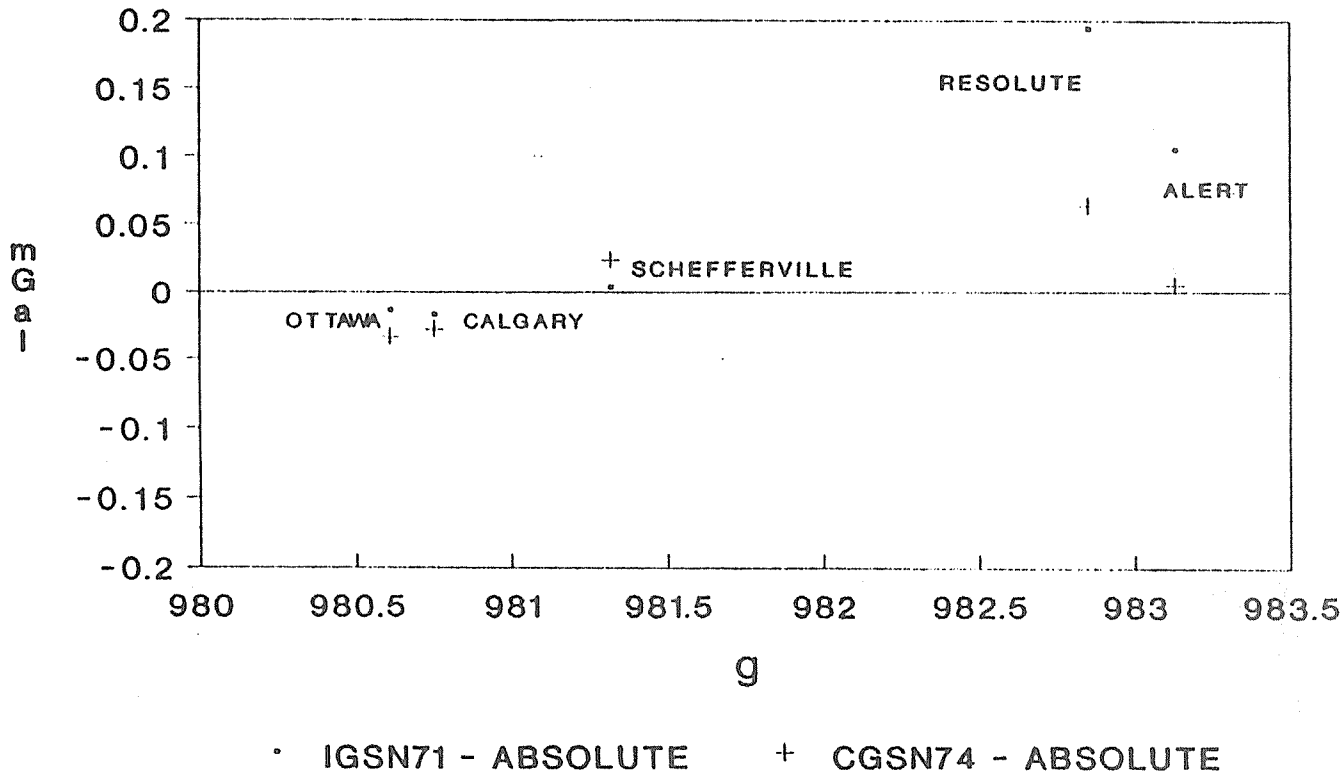


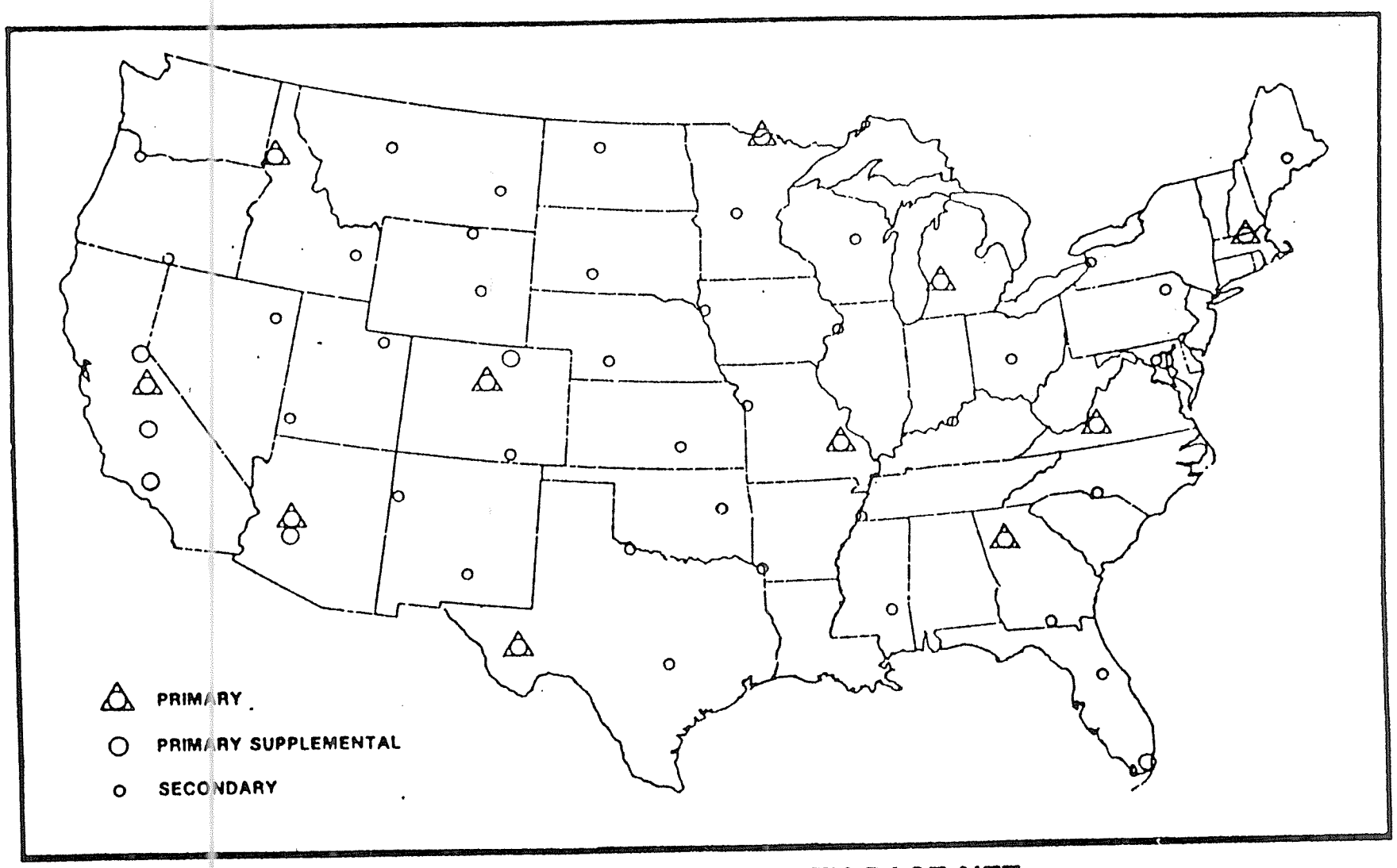
Figure 4

COMPARISON OF IGSN71 AND CGSN74 WITH RECENT ABSOLUTE MEASUREMENTS



AUG/90

Figure 2



U.S. ABSOLUTE GRAVITY BASE NET

Figure 3

INTERNATIONAL GRAVITY COMMISSION
SUBCOMMISSION FOR WESTERN EUROPE

ACTIVITY REPORT 1987/1990

Prepared by I. Marson

Introduction.

Since its establishment the SCWE has devoted the effort of its members to the promotion of activities in the framework of its role within the IGC. After the realization of the Catalogue of Coastal Gravity stations, in its first years of life, which has encountered, and still is, the interest of many gravity agencies, the SCWE has devoted its effort to the problem of gravity standardization. In this field the actions of the memebers of the Subcommission have been adressed towards the review of the status of IGSN71, the control of its accuracy level, and, when possible, of its maintanance. To this purpose, the Subcommission has promoted the common adjustment of the several national gravity networks, which have been performed in these last twenty years, to compute the so called Unified European Gravity Network. This project, initiated several years ago, has taken a large amount of time for the collection of all the needed original gravity observations, to overcome some difficulties due to the release of the original data by some countries, for their homogeization in a unique notation and format, and for the computation of the earth tide corrections. Nowadays, almost all the countries willing to partecipate have sent their data, allowing the directing board of the SCWE to announce the release of the UEGN for the next meeting of IUGG (Vienna, 1991).

Considering the growing importance of absolute gravimetry, especially in the frame of gravity standards, the SCWE has promoted the establishmnet and updating of a Catalogue of Absolute Gravity stations in Europe to allow for a large spread of information about this field of gravity activity which is considered by many scientists as the key tool for the solution of the standardization problem at its higher degree of accuracy.

Finally, an attempt to resort a NEWS LETTER has failed due to the lack of response.

STATUS OF IGSN71.

The SCWE has received from BGI a serie of microfiches containing the station descriptions of the entire IGSN71 system. Microfiches of interest have been sent to all the members of the Subcommission who have requested them. Several representative have send, in the course of these years, their response about the status of IGSN71 in their country. This information has been also transmitted to the BGI. In spite of the large amount of time allowed for the review (the first circular letter devoted to this topic goes back to April 1988), the review has not been fully realized. However, we do have now information concerning about 80% of the IGSN71 sites in Europe.

Judging from the letters and discussion with some of the

members, I have reached the conclusion that the IGSN71 system in Europe is nowadays rarely used as reference gravity net, having been superceded by national first order nets based, when possible on absolute sites, and tied to IGSN71. The main reason for this is related to the choice of many IGSN71 sites which was adequate for the 50's and 60's, but not anymore since the urbanization of several areas and the related structures (mainly roads and traffic) prevent in fact an easy access and use of several sites. It should also be considered that the higher sensitivity of the modern gravimeters does not allow for measurements in severe noisy sites. To this we should also add the fact that about 40% of the IGSN71 sites are actually destroyed. Therefore the most part of gravity observers rely on more modern networks, which may be based on IGSN71 standard, but actually are not IGSN71. A practical consequence of this is a slow, but continous abandonment of IGSN71, which is practically replaced by other networks or altogether by absolute sites.

Let us now examine, country by country, the status of IGSN71:

SWEDEN : there are 20 sites in the catalogue, but one of them (21562Q) is actually in Denmark. Four sites appear to be destroyed (21562K, 21581J, 21597J, 21597K). The station description of 21581T is missing. In Sweden 75% of IGSN71 is still available.

FINLAND : there are no original IGSN71 sites; however there are some 40 sites of the Finnish network tied to the IGSN71 system.

UNITED KINGDOM : all but two of the IGSN71 sites in Britain are considered of historical interest only, having been superceded by the National Garvity Reference Net (1973), whose scale and datum are in excellent agreement with IGSN71. In this case we are facing practically an obsolete system

BELGIUM : four sites out of seven have been destroyed; the remaining three are considered as obsolete because of difficulty in their access (21604L), poor ground stability (21604B), poor environmental conditions (temperature changes, 21604A). The criticism regarding these sites points the attention towards the site selection criteria and the sensitivity of modern gravimeters.

GERMANY : 45 sites out of 115 are certainly lost, which gives an estimate of 57% of IGSN71 sites which may still be used (some of these have slight changes in height)

AUSTRIA : shows the most severe situation with all the sites destroyed or obsolete.

SWITZERLAND : none of the eight sites appear to be destroyed, however IGSN71 is rarely used, having been substituted by th Swiss fundamental Net.

ITALY : there are 118 IGSN71 sites, 20 of them appear to be destroyed (17912P, 17912Q, 17912R, 17912S, 17912O, 17912N, 17912J, 17912B, 17904P, 17904J, 14396J, 14395L, 14375R, 14375R, 14375J, 14375B, 14374J, 18049R, 17930L, 17912M, 17912L), and 5 obsolete (17905P, 17905N, 17905J, 17904L, 17930N). Therefore, in Italy, 75% of IGSN71 is still available.

GREECE : no original IGSN71 sites are available, however IGSN71 standard has been transferred by means of ties to Rome and Edinburgh. There are at least 120 high precision gravity stations referred to the IGSN71 datum which are parts of several microgravimetric networks.

If the actual use of IGSN71 does not appear to be very intensive, its accuaracy in Europe is well within its confidence limits. This sentence is based on the comparison with absolute measurements made with the IMGC apparatus at IGSN71 sites (Fig 1), on a network realized with some of the 118 IGSN71 sites in Italy and measured with five La Coste Romberg gravimeters (Fig. 2) and on a readjustment of the original IGSN71 observations in Europe and the absolute measurements made with the IMGC instrument. Three different approaches which, however, give the same answer: considered its worldwide scale, the IGSN71 is still a valid Standardization Network.

UEGN.

The common adjustment of the Unified European Gravity Network might be a valid update of the IGSN71 system in Europe. To this purpose the Subcommission has collected, thanking to the kind cooperation of its memenbers, some 10000 original observations between about 500 sites. The countries which are partecipating with their data to the project are: Norway, Sweden, Finland, Denmark, United Kingdom, Netherland, Belgium, Luxemburg, Federal Republic of Germany, Austria, Switzerland, Italy and Portugal. From France, the Subcommission has received, so far, only the already adjusted national net. Greece might partecipate with some data not belonging to the first order gravity net (which is considered as confidential by the Hellenic Military Geographical Service). The Subcommission has also performed new measurements to strengthen the network, but more ties are still necessary. The data have been preprocessed to a unique notation and format, while the computation of earth tide parameters is underway. The adjustment of the network is taking more time than expected, but it should be considered that the Subcommission man-power is constituted only by its members (part time) without a specific financial support. To this regard the SCWE is gratefull to the CNR of Italy and DAAC of Germany, which have provided a financial support to allow dr. Boedecker and myself to spend a couple of months together to finalize the adjustment of the network.

CATALOGUE OF ABSOLUTE GRAVITY STATIONS.

The realization of a Catalogue of Absolute gravity stations is considered by the SCWE as a fundamental task for the near future. The impressive change, from an operative point of view,

given to Absolute gravimetry by the release of the JILA type gravimeters has allowed an intensive use of this tool in several areas which range from geodetic metrology to the monitoring of time-dependent gravity variations. In Western Europe five transportable absolute gravimeters are now available for field work (and others are announced) so that the number of new or repeated absolute sites is rapidly increasing. All the international gravity comunity may have a benefit from this fact, therefore it would be really worthwhile to have a continously updated Catalogue, which reports stations descriptions and gravity values. This idea, which has encountered the favour of several members of SCWE, will be further discussed within the members of IGC, since its realization requires the constant cooperation of several intersted scientists some of them not members of the SCWE.

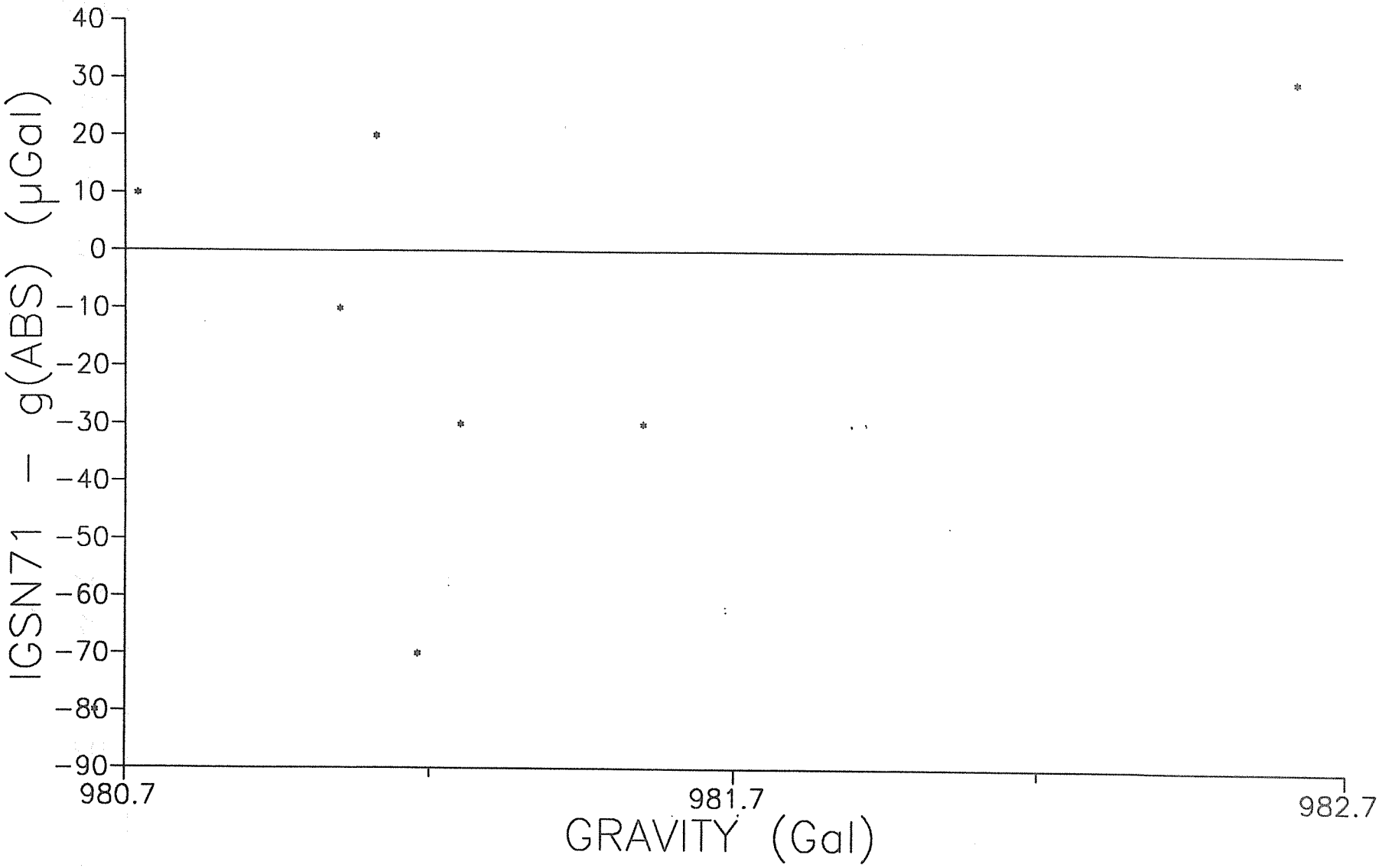


FIG 1. Difference between IGSN71 and Absolute measurements.

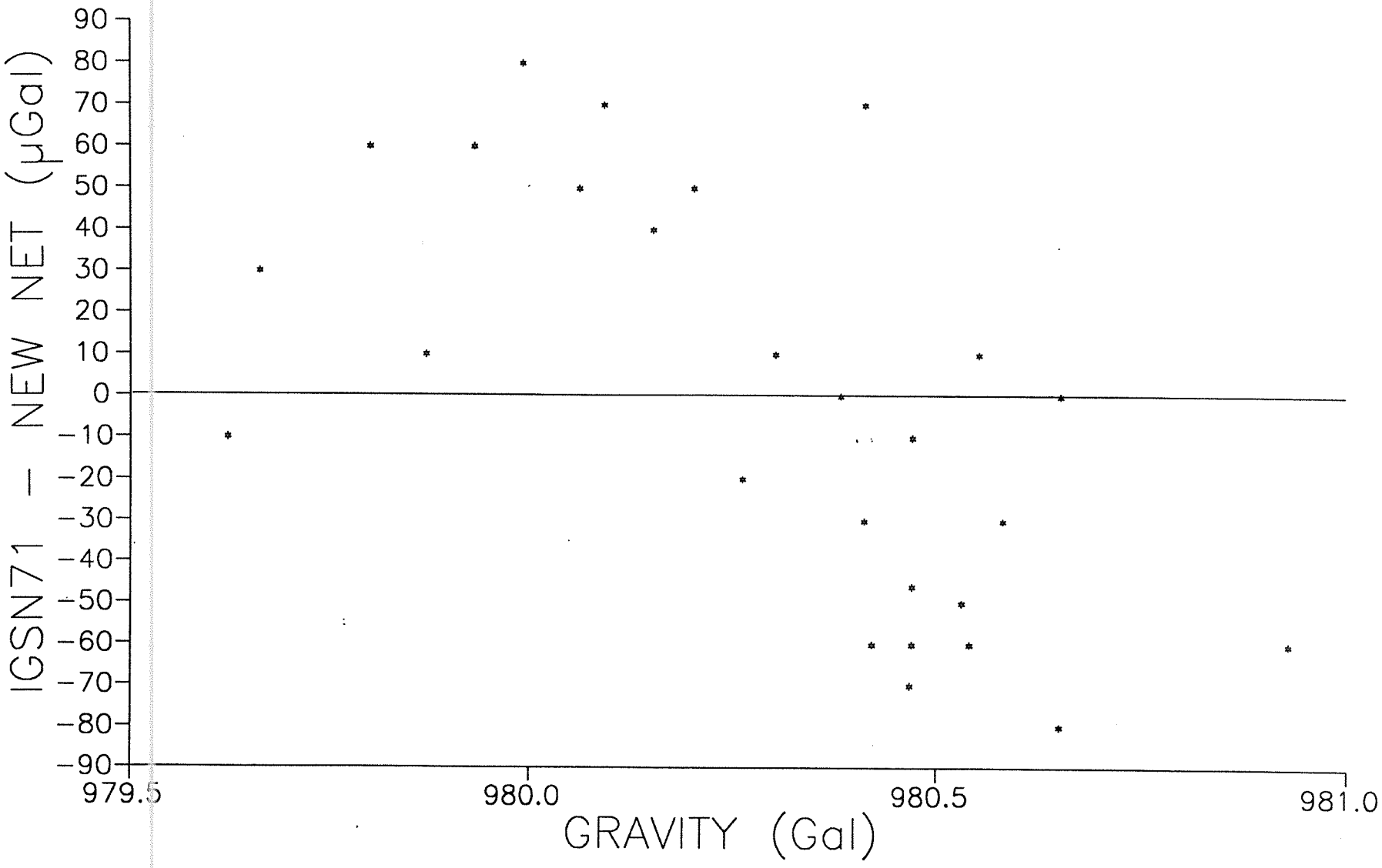


FIG 2. Differnce between IGSN71 and a new network based on IGSN71 sites.

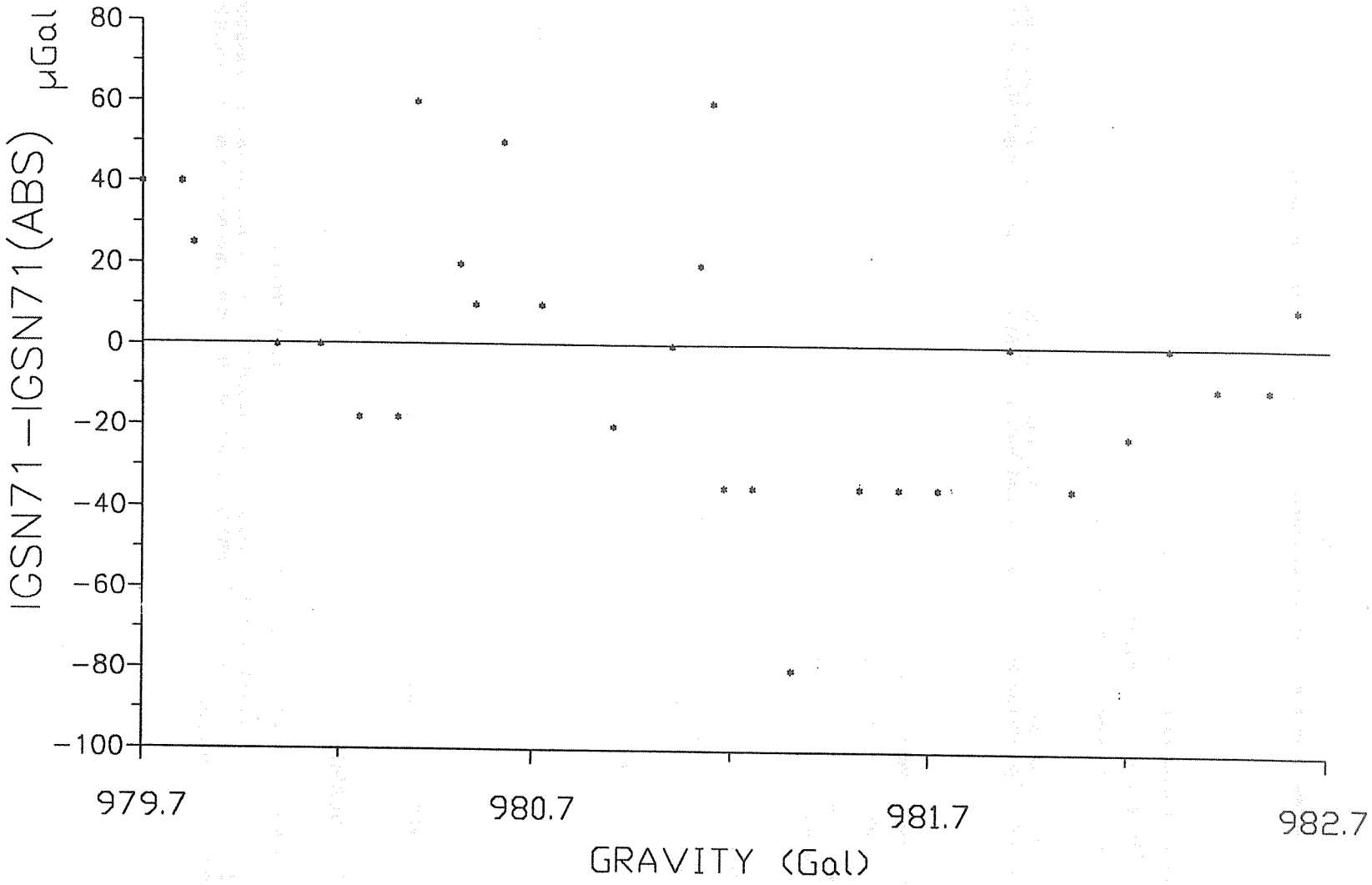


FIG 3. Difference between IGSN71 and the results of a readjustment of the network based on Absolute measurements.

OTHER ADMINISTRATIVE MATTERS
DISCUSSED BY IGC GENERAL ASSEMBLY
Sept. 13, 1990

FORMAT FOR NATIONAL REPORTS

National reports are intended to be a summary of activities in the general field of gravimetry in the respective countries during the specified period (see approved program and functions of the IGC in the Geodesist's Handbook).

A. CONTENT

Such reports should cover the following areas :

a) Regional gravimetry (gravity mapping)

b) Microgravimetry

c) Gravity reference networks

d) Gravity data base activities

e) Instrumental developments and investigations

f) Other studies in gravimetry
   i) interpretation and analysis
   ii) theoretical studies

g) Software development

h) Bibliography (reference list)

   Example : Agar, C.A. and Liard, J.O. 1982. Vertical gravity gradient surveys : field results and interpretations in Bristish Columbia, Canada, Geophysics, 47, 919-925.

B. FORMAT

Each report should be typed double spacing on A4 paper (margin : 3 cm) and should not exceed 7 pages (excluding bibliography).

C. GUIDELINES FOR SUBMISSION

a) National reports on gravimetry are to be submitted as part of the overall national reports to the IAG General Assembly.

b) In order for the President of the Commission to prepare a summary report of Commission activities to the quadrennial meeting of the IAG, members are asked to send a summary of national activities in gravimetry to the President at least six months before the IAG meeting.

NOMINATION PROPOSALS

The following have been proposed and approved by the IGC assembly. They will have to be endorsed by the IUGG at its next general meeting in Vienna (August 1991) :

IGC

President :	I. MARSON/Italy
1st Vice President :	G. BOEDECKER/F.R.G.
2nd Vice President :	J. MAKINEN/Finland
Secretary :	N. COURTIER/Canada

BGI Directing Board

P. MEDVEDEV/U.S.S.R. to replace Pr. Yu.D. BOULANGER
E. GROTEN/F.R.G. to replace Pr. J. KRYNSKI

RESOLUTION

The International Gravity Commission

- recognizing the efficient and valuable service which the Bureau Gravimétrique International provides to the world geoscientific community and,
- recognizing the support in the form of office space, staff and operational funding, currently provided to the Bureau by the Institut Géographique National, the Centre National d'Etudes Spatiales, the Centre National de la Recherche Scientifique, the Institut National des Sciences de l'Univers, the Bureau de Recherches Géologiques et Minières (France),
- requests the President of the Commission to formally thank these organizations for their support and emphasize the importance of the Bureau to future international geoscience projects.

13th MEETING OF THE INTERNATIONAL GRAVITY COMMISSION

(September 10-14, 1990)

Tuesday, Sept. 11

a.m. Registration

OPENING ..... J. Tanner, G. Balmino

Administrative Session ..... Chairman : J. Tanner

I.G.C. Reports ..... J. Tanner

Technical Reports of the Working Groups ..... W.G. Chairmen

BREAK

Technical Reports of the Working Groups (cont.) ..... W.G. Chairmen

Report of BGI ..... G. Balmino

LUNCH

p.m. Administrative session (cont.)
Reports of Sub-Commissions ..... Presidents of S.C.

IGC Next four year program
General Assembly in Vienna : activities
Next (14th.) IGC general meeting ..... Discussion moderator : J. Tanner

BREAK

Scientific Session n° 1
High Precision Relative Gravity Measurements :
Part 1 : Instrumental Techniques ..... Chairman : E. Groten

Ducarme B., M. Van Ruymbeke :
New Feedback Electronics for LaCoste & Romberg Gravimeters

Becker M. : High Precision Gravimetry (CANCELED), Replaced by

Ducarme, B., N. D'Oreye : Preliminary Test of the Maximum Voltage Retroaction (NVR) System VRD 90.

Wenzel H.G. :
The Hornisgrinde Black Forest Gravimeter Calibration Line

Wednesday, Sept. 12

a.m. Scientific Session n° 2
High Precision Relative Gravity Measurements :
Part 2 : Environmental Problems and Applications ..... Chairman : Ch. Poitevin

Gerstenecker C. :
Temperature Effects on Gravimeters

Wang Qian Shen :
The Microgravity Survey of the Ming Dynasty Emperor Mausoleum and its Interpretation (CANCELED)

Elstner C. :
Results of High Precision Gravity Measurements (CANCELED)

Tresl J. :
Man-made Gravity Changes in a Coal Mining Area (CANCELED)

Steiman M. :
Microgravimetry & Gravity Gradients (CANCELED), Replaced by :

Vitushkin L.F., D.I. Mendeleyev :
Precision Laser Interferometry and Measurement of Gravity Potential Second Derivatives

BREAK

Ajakaiye D.E. :
Environmental Problems in Precise Relative Gravity Measurements under Tropical Conditions (CANCELED), Replaced by :

Ekman M., J. Makinen :
Land Uplift and Gravity Change in Fennoscandia 1966-1989

Scientific Session n° 3
Gravity Campaigns ..... Chairman : G. Balmino

Nagar V.K. :
Report on Gravimetric Work Done in India (CANCELED)

Tealeb A.A. :
Report on Gravity Measurements in Egypt (CANCELED)

Sledzinski :
Geokart Activities in Gravimetry (CANCELED)

Bhattacharji J.C. :
Geodesy in Himalaya (CANCELED)

Roder R.H., W. Torge, M. Schnüll, L. Timmen, Jia Minyu, Xu Jusheng, Sun Heping, Xing Canfei :
High Precision Gravity Control Network in Yunnan/China 1990

LUNCH

p.m. Leontiev I. :
Gravity Changes at Large Gas Fields

Hsu H.T. :
Precision Gravity Measurements for Oil Exploration (CANCELED)

Boedecker G. :
Terrain Effects from Series Developments Using FFT Methods

Scientific Session n° 4
New Regional Gravity Maps ..... Chairman : J. Tanner

Ajakaiye D.E. :
New Gravity Map of Nigeria (CANCELED)

Izzeldin A.Y. :
Main Features of the Gravity Map of Sudan (CANCELED)

BREAK

Fairhead D. :
Regional Gravity Maps and Projects in Africa, South America, South-East Asia and Europe

Chevalier P. :
The African Gravity Project (AGP)

Windle I. :
The South America Gravity Project (SAGP)

Bowin C. :
Free-Air Gravity Anomaly Map of the World, 2nd. Edition (CANCELED), Replaced by :

Medvedev, P.P., V.V. Bojkov et al. :
Comparison of Gravimetric, Altimetric and Satellite Tracking Data on the Earth's Global Gravity Field

Hipkin R. :
Regional Gravity for the British Isles and N.W. European Shelf

Kogan M.G. :
The Ground-Truth Check of New Global Gravity Field Models (CANCELED), Replaced by :

Kopayev, A.V., V.K. Milukov, V.N. Rudenko, V.D. Yushkin :
Precise Gravimetric Observations at Belomorsk During the Full Solar Eclipse on July 22, 1990

Makris J. :
Regional Gravity of the Red Sea and East Africa (CANCELED)

Thursday, Sept. 13

a.m. Scientific Session n° 5
Intercomparison of Absolute Gravimeters..... Chairman : I. Marson

Becker M., B. Bernard, Yu.D. Boulanger et al. :
Gravity Measurements at the 3rd International Comparison of Absolute Gravimeters

Boulanger Yu.D. :
Results of the 3rd. International Comparison of Absolute Gravimeters in Sèvres.

BREAK

Faller J. :
The JILA Absolute Gravimeter : What's Happening ?

Chartier J.M. :
Behaviour of Stabilized Lasers Used in Absolute Gravimeters

Torge W., Roder R.H., Elstner C., Timmen L. :
Absolute and Relative Gravity Measurements at Hannover and Potsdam in the Period 1988-1990

Discussion

LUNCH

p.m. Scientific Session n° 6
Absolute Measurements and IAGBN ..... Chairman : G. Boedecker

Makinen J., R. Vieira, A.G. Camacho, M.J. Sevilla :
Absolute Gravity Measurements in Madrid

Qiu Qixian :
The Results of Horizontal and Vertical Gradient Measurements at Beijing Station and IAGBN (CANCELED)

Kopayev :
Absolute Gravimetry and Gravity Gradients

BREAK

Ruess D. : Absolute Gravity (CANCELED)

Klopping F.J., G. Peter :
Floor-Gravimeter System Response on JILAG 4

Boedecker G. :
Status of IAGBN (text already published in issue n° 66 of B.I.)

(Evening : IGC Dinner)

Friday, Sept. 14

a.m. Scientific Session n° 7
Non Newtonian Gravity Experiments..... Chairman : J. Faller

Faller J. :
Validation of the Inverse Square Law of Gravitation Using the 300 m Tower at Erie, Colorado : Newton Saved on the Plains of Colorado !

Tscherning C.C. :
Re-Analysis of the Tower Gravity Experiment (CANCELED)

Romaides A.J., P. Kasameyer :
A Tower Gravity Experiment ; Past, Present and Future

Shaw G.L., A.J. Romaides :
Third Generation Gyro - No Evidence for Anomalous Weight Reduction

Eckhardt, D.H. :
Majorana Shielding (distributed)

BREAK

Hipkin R. :
Testing Newton's Law in an Underwater Tower

Quinn T.J. :
Fifth Force and Gyroscope Experiments at the BIPM

Denis M. :
Experiments on Gravity Anomalies During the Total Eclipse in Finland on 22 July 1990

Savrov L. :
Gravity Observation During the Total Solar Eclipse of July 22, 1990 in the Region of Bielomorsk

Makinen J. :
Gravity Measurements During the July 22, 1990 Eclipse in Finland

LUNCH

p.m. Scientific Session n° 8
Dynamic Gravimetry and Gradiometry ..... Chairman : R. Rummel

Peters M.F. :
Airborne Gravimetry

Hein G. W. et al. :
Experiments for an Integrated Precise Airborne Navigation and Gravity Recovery System (CANCELED)

Hsu H.T. :
Gravimetric Test in Helicopter (CANCELED)

Rummel R. :
ARISTOTELES, Surface Gravity from Space Geometry

BREAK

Touboul P., A. Bernard :
GRADIO Spaceborne Gravity Gradiometer - invited -

Migliaccio F., F. Sanso, M. Brovelli :
Inversion of an overdetermined Boundary Value Problem - Theory and Results

Balmino G., J.P. Barriot :
Methods of Global Recovery of Harmonic Coefficients from SGG in the General Case - invited -

Klingele E.E., I. Marson :
Interpretation of Gradiometric Data.

CLOSURE OF I.G.C. MEETING

LIST OF PARTICIPANTS

NOM	ADDRESS	PHONE	FAX	TELEX
BALMA G.	BUREAU GRAVIMETRIQUE INTERNATIONAL 18, Avenue E. Belin 31055 TOULOUSE CEDEX FRANCE	61.33.28.91	61.25.30.98	530776 F
BALMINO G.	BUREAU GRAVIMETRIQUE INTERNATIONAL 18, Avenue E. Belin 31055 TOULOUSE CEDEX FRANCE	61.33.28.89	61.25.30.98	530776 F
BAYER	CENTRE GEOLOGIQUE & GEOPHYSIQUE U.S.T.L. Place Eugène Bataillon 34060 MONTPELLIER Cedex FRANCE	67.63.49.83		
BERTHAULT	28, Blvd. Thiers 78250 MEULAN FRANCE	34.74.29.26		
BOEDECKER G.	BAYER AKADEMIE D. WISSENSCH. Marstallplatz 8 D-8000 MUNCHEN 22 F.R.G.	(89) 23031212	(89)23031240	5213550
BOUET J.	6, Avenue de Mannassé 91540 MENNECY	45.50.74.90		F
BOULANGER J.D.	SOVIET GEOPHYSICAL COMMITTEE Ul. Molodezhnaya 3 117296 MOSCOW USSR	9300546		411478 SGC SU
BROVELLI M.	ITM - POLITECNICO DI MILANO Piazza Leonardo da Vinci, 32 20133 MILANO ITALY	(021) 23996507	(021)23990530	333467 POLIMI I
CHARTIER J.M.	B.I.P.M. Pavillon de Breteuil 92310 SEVRES FRANCE	16.1.45.07.70.51	16.1.45.34.20.21	201067 P
CHEVALLIER P.	UNIVERSITY OF LEEDS INDUSTRIAL SERVICES LTD. 175, Woodhouse Lane LEEDS LS2 3AR UNITED KINGDOM	44.0532.333.444	44.0532.429.234	556473 UNILDS G
DENIS M.	7, Rue Gustave Charpentier 78370 PLAISIR FRANCE	16.1.30.54.23.43		
DEMIANOVA T.	INSTITUTE OF EARTH PHYSICS ACADEMY OF SCIENCES USSR B. GRUZINSKAYA 10 123810 MOSCOW USSR	2542496		
DUCARME D.	OBSERVATOIRE ROYAL DE BELGIQUE Avenue Circulaire 3 B-1180 BRUXELLES BELGIUM	32.02.373.02.11	32.02.374.98.22	21565 OBSBEL
EDJE R.J.	PROUDMAN OCEANOGRAPHIC LAB. BIDSTON OBSERVATORY Birkenhead WIRRAL L60 6RP UNITED KINGDOM	051.653.8633	051.653.6269	628591
FAIRHEAD J.D.	UNIVERSITY OF LEEDS INDUSTRIAL SERVICES LTD. 175, Woodhouse Lane LEEDS LS2 3AR UNITED KINGDOM	44.0532.333.444	44.0532.429.234	556473 UNILDS G

NOM	ADDRESS	PHONE	FAX	TELEX
FALLER J.	JILA CAMPUS BOX 440 UNIVERSITY OF COLORADO BOULDER, Colorado 80309 U.S.A.	(303)492-8502	(303)492-5235	855942
GERSTENECKER C.	INSTITUT FUR PHYSIK GEODASIE TECHNISCHE HOCHSCHULE Petersenstrasse 13 D-6100 DARMSTADT F.R.G.	(6151)163209		
GIL A.J.	INSTITUTO DE ASTRONOMIA Y GEODESIA FACULTAD DE CIENCIAS MATEMATICAS UNIVERSIDAD COMPLUTENSE CIUDAD UNIVERSITARIA 28040 MADRID SPAIN	(91)244.25.01	(91)243.94.89	41802 UCMAT E
GROTEN E.	TECHNICAL UNIVERSITY INSTITUTE OF PHYSICAL GEODESY Petersenstrasse 13 D-6100 DARMSTADT F.R.G.	(6151)163109	(6151)165489	4199579 TH D
HALLER L.A.	LANTMATERIVERKET S-80182 GAVLE SWEDEN	(46)26 153737	(46)26 128400	47359 LMV S
HIPKIN R.	EDINBURGH UNIVERSITY Dept. of Geology & Geophysics JCMB Mayfield Road EDINBURGH, EH9 ZJZ UNITED KINGDOM	44.031.6671081 ext. 2951	44.031.6624712	727442 UNIVED G
HUNT N.	UNIVERSITY OF LEEDS INDUSTRIAL SERVICES LTD. 175, Woodhouse Lane LEEDS LS2 3AR UNITED KINGDOM	44.0532.333.444	44.0532.429.234	556473 UNILDS G
HSU H.T.	INSTITUTE OF GEODESY & GEOPHYSICS CHINESE ACADEMY OF SCIENCES Xu Dong Road 54 WUHAN CHINA	813401-362		40170 WCTEL CN
JEVERDAN G.	INST. POLYTECHNIQUE DE IASI IASI ROUMANIA			
KIVINIEMI E.E.	FINNISH GEODETIC INSTITUTE ILMALANKATU 1A 00240 HELSINKI FINLAND	358.0.410433	358.0.414946	
KOPAYEV A.V.	STERNBERG STATE ASTRONOMICAL INSTITUTE UNIVERSITETSKY PROSP. 13 V-237 MOSCOW 119899 U.S.S.R.	939-53-27		
LEONTIEV I.	NDO "SOJUZGASTECHNOLOGY" USSR MOSCOW REGION Leninsky district vil Kazvilka VNIIGAZ U.S.S.R.	399-93-60		846462 PLAST
LINDNER K.	GEODATISCHES INSTITUT UNIVERSITAT KARLSRUHE Englerstrasse 7 D-7500 KARLSRUHE 1 F.R.G.	721-6084129		
LOUIS P.	CENTRE GEOLOGIQUE ET GEOPHYSIQUE U.S.T.L. Place Eugène Bataillon 34060 MONTPELLIER Cedex FRANCE	67.63.49.83		
LOUIS M.	ASSOCIATION INTERNATIONALE DE GEODESIE 140, Rue de Grenelle 75700 PARIS			

NOM	ADDRESS	PHONE	FAX	TELEX
McCONNELL	GEOLOGICAL SURVEY OF CANADA Geophysics Division 1, Observatory Crescent OTTAWA, Ont. K1A OY3 CANADA	1.613.995.5307	1.613.952.8987	0533117 EMAR OTT
MAKINEN J.	FINNISH GEODETIC INSTITUTE Ilmalankatu 1A SF-00240 HELSINKI FINLAND	358.0.410433	358.0.414946	
MARSON I.	IST. MINIERE E GEOFISICA APPLI-CATA Via Valerio 10 34100 TRIESTE ITALY	39-(0)40-568201	39-(0)40)-5603176	460014 FISICA I
MEDVEDEVP P.	SOVIET GEOPHYSICAL COMMIT-TEE U.S.S.R. Molodezhnaya 3 MOSCOW 117296 U.S.S.R.			411478 SGC SU
MIGLIACCIO F.	ITM - POLITECNICO DI MILANO Piazza Leonardo da Vinci 32 20133 MILANO ITALY	02/23995507	02/23996530	333467 POLIMI I
MORELLI C.	UNIVERSITA DI TRIESTE IST. MINIERE E GEOFISICA APPLI-CATA 34136 TRIESTE ITALY	040/52465	040/560.3176	460014
NAKAGAWA I.	DPT. OF GEOPHYSICS KYOTO UNIVERSITY Sakyo-Ku KYOTO 606 JAPAN	075-753.3911	075-753.3917	5422302 SCIKYU J
PETER G.	NOAA/NGS - Code N/CG114 11400 Rockville Pike Rockwall Bldg., Room 426 B ROCKVILLE, Md. 20852 U.S.A.			
PETERS M.F.	DEPT. OF THE NAVY Code 5110 NAVAL RESEARCH LABORATORY WASHINGTON, D.C. 20375-5000 U.S.A.	(202)767-2024	(202)767-1067	
POITEVIN C.	OBSERVATOIRE ROYAL DE BEL-GIQUE Centre de Géophysique Interne Avenue Circulaire 3 B-1180 BRUXELLES BELGIUM	32.2.373.0211	32.2.374.9822	29565 OBSBEL B
QUINN T.J.	B.I.P.M. Pavillon de Breteuil 92312 SEVRES CEDEX FRANCE	1.45.07.70.70	1.45.34.20.21	
RICHTER B.	INSTITUT FUR ANGEWANDTE GEODASIE Richard Strass Allee 11 D-6000 FRANKFURT M70 F.R.G.			
ROLAND E.	NORWEGIAN MAPPING AUTHOR-ITY N-3500 HONEFOSS NORWAY	47.67.24100	47.67.26190	79636 KARTV-N
ROMAIDES A.	AIR FORCE GEOPHYSICS LAB-ORATORY HANSCOM AFB/LWG BEDFORD, Mass. 04731 U.S.A.	617.377.3486	617-377-2707	928123
RUESS D.	FEDERAL OFFICE FOR METROLOGY AND SURVEYING Schiffamtsgasse 1-3 A-1025 WIEN AUSTRIA	(0222)35.76.11-23 12	(0222)216.10.62	115468 BEVWN A

NOM	ADDRESS	PHONE	FAX	TELEX
RUKAVISHNIKOV R.B.	INSTITUTE OF PHYSICS OF THE EARTH B. Grusinskaya 10 MOSCOW D-242 USSR	254-45-59		
RUMMEL R.	DELFT UNIVERSITY OF TECHNOLOGY FACULTY OF GEODESY Thijsseweg 11 2629 JA DELFT NETHERLANDS	31.15.785100	31.15.782348	38151 BHT HD NL
SAKUMA I.	B.I.P.M. Pavillon de Breteuil 92312 SEVRES CEDEX FRANCE	1.45.07.70.70	1.45.34.20.21	
SANSO F.	ITM - POLITECNICO DI MILANO Piazza Leonardo da Vinci 32 20133 MILANO ITALY	02/23996504	02/23996530	333467 POLIMI I
SARRAILH M.	BUREAU GRAVIMETRIQUE INTERNATIONAL 18, Avenue E. Belin 31055 TOULOUSE CEDEX FRANCE	61.33.28.93	61.25.30.98	530776 F
SAVROV L.A.	ASTRONOMIC STERNBERG INSTITUTE MOSCOW UNIVERSITY MOSCOW U.S.S.R.	(095) 939-53-27	(095) 939-01-26	411483 MGU SU
SEBA A.	SONATRACH Direction des Etudes et Synthèses Département Géophysique Capitaine Azzoug Côte Rouge Hussein Dey ALGER ALGERIA	77.12.77-662600		65405
SEVILLA M.J.	INSTITUTO DE ASTRONOMIA Y GEODESIA FACULTAD DE CIENCIAS MATEMATICAS UNIVERSIDAD COMPLUTENSE 28040 MADRID SPAIN	(91)2.435637	(91)2.43.94.89	41802 UCMAT E
SMITH I.F.	BRITISH GEOLOGICAL SURVEY BGS KEYWORTH NOTTINGHAM NG12 5GG UNITED KINGDOM	06077 6111 ext 3391	00077 2227	
STEIMAN M.B.	NPO "SOJUZGASTECHNOLOGY" USSR MOSCOW REGION LENINSKY DISTRICT VII Razvilka VNIIGAZ U.S.S.R.	399-94-77		846462 PLAST
STEINHAUSER P.	ZENTRALANSTALT FUR METEOROLOGIE UND GEODYNAMIK Hohe Warte 38 1-1190 WIEN AUSTRIA	0222.36.44.53/2001	329.12.33	131837 A METW A
TANNER J.	R.R. N°1 UNION, ONTARIO NOL 2LO CANADA	1.519.631.3190	1.519.633.4997	
TIMMEN L.	INSTITUT FUR ERDMESSUNG UNIVERSITY OF HANNOVER Nienburger strasse 6 D-3000 HANNOVER 1 F.R.G.	0511.7623452	0511.7624006	
TORGE W.	INSTITUT FUR ERDMESSUNG UNIVERSITY OF HANNOVER Nienburger strasse 6 D-3000 HANNOVER 1 F.R.G.	0511.7622795	0511.7624006	923868 UNIHN D

NOM	ADDRESS	PHONE	FAX	TELEX
TOUSTOU D.	BUREAU GRAVIMETRIQUE INTERNATIONAL 18, Avenue E. Belin 31055 TOULOUSE CEDEX FRANCE	61.33.28.90	61.25.30.98	530776 F
TSCHERNING C.C.	GEOPHYSICAL INSTITUTE Haraldsgade 6 DK-2200 COPENHAGEN N DENMARK	45.31.810447	45.35.822.565	16469
VALES Nicole	BUREAU GRAVIMETRIQUE INTERNATIONAL 18, Avenue E. Belin 31055 TOULOUSE CEDEX FRANCE	61.33.28.92	61.25.30.98	530776 F
VIEIRA R.	INSTITUTO DE ASTRONOMIA Y GEODESIA FACULTAD DE CIENCIAS MATEMATICAS UNIVERSIDAD COMPLUTENSE 28040 MADRID SPAIN	91.2442501	91.2439489	41792 UCMAT E
VITUSHKIN L.	MENDELEYEV INSITUTE OF METROLOGY MOSKOVSKY PR. 19 198005 LENINGRAD USSR	2591039		
WENZEL H.G.	GEODATISCHES INSTITUT UNIVERSITAT KARLSRUHE Englerstrasse 7 D-7500 KARLSRUHE 1 F.R.G.	49.721.6082307	49.721.694552	721166 UNIKAR
WINDLE I.	UNIVERSITY OF LEEDS DEPT. OF EARTH SCIENCES LEEDS L52 9JT UNITED KINGDOM	532.431751 ext. 6470		

New feedback electronics for La Coste & Romberg gravimeters

M. Van Ruymbeke
Centre de Géophysique Interne
Observatoire Royal de Belgique
avenue Circulaire, 3
B-1180 Brussels

SUMMARY

Since several years we develop a feedback electronics called "Maximum Voltage Retroaction" to replace the original CPI card. The feedback voltage is applied to the capacitor selected by rates of charge comparison for the two arms of the bridge. The force and the range are directly proportional to the square of the voltage.

For an high precision system with a large range it is necessary to increase both feedback voltage and selection frequency to improve the S/N ratio.

Main technical problems are to minimize delay and hysteresis.

The output is under analogical and digital forms (on/off cycle counting).

Up to now we tested three different prototypes : (Van Ruymbeke M. 1989, 1990).

1. Introduction

To install feedback electronics on a gravimeter it is necessary to apply a variable force in order to keep the moving mass at a fixed positions.

Besides the mechanical feedback implemented by LaCoste on the early ET meters, two methods have been experienced :

1. the force is produced by the action of a variable magnetic field on a permanent magnet (Orejana & Vieira, 1983),

2. differential electrostatic force is applied on the plates of a built in capacitive bridge. This method was first developed by Larson (1966) to modify the ET meters and later on applied to LaCoste & Romberg (LCR) model G and D meters (Harrison & Sato, 1984; Van Ruymbeke, 1985; Röder & Alii 1987).
   In Larson's and Harrison - Sato technics the restoring force is directly proportional to the square of the modulated voltage difference. It is also possible to replace this modulated force by the action of a constant force applied discontinuously (Vaillant & Alii, 1986). This principle is called Pulse Width Modulation (P.W.M.).

We realized one step further by using the excitation voltage of the PWM system to measure directly the capacities of the bridge (Van Ruymbeke, 1989 and 1990). The built in CPI card of the LCR meters is no more necessary. The important advantage is the direct connexion of one capacitor plate to the ground. For a gravimeter only the two fixed plates have to be electrically isolated and the moving mass can be grounded.

2. The Maximum Voltage Retroaction (M.V.R.) Principle.

The Maximum Voltage Retroaction (M.V.R.) is a special case of classical electrostatic feedback. If one increases indefinitely the gain of the retroaction loop, the signal will induce a maximum force on one capacitor and no force on the other or inversely. Let us adapt a system (figure 1) to determine during the charge of the capacitors which one has the smallest capacity. It corresponds to the circuit with the fastest charge rate (minimum RC value) and also to the too large gap between the moving mass and the fixed plates of the capacitive transducer. The applied voltage will exert a maximum electrostatic attraction that will move the plate back to the center and finally overshoot the equilibrium position if no reset is applied. After a short interval a new selection will operate and each time the full feedback force will be applied to the smallest capacitor. The system is autostabilizing and can be connected with any polarity. The gain is infinite. The mean force applied to the system is obtained by analogic filtering or by directly counting the number of cycles with direct or inverse polarity.

A small hysteresis between the positions where the signals reverse when the mass goes up or down may induce a residual oscillation of the beam.

There are two main adjustable parameters : the applied voltage and the delay between two selections.

The range increases as the square of the voltage so that 40 volts insures a 60 milligal range for a LaCoste & Romberg gravimeter.

It is difficult to design a system with a large range (suitable for field measurements) and a high sensitivity (suitable for gravity tides recording). A two voltages supply is a solution to use in both conditions.

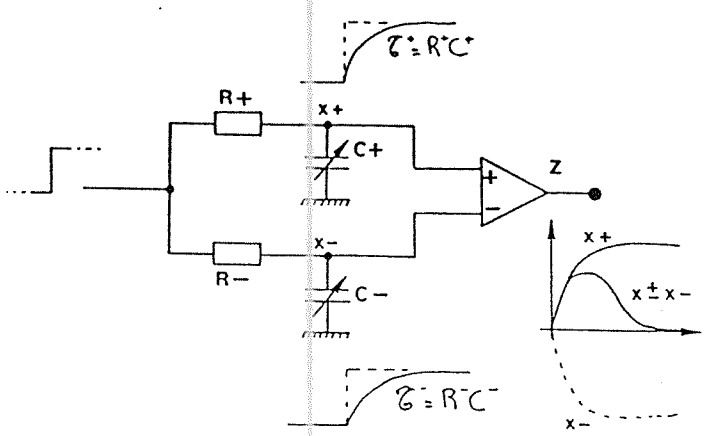
It is a reason why up to now we did produce different versions of the MVR electronics. One of them is the VRD 90.

3. The "VRD 90 type" Maximum Voltage Retroaction

This circuit is built with four voltage comparators. (figure 2). The cycle is defined by a modulation of the bridge supply. For low supply, the two output transistors of the comparators are open.

When the supply increases to high voltage the first comparator which has a x larger than REF, grounds the second capacitor. Its x signal returns to ground and so never could ground the first capacitor. This one stay permanently at high voltage until the supply return to ground.

Different experiments confirm the characteristics of this new system (Ducarme, B., d'Oreye, N., 1990).



C+ < C−	> 0	Condition A
C+ > C−	< 0	Condition B

Figure 1

Maximum Voltage Retroaction consists :

In condition A to put supply U on C+ (x+ = U) and to ground C− (x− = 0).
In condition B to put supply U on C− (x− = U) and to ground C+ (x+ = 0)
After a fixed period both signals are grounded and a new going up pulse is generated to select condition A or B.

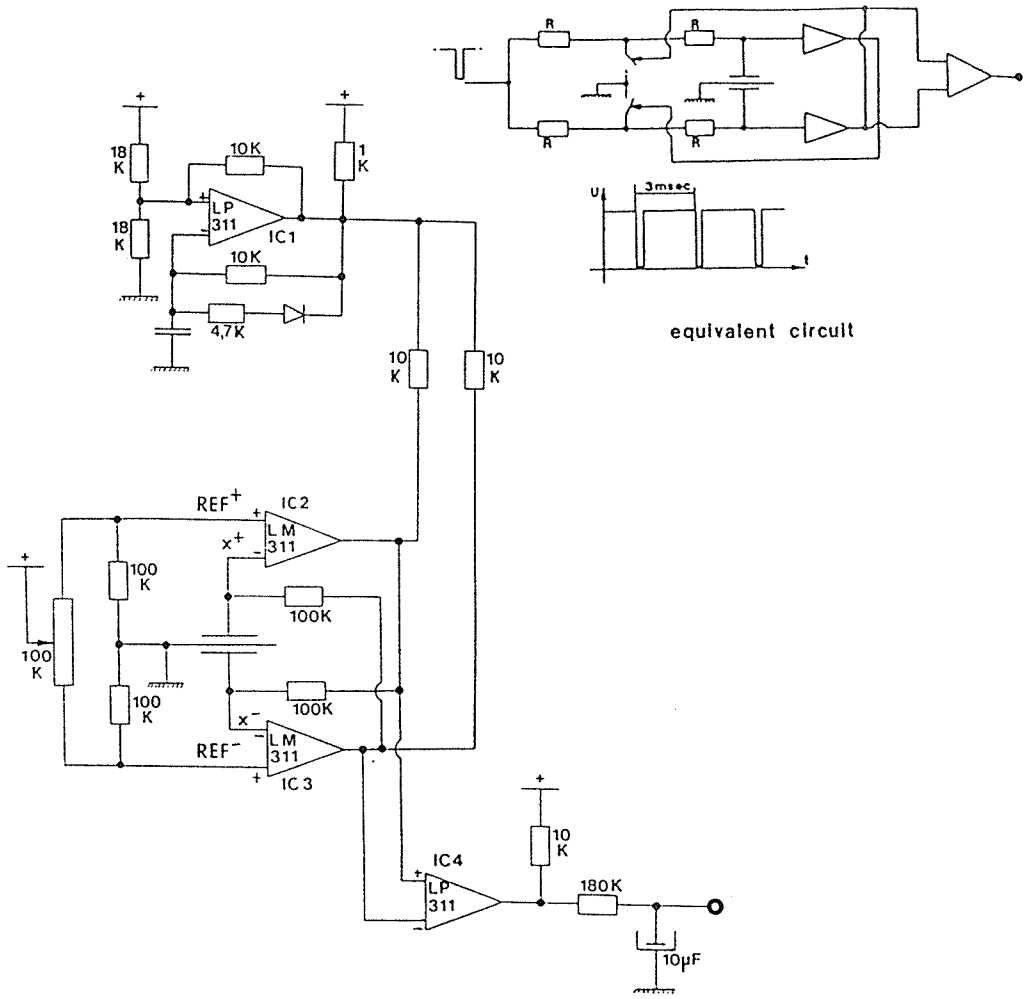


Figure 2

An oscillator (IC 1) supplies through 10 KΩ the transistor outputs of IC 2 & 3. These outputs charge the two capacitors of the bridge with 100 KΩ.
Ref+ and Ref− reference voltages are defined by potentiometer P1 and allows to fixe the reading line.
The IC 4 comparator output is high or low in function of the A or B conditions (figure 1) a low pass filter gives a signal Z representing the mean force acting on the mass.

BIBLIOGRAPHY

Ducarme B., d'Oreye N., 1990: Preliminary test of the Maximum Voltage Retroaction (MVR) System VRD90. Bull. Inf. Bureau Grav. Int., 67, ...

Harrison, J.C., Sato, T., 1984: implementation of electrostatic feedback with a LaCoste-Romberg model G gravimeter. Jour. Geophys. Res., 89, 7957- 7961.

Larson, J.V., Weber J., 1966: Operation of La Coste and Romberg Gravimeter at Sensitivity Approaching the Thermal Fluctuation Limit. Jour. Geophys. Res., 71, 24, 6005-6009.

Orejana, M., Vieira, R., 1983 : Transforming an Askania GS15 gravimeter in a zero-gravimeter. Proc. of the Ninth. Int. Symp. Earth Tides, New York, 1981.

Röder, R.H., Schnüll, M., Wenzel, H.G., 1987 : SRW feedback for LaCoste-Romberg gravimeters with extended range. IAG section 3 meeting: Advances in Gravimetric Techniques, 1987, August 9-22, Vancouver. Bull. Géod.

Vaillant, J.D., Gagnon, C, Halpenny, J.F., 1986 : An inherently linear electrostatics feedback method for gravity meters. Jour. Geophys. Res., 91, 10463- 10469.

Van Ruymbeke M., 1985: Transformation of nine La Coste Romberg gravimeters in feedback systems. Bull. Inf. Marées Terrestres, 93, 6202-6228.

Van Ruymbeke M., 1989: New development of feedback electronics Working Group on High Precision Tidal Data Processing, Bonn, October 4-6 1988 Bull. Inf. Marées Terrestres, 104, 7292-7298

Van Ruymbeke M., 1990: A new feedback system for instruments equipped with a capacitive transducer. XIth Int. Symp. on Earth Tides, Helsinki, July 31 - August 5, 1989.

Preliminary Test of the Maximum Voltage Retroaction (M.V.R.) System VRD 90

B. Ducarme*, N. d'Oreye**
Observatoire Royal de Belgique
avenue Circulaire 3
B-1180 Bruxelles

SUMMARY

A newly designed version VRD 90 of the Maximum Voltage Retroaction (M.V.R.) feedback system has been installed on the LCR G487 gravimeter. It insures a 5 mgal feedback range. From calibration against the micrometric screw it appears that a quadratic function insures very accurately the conversion from millivolt to microgal. Several tests demonstrated that the precision of the gravity readings reaches 2 microgals in microgravimetric ties.

1. Introduction

A new version (VRD 90) of the Maximum Voltage Retroaction (M.V.R.) feedback system has been installed on the LaCoste & Romberg gravimeter G 487 (Van Ruymbeke, 1990). It works with a 16 volts feedback voltage at a 2Khz frequency and insures a 5 mgal feedback range. The working sensitivity of the order of 2 mV/μgal is large enough to obtain good tidal records

In this paper we are mainly concerned with the linearity of the system and its precision in microgravimetric field measurements.

2. Micrometric Calibration

As a first step we decided to calibrate the 10 mgal range of the electronics by means of the micrometer. We performed a complete back and forth cycle (figure 1) with 200 μgal steps at two minutes intervals. After correction of the tidal influence the difference between the up and down values were very small (table 1). Their standard deviation was only 3.3 mV which is equivalent to 2.4 μgal. As we used a model G gravimeter the reading error of the dial is 1 μgal (0.1 division) and on the difference of two readings we should expect a standard deviation of 1.4 μgal.

After a linear regression on the mean values of table 1 we obtained residues with a strong parabolic dependance. A parabolic fit reduces the standard deviation of the residues to 1 μgal on the ± 2 mgal range. The maximum discrepancy is 2.5 μgal.

The corresponding regression equation is

$$M = -0.7300\ V + 0.00297\ V^2$$
$$\pm 0.0012 \qquad \pm 0.00018$$

It should be noted that for measurements symetrical to zero this non linearity effect is compensated.

To perform differential gravity observations we decided to decrease the filtering. It was thus necessary to recalibrate the system. We performed 5 consecutive cycles with 200 μgal steps on a range of 1 mgal. The associated error on the mean coefficient of sensitivity was less than 0.2%.

3. Repeatability

To perform a single gravity reading it is necessary to allow enough time for stabilisation after beam release.

As a first repeatability check we did reoccupy the same site with intermediate clamping and reinstallation of the gravimeter. We performed 10 gravity readings at 6 minutes interval.
After tidal correction the resulting dispersion is 2 μgal (table 2). Systematic fluctuations are apparent. We also observed microgravity ties between the two absolute gravity stations of the observatory buildings. We performed 6 ties between the two stations with a ten minutes interval between the observations.

The range was 600 μgal between − 300 mV and + 900 mV.

We found $\Delta g = 605.6\ \mu gal \pm 1.1$

The same gravity difference had been observed by Röder and Schnüll (personal communication, 1987) who found

$$\Delta g = 604.4\ \mu gal$$

The standard deviations on the readings on each station were respectively 2.5 μgal and 1.8 μgal. The expected standard deviation on the gravity differences is thus 3 μgal. However the observed one is only 2.5 μgal. It is due to the fact that correlated fluctuations of the readings are visible at both stations.

4. Discussion of errors

The main advantage of feedback gravimeters is the suppression of the reading error of the dial and of cyclic micrometer errors. However we have to consider the error of the transfer function mV to μgal. In our case the error associated with the uncertainty of the calibration reaches 1 μgal (cfr. § 2).

---

* Chercheur Qualifié FNRS (ORB/UCL)

** Centre de Géophysique Interne

Among the other sources of errors in the gravity readings let us point out the levelling errors. The gravity error for a given levelling error α is

$$e = -\frac{\alpha^2}{2} g$$

If we suppose accidental levelling errors uniformly distributes between $-\alpha_0$ and $+\alpha_0$ the mean variance of the gravity error is given by

$$\sigma^2 = \frac{1}{2\alpha_0} \int_{-\alpha_0}^{\alpha_0} \left(-\frac{\alpha^2}{2} g\right)^2 d\alpha = \frac{\alpha_0^4}{20} g^2$$

The corresponding standard deviation for different levelling accuracies is thus

10"	0.5 μgal	20"	2.1 μgal	40"	8.4 μgal

If we consider the two levels we obtain respectively

10"	0.7 μgal	20"	3.0 μgal	40"	11.9 μgal

A 10" precision, corresponding to a levelling error of 0.2 spirit level division, is possible in good conditions and we can expect a 1 μgal contribution to the standard deviation of the observations. Of course in difficult environmental conditions with large temperature variations much larger errors could be expected.

5. Conclusions

The new MVR feedback system is providing enough precision for tidal registration and allows to perform microgravimetric observations at the microgal level.

To insure a similar precision for larger gravity differences of the order of several mgal it will be necessary to modelize very accurately the calibration function to convert the voltage differences into gravity differences.

It is clear that levelling has to be improved to reach the required level of precision (10") in field conditions.

BIBLIOGRAPHY

Van Ruymbeke, M., 1990: New feedback electronics for LaCoste & Romberg gravimeters.
Bull. Inf. Bureau Gravimétrique Int., 67, pp...

Table 1

Micrometer Calibration

Micrometer units	beam up (Volt)	beam down (Volt)	up-down (mV)
- 2.5	3.659	3.667	- 8
- 2.3	3.385	3.387	- 2
- 2.1	3.107	3.106	+ 1
- 1.9	2.829	2.826	+ 3
- 1.7	2.546	2.546	+ 0
- 1.5	2.267	2.266	+ 1
- 1.3	1.987	1.989	- 2
- 1.1	1.710	1.708	+ 2
- 0.9	1.433	1.430	+ 3
- 0.7	1.152	1.150	+ 2
- 0.5	0.875	0.875	0
- 0.3	0.599	0.599	0
- 0.1	0.322	0.321	+ 1
0.1	0.049	0.052	- 3
0.3	- 0.223	- 0.230	+ 7
0.5	- 0.498	- 0.501	+ 3
0.7	- 0.772	- 0.772	0
0.9	- 1.041	- 1.042	+ 1
1.1	- 1.313	- 1.312	- 1
1.3	- 1.581	- 1.583	+ 2
1.5	- 1.855	- 1.852	- 3
1.7	- 2.122	- 2.123	+ 1
1.9	- 2.393	- 2.391	- 2
2.1	- 2.660	- 2.654	- 6
2.3	- 2.926	- 2.921	- 5
2.5	- 3.193	- 3.198	+ 5

Table 2

LCZ 487 90/09/03
Repeatability of gravity points. Data are corrected for a linear drift of 0.75 mV / min

Time	V (mV)	$V - \overline{V}$ (mV)
13h43m	801	1
49m	795	- 5
53m	793	- 7
14h01m	803	+ 3
07m	803	+ 3
13m	801	+ 3
17m	799	+ 1
24m	799	- 1
30m	804	- 1
37m	799	+ 4

mean value $\overline{V}$ = 800 mV
standard deviation 3.5 mV = 2 μgal

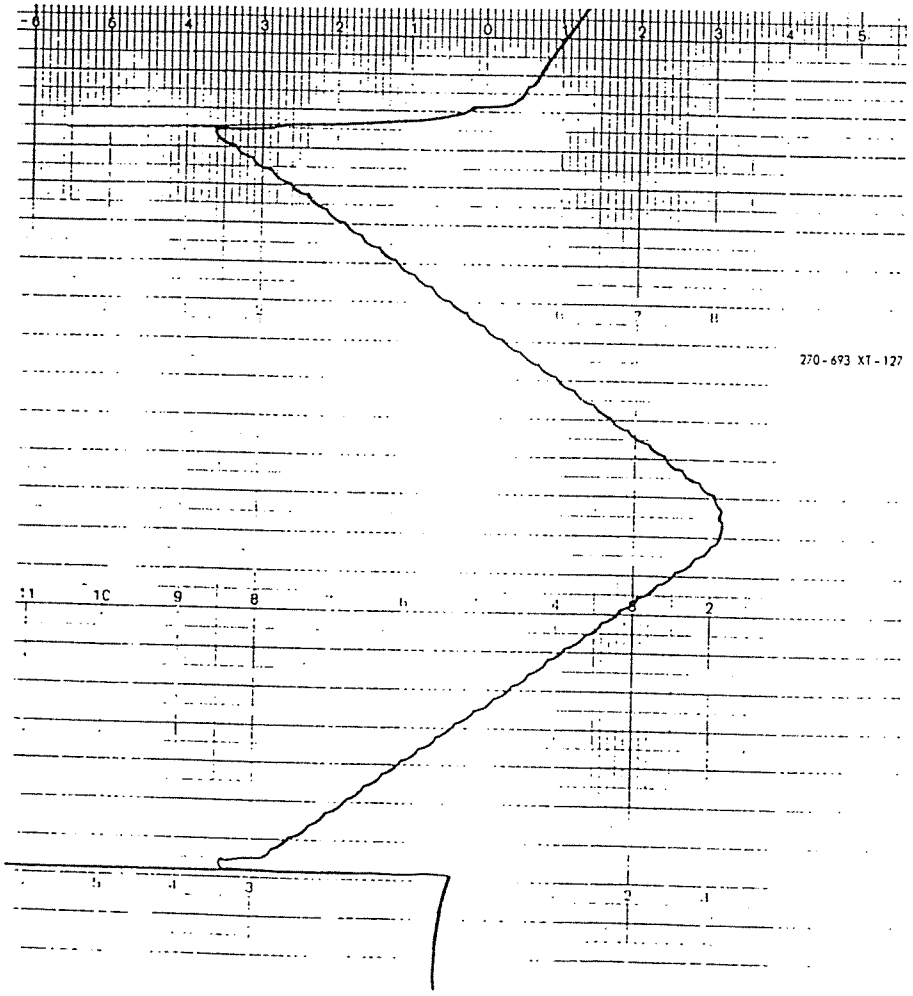


Figure 1 : Micrometric calibration with 200 μgal steps on the full 5 mgal range.

PRECISION LASER INTERFEROMETRY AND MEASUREMENT OF GRAVITY POTENTIAL SECOND DERIVATIVES

L.F. Vitushkin, D.I. Mendeleyev

Research Institute of Metrology

Laser interferometric systems are practically the only measuring means which measure relative displacements of distant test masses with high accuracy. A set of free moving test mass is well suitable for measuring gravity field parameters, e.g., the first and second derivatives of the gravity potential ϕ.

Synge I.L. [1] within the frames of the general relativity has shown that it is possible to measure space-time curvature by means of a "five-points curvature detector", proposed by him, which consists of the free moving (four) mirrors and a free moving light source. For this aim in view it is necessary to measure time of light propagation through ten optical paths between the test masses, forming parts of the curvature detector.

It may be argued that the gravity fields parameters in the Newtonian Gravity theory such as the first and second derivatives of the gravity potential can also be measured using a system of the free falling test masses, determining the light beam propagation time between the masses. Synge I.L. [1] payed attention to the fact that an optical interferometer is practically the differential chronometer that measure the time difference of light propagation in the interferometer arms.

Thus, the system for measuring the second derivatives of ϕ may be represented as a set of the free moving test masses (e.g., as shown in Fig. 1) with the interferometer optical elements attached to them, which measure variations of the distance between the test masses in the free fall. Such a system can measure all the second derivatives simultaneously.

The first step to realization of such a ballistic laser interferometer system is an absolute laser gravimeter the second free moving mass being the Earth.

The next step is a ballistic vertical gradiometer - an apparatus for measuring the vertical gradient of the gravity acceleration :

$$\gamma_{ZZ} = \frac{\partial^2 \phi}{\partial Z^2} = \frac{\partial g}{\partial Z}$$

where Z is the vertical coordinate, g is the gravity acceleration. Such an apparatus, based on the two free falling masses, was suggested by R. Stone in 1972 [2]. Its design is illustrated in Fig. 2. The γ_{ZZ} value can be calculated from measuring variations of the distance between two test masses A and B or from the difference of their vertical velocities.

To measure other second derivatives of the gravity potential it is necessary to have an interference scheme which measures the distance between test masses AC, AD, BC, BD, DC in the free fall, that is, the masses arranged in a horizontal plane or between the masses located in an inclined plane. Such a scheme (Fig. 3) has been proposed by the author together with Kazakov A.Ja., Razumovskii N.A. and Smirnov M.S. In a particular case the test masses A and B, shown in Fig. 3, can lie horizontally.

Certainly, a technical implementation of the interference system which is to measure the distance between pairs of the test masses in the tetrahedron, shown in Fig. 1, in the free fall, will be rather complicated, but, in principle, its design, based on the interference scheme of the type, shown in Fig. 2 and Fig. 3, can be realized. The interference system of the Fabry-Perot type can appear to be more sensitive and more simple for the realization in the ballistic vertical gradiometer. This version of the ballistic gradiometer has been proposed by the author together with Griaznevich V.P. (Fig. 4).

To evaluate the ultimate accuracy of the ballistic laser interferometer system, necessary for measuring the second derivatives of the gravity potential, let us estimate the limit accuracy of displacement measurement, using laser interferometers and, as an illustration, the accuracy of measuring the vertical gradient of the free fall acceleration.

A quantum limit of accuracy (minimum detectable displacement) of the interferometric measurements of the test masses relative displacements for the two-beam interference scheme of the Michelson interferometer type can be estimated by equation (1) ([3,4] and others) :

$$\Delta l_{\min}^{(IM)} = \frac{1}{2\pi}\left(\frac{hc\lambda\Delta f}{P_o}\right)^{1/2} \tag{1}$$

where h is the Planck constant, C is the speed of light, λ is the wavelength of the laser light, Δf is the bandwidth, P_o is the intensity of the input laser radiation of the interferometer. It is supposed that the given limit is determined by photodetection shot noise with a photodetector quantum efficiency equal to 1. Equation (1) can be expressed in the following form :

$$\Delta l_{\min}^{(IM)} \approx \lambda/\sqrt{N} \tag{2}$$

where N is the number of photons detected.

With $P_o = 1$ mW, $\lambda = 633$ nm, $\Delta f = 1$ kHz we obtain $\Delta l_{\min}^{(IM)} \approx 6.10^{-14} m$.

With the Fabry-Perot multibeam intereferometer it is possible to get the following estimation of the quantum limit of displacement resolution $\Delta l_{\min}^{(FP)}$:

$$\Delta l_{\min}^{(FP)} \approx \Delta l_{\min}^{(IM)}(1-R) \tag{3}$$

where R is the energetic reflection factor of the interferometer mirrors.

With $R = 0{,}999$ the limiting resolution of the Fabry-Perot interferometer, $\Delta l_{\min}^{(FP)}$, is 10^3 times less than $\Delta l_{\min}^{(IM)}$. There are more accurate expressions for the limiting interferometers resolution (see, for example [5]).

It is essential that the displacement resolution values close to the above limiting ones have been obtained experimentally. These experiments were carried out while developing the laser-interferometric gravitational radiation detectors (e.g., [6,7,8]).

To evaluate relative displacements of the two free-falling test masses, being located vertically at the distance ΔZ_o at the initial moment, it is possible to take advantage of the equation :

$$\delta_Z = \Delta V_o t + \frac{\Delta Z_o}{2}\gamma_{ZZ} t^2 + \frac{\gamma_{ZZ}\Delta V_o}{6}.t^3 \qquad (4)$$

where δ_Z is the distance variation between the two test masses during the fall, t is the fall time, ΔV_o is the difference of initial velocities.

Equation (4) was derived providing $\gamma_{ZZ} \ll 1$. With the zero initial velocities of the test masses and providing simultaneous beginning of their fall ($\Delta V_o = 0$), we obtain :

$$\delta_Z = \frac{\Delta Z_o \gamma_{ZZ} t^2}{2} \qquad (5)$$

Taking into account the dual passage of the optical beams in the Michelson interferometer with the initial distance $\Delta Z_o = 0{,}25$ m, the fall time $t = 0{,}4$ s (the path in the fall = 0,8 m) and using equation (5) we obtain that the measurement uncertainty of the relative to each other displacements of the two free falling masses, equal to 4.10^{-10} m = 0,4 nm, causes the vertical gradient measurement uncertainty γ_{ZZ} approximately 10^{-8} s^{-2} = 10 Eötvös.

The above values of the displacement measurement uncertainty are much more than the quantum limit of resolution. Thus, it can be concluded that the measurement accuracy of laser interferometers is sufficient for detection of the free falling test masses relative displacements caused by real irregularities of the Earth gravitational field and, hence, allows to measure the second derivatives of the gravity potential. At the same time the interference schemes described here which allow to measure the relative displacements of the test mass pairs, differently oriented in space, can serve at least as a basis for developing a ballistic laser-interferometric detector for measuring the gradient potential second derivatives.

Implementation of the proposed detector for measuring the second derivatives of the gravity potential as well as the vertical gradiometer requires the solution of a variety of technical problems. In particular, in practice there is a nonzero random scatter of the test masses initial velocities which results in a corresponding measurement uncertainty. However there are some approaches much more decreasing this uncertainty. A wide experience in solving problems concerned with designing the ballistic absolute gravity meters can render assistance for the development of the ballistic vertical gradiometers and second derivative detector.

In conclusion it should be noted that it is quite necessary to investigate the possibility to use the multibeam interference schemes of the Fabry-Perot interferometer type not only for the ballistic vertical gradiometers, as it was written above, but also for the ballistic gravimeter.

References

1. Synge I.L., Relativity, The General Theory. North-Holland, Amsterdam, P. 408 (1960).
2. Stone R.S. U.S. Patent 3704626. Dec. (1972).
3. Edelstein W.A. et al. J. Phys. E. V. 11, p. 710 (1978).
4. Vituschkin L.F., Ivanovskaya M.J., Kolosnitsin N.I., Problemy teorii gravitatsii i elementarnych chastits. (Problems of the gravitation theory and elementary particles) vyp. 12., p. 102 (1981) (in Russian).
5. Vituschkin L.F., Smirnov M.Z., Doklady Akademii Nauk SSSR. V. 297, N° 1, P. 76 (1987) (in Russian).
6. Billing H. et al., J. Phys. E., V. 12, p. 1043 (1979).
7. Forward, R.L., Phys. Rev. D., V. 17, p. 379 (1978).
8. Shoemaker D. et al. : Phys. Rev. D., V. 38, p. 423 (1988).

Fig. 1

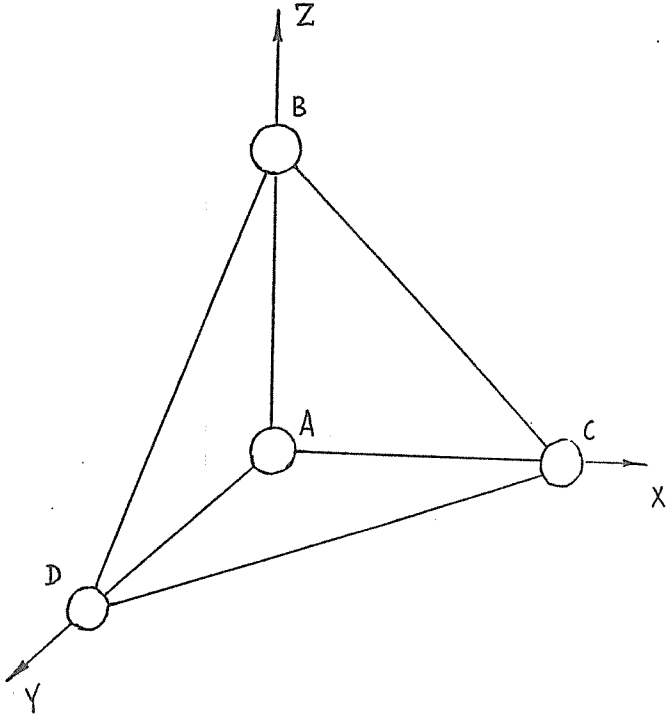


Fig. 2

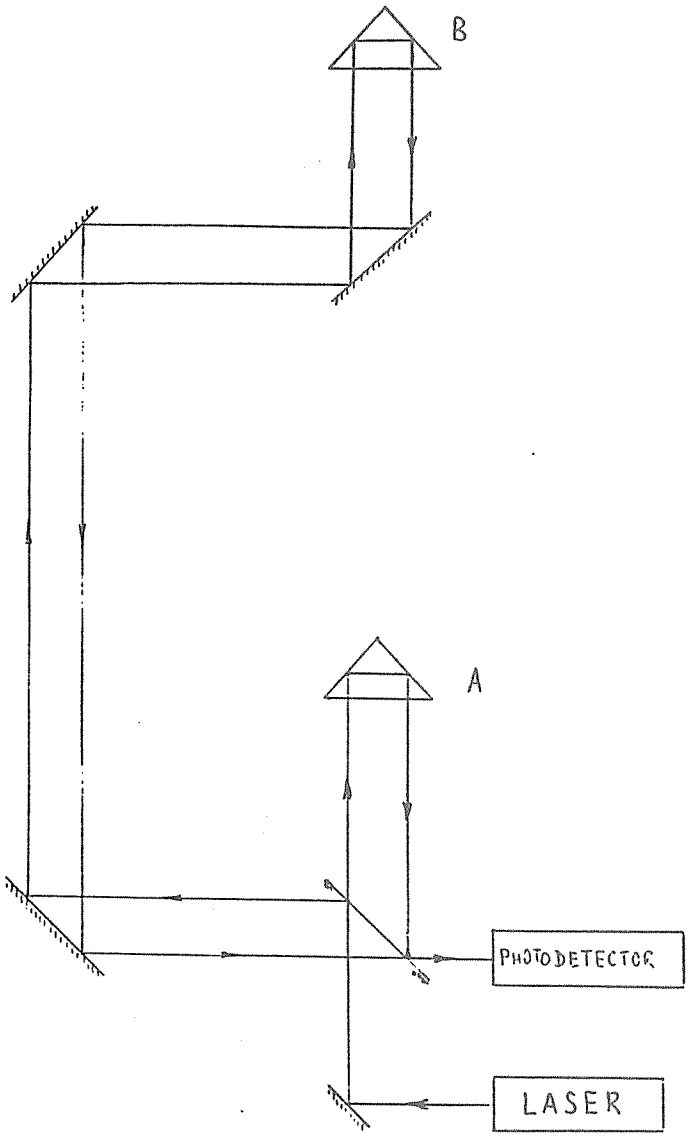


Fig. 3

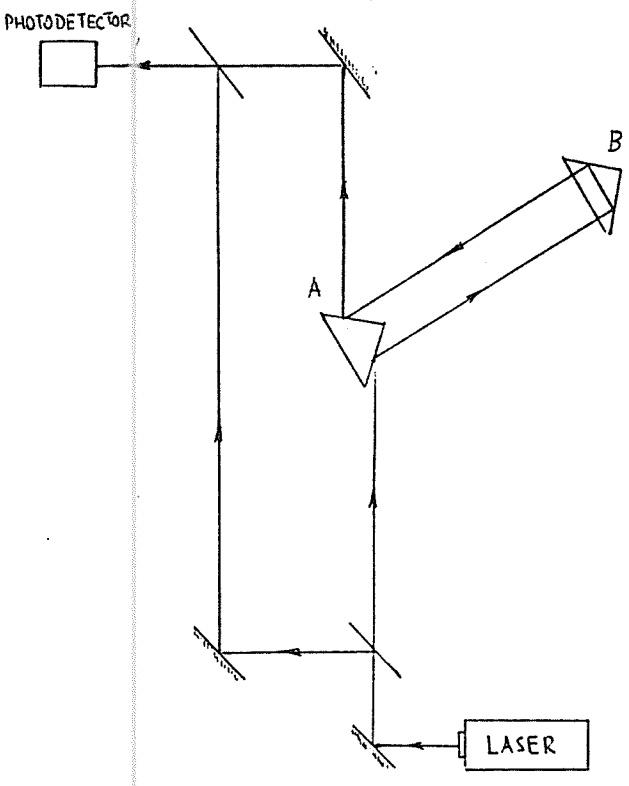
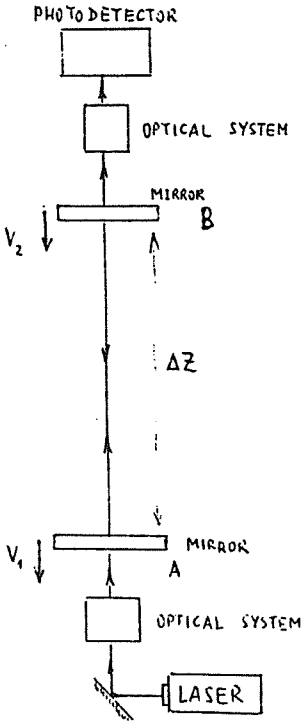

PHOTODETECTOR
B
A
LASER

Fig. 4


PHOTODETECTOR
OPTICAL SYSTEM
MIRROR
B
V_2
ΔZ
MIRROR
A
V_1
OPTICAL SYSTEM
LASER

LAND UPLIFT AND GRAVITY CHANGE IN FENNOSCANDIA 1966 - 1989

MARTIN EKMAN

National Land Survey
Division of Geodetic Research
S - 801 82 Gävle, Sweden

JAAKKO MÄKINEN

Geodetic Institute
Ilmalankatu 1A
SF - 00240 Helsinki, Finland

Abstract

An analysis of all gravity measurements 1966 - 1989 on the Fennoscandian land uplift gravity line 63° is made. The relation between gravity change and land uplift is found to be - 0.24 ± 0.03 µgal/mm. The influence of various weighting schemes is discussed.

1. Introduction

The measurements made on the Fennoscandian land uplift gravity lines (Figure 1) 1966 - 1984 were published by Mäkinen et al. (1986). An analysis of the results on the 63° line was given by Ekman et al. (1987). They found that west of the land uplift maximum (Vågstranda - Kramfors) the relation between gravity change and land uplift was - 0.23 ± 0.07 µgal/mm; east of the maximum (Vaasa - Joensuu) it was - 0.22 ± 0.06 µgal/mm. Given the standard errors, these values contain the whole range between the two theoretically predicted extreme values: - 0.17 µgal/mm for the Bouguer model (crustal uplift with full addition of mass from the upper mantle) and - 0.31 µgal/mm for the free air model (crustal uplift without additional mass). New observations have been made since 1984; we will here present an analysis for the extended period 1966 - 1989.

2. Main results

The gravity differences are collected in Table 1. To see how the new data influence the results we first perform an unweighted linear regression of the annual means in the same manner as Ekman et al. (1987). On the western part we find

$$\dot{g} = -1.58 \pm 0.27 \quad \mu\text{gal/year}$$

to be compared with the earlier result of

$$\dot{g} = -1.64 \pm 0.47 \quad \mu\text{gal/year}$$

On the eastern part we find

$$\dot{g} = 0.99 \pm 0.18 \quad \mu\text{gal/year}$$

to be compared with

$$\dot{g} = 0.95 \pm 0.25 \quad \mu\text{gal/year}$$

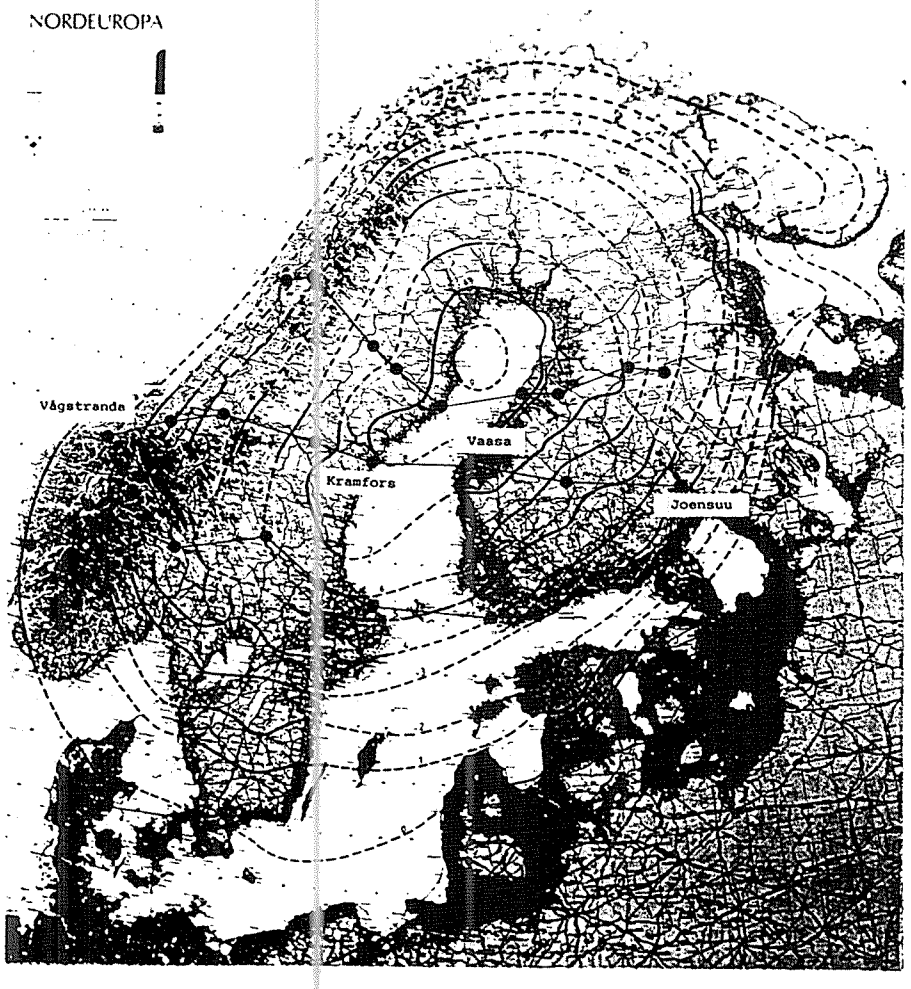


Figure 1. Apparent land uplift (mm/year) and the land uplift gravity lines. The 63° line is the second from the north.

Table 1. Measured gravity differences, 63° line. Below each year is given the LCR gravimeter number and the gravity difference in µgal.

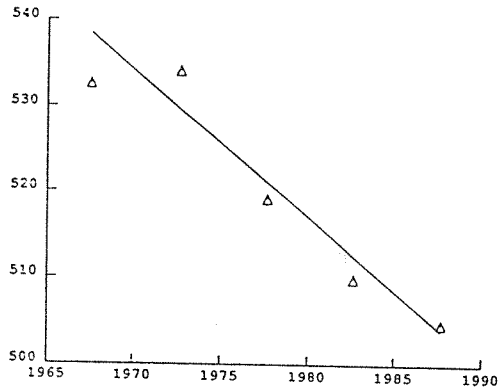
a. Western part (Vågstranda - Kramfors)

1967.5	
G-24	526.7
G-55	549.0
G-69	522.2
Mean	532.6 ± 8.3
1972.7	
G-45	519.4
G-54	532.0
G-55	517.7
G-62	534.9
G-100	519.8
G-142	571.8
G-195	519.8
G-258	538.2
G-290	553.2
Mean	534.1 ± 6.1
1977.7	
G-45	499.4
G-54	537.3
G-55	508.7
G-69A	518.4
G-100	523.6
G-120	519.5
G-139	529.9
G-290	504.1
(G-317	593.8)
G-378	533.0
D-16	517.1
Mean	519.1 ± 3.9
1982.7	
G-45	494.5
G-258	502.3
G-378	517.3
D-38	525.5
Mean	509.9 ± 7.0
1987.7	
G-54	506.0
G-55	519.5
G-290	497.2
G-378	(457.2)
G-569	509.1
G-600	509.5
G-665	485.1
G-786	500.8
G-863	491.4
D-56	524.7
Mean	504.8 ± 4.2

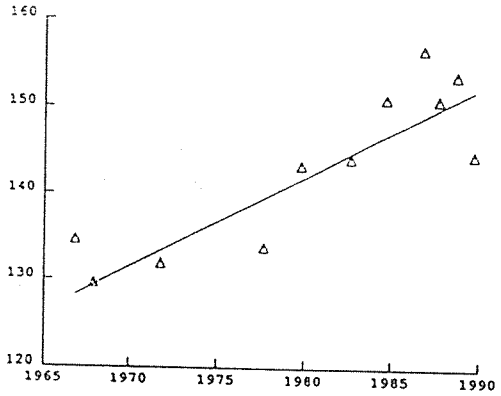
b. Eastern part (Vaasa - Joensuu)

1966.8	
G-55	131.7
G-62	140.1
G-67	134.5
G-69	132.1
Mean	134.6 ± 1.9
1967.9	
G-24	120.5
G-55	116.9
G-69	142.1
G-115	138.8
Mean	129.6 ± 6.4
1971.8	
G-55	119.0
G-62	115.4
G-100	132.6
G-142	156.9
G-258	135.8
Mean	131.9 ± 7.4
1977.7	
G-45	144.1
G-54	132.0
G-55	136.9
G-69A	140.4
G-100	139.1
G-120	142.0
G-139	142.1
G-290	118.3
(G-317	131.0)
G-378	128.8
D-16	113.9
Mean	133.8 ± 3.3
1979.8	
G-54	138.9
G-55	132.2
G-258	144.7
G-290	160.1
D-38	140.6
Mean	143.3 ± 4.7

1982.7	
G-45	145.2
G-55	139.5
G-258	154.9
G-378	139.9
G-600	143.6
D-38	141.7
Mean	144.1 ± 2.3
1984.7	
G-55	146.6
G-434	162.3
G-487	136.4
G-600	158.9
Mean	151.0 ± 5.9
1986.8	
G-55	154.4
G-600	158.7
Mean	156.6 ± 2.1
1987.7	
G-54	152.2
G-55	151.9
G-290	151.1
G-378	145.2
G-569	148.5
G-600	147.5
G-665	152.4
G-786	151.4
G-863	148.5
D-56	159.8
Mean	150.9 ± 1.2
1988.7	
G-55	151.4
G-600	156.0
Mean	153.7 ± 2.3
1989.7	
G-55	148.2
G-600	140.9
Mean	144.6 ± 3.7



a. Western part (Vågstranda - Kramfors)



b. Eastern part (Vaasa - Joensuu)

Figure 2. Change of gravity difference with time, 63° line (μgal/year).

The increased data length does not change the value of $\dot{g}$ but reduces the standard error.

There is an important objection against unweighted regression in this case: Three of the new annual means are based on two gravimeters only, and should not get the same weight as a mean of, say, 10 gravimeters. One way of overcoming the problem is to weight the annual means in the regression according to the number of gravimeters. Obviously, this leads to the same result as unweighted regression using the individual gravimeters.

Weighting with the number of gravimeters we obtain on the western part (Figure 2a)

$$\dot{g} = -1.71 \pm 0.28 \quad \mu\text{gal/year}$$

and on the eastern part (Figure 2b)

$$\dot{g} = 1.04 \pm 0.18 \quad \mu\text{gal/year}$$

Dividing by the apparent land uplift difference of 7.0 mm/year on the western part we find a relation between gravity change and land uplift of

$$\dot{g}/\dot{h} = -0.24 \pm 0.04 \quad \mu\text{gal/mm}$$

The same operation on the eastern part, with the apparent land uplift difference - 4.3 mm/year, also yields

$$\dot{g}/\dot{h} = -0.24 \pm 0.04 \quad \mu\text{gal/mm}$$

Combining the two independent values of g/h we obtain

$$\dot{g}/\dot{h} = -0.24 \pm 0.03 \quad \mu\text{gal/mm}$$

However, the standard errors are somewhat optimistic since the uncertainty in the land uplift determination is not included.

Remark: Since the above land uplift differences do not contain any geoid uplift they are, in principle, valid only for the free air model. Assuming a geoid uplift corresponding to the Bouguer model, the land uplift differences would increase very slightly, reducing the value of $\dot{g}/\dot{h}$ by about 5 %.

3. Weighting considerations

In our regression we weighted the annual means according to the number of gravimeters, which is equivalent to unweighted regression using the individual gravimeters. This might be questioned since the standard errors of the gravimeters vary considerably. For comparison we performed a regression for the eastern part using individual gravimeters and weighting them according to their inverse squared standard errors; this changed $\dot{g}/\dot{h}$ by - 0.03 µgal/mm. On the other hand, experience shows that results from different gravimeters differ more than would be expected from their standar errors, i.e. there are unaccounted systematic effects. This weighting problem will be discussed elsewhere.

A related problem is that in a few cases an individual gravimeter deviates considerably from the others without any physical explanation. Test calculations show that omitting such gravimeters may change $\dot{g}/\dot{h}$ by maximally + 0.03 µgal/mm, on the western part.

Our regression is based on weighting the annual means according to the number of gravimeters. Another principle, adopted by Sjöberg (1988), would be to weight the annual means according to their standard errors (Table 1). However, several of these standard errors are founded on very few degrees of freedom. With this method Sjöberg (1988), using the years 1966 - 1984, arrived at $\dot{g}/\dot{h}$ = - 0.16 ± 0.04 µgal/mm. It is easily seen that his solution is essentially determined by two means in the eastern part, 1966 and 1982, which both get high weights and are at influential places near the extremes of the time range. Because of the few degrees of freedom, the standard errors of the annual means are, in our opinion, not very suitable as a basis for weighting.

4. Conclusions

We have found that

$$\dot{g}/\dot{h} = -0.24 \pm 0.03 \quad \mu gal/mm$$

This value is still in the middle between the two theoretically predicted extreme values; it does not yet allow any conclusions on the land uplift process. It seems fairly probable, however, that such conclusions might be drawn after the next complete measurement of the 63° line.

Acknowledgement: The new measurements were performed by the Finnish Geodetic Institute; the Institute of Astronomy and Geodesy (UCM - CSIC), Madrid; the Institute of Geophysics, University of Uppsala; the National Land Survey of Sweden; and the Norwegian Mapping Authority.

References

Ekman, M, Mäkinen, J, Midtsundstad, Å, Remmer, O: Gravity Change and Land Uplift in Fennoscandia 1966 - 1984. Bulletin Géodésique, 61/1, 1987.

Mäkinen, J, Ekman, M, Midtsundstad, Å, Remmer, O: The Fennoscandian Land Uplift Gravity Lines 1966 - 1984. Reports of the Finnish Geodetic Institute, 85:4, 1986.

Sjöberg, L E: The Secular Change of Gravity and the Geoid in Fennoscandia. In Publications of the Danish National Survey and Cadastre, 4/1, 1988.

High Precision Gravity Control Network in Yunnan/China 1990

by

W. Torge[1], R.H. Röder[1], M. Schnüll[1] and L. Timmen[1]

and

Jia Minyu[2], Xu Jusheng[2], Sun Heping[2] and Xing Canfei[3]

Abstract

In a joint project between the Institute of Seismology, State Seismological Bureau, Wuhan, and the Institut für Erdmessung, University of Hannover, a gravity control system has been established in the Yunnan earthquake region in China 1990. By using relative and absolute gravimetry a system of 37 gravity points including six absolute stations is now available for monitoring gravity changes with time, caused by height and/or subsurface mass variations. Additionally observed absolute stations in Beijing and Wuhan serve as reference and for strengthening a large-scale calibration line. The International Absolute Gravity Basestation in Beijing was also occupied at this campaign.

1. Introduction

For investigations in earthquake prediction, the State Seismological Bureau (SSB) of China established the "Western Yunnan Earthquake Prediction Study Area (WYEPSA)" which covers 30000 km^2 in the Yunnan Province (Lai and Shao 1985). The high tectonic activity in that area is characterized by a large number of earthquakes. About 300 earthquakes with a magnitude of M≥2.0 are recorded every year. Between 1901 and 1985, 22 earthquakes with M≥6.0 occurred.

The experimental field is located in the eastern edge of the tectonic zone of the Himalaya-Burma arc. Here, the crust is strongly subjected to compression under the interaction of the Indian plate and the Eurasian plate. The highly active Honghe fracture zone crosses the testing area from north to south (Fig. 1.1).

Repeated gravity measurements and three-dimensional geometric network control represent geodetic tools for monitoring movements of the earth's surface. With the Global Positioning System (GPS) it is possible to determine inter-station connections with high relative accuracy. Absolute gravity observations in combination with relative gravity measurements are an efficient method for detecting vertical movements and subsurface mass

[1] Institut für Erdmessung (IfE), Universität Hannover
Nienburger Straße 6, D-3000 Hannover 1, Federal Republic of Germany

[2] Institute of Seismology (IoS), State Seismological Bureau (SSB)
Xiao Hongshan, Wuhan 430071, Peoples Republic of China

[3] Seismological Bureau of Yunnan Province
Black Dragon Pool, Kunming, Peoples Republic of China

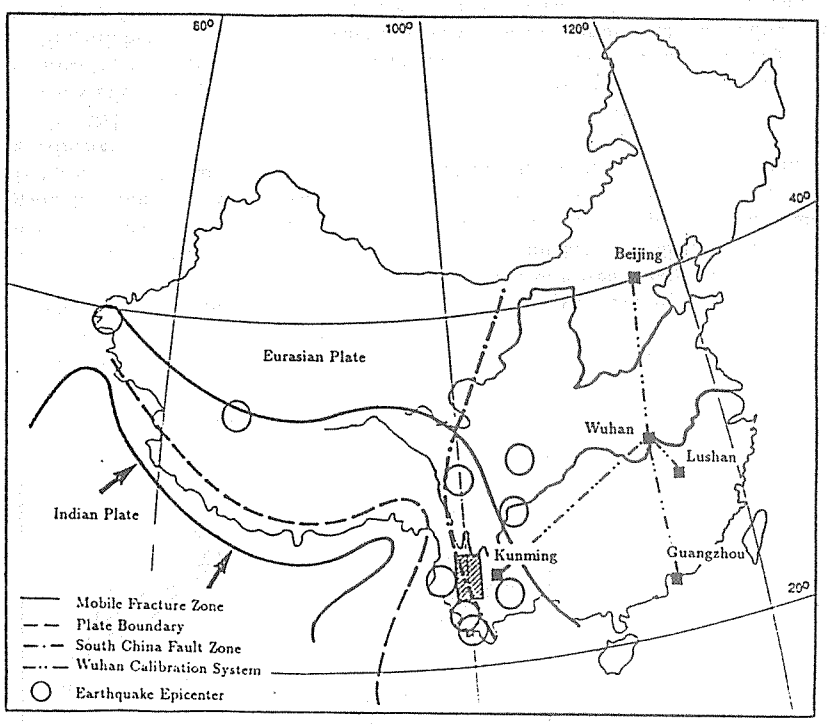


Fig. 1.1 The WYEPSA and the Wuhan Gravimeter Calibration System

shifts. Absolute gravity data especially provide the gravity datum and a local calibration for relative type instruments. In addition, they support homogenity of a gravity network (Torge 1986). By using the geometric as well as the gravimetric information, it is possible to distinguish between gravity changes caused either by vertical surface movements, or by mass changes in the earth's interior.

In 1988 the Institut für Erdmessung (IfE), University of Hannover, and the Institute of Seismology (IoS), State Seismological Bureau (SSB) of China, performed a GPS field campaign in the WYEPSA (Seeber and Lai 1989). In 1990 (April 20 to May 31) a gravimetric campaign followed, which is described in this report presenting first results. Repetitions are scheduled for 1991 (GPS) and 1992 (gravimetry), respectively.

Besides the establishment of a gravity control network in the Yunnan area, a station of the International Absolute Gravity Basestation Network (IAGBN), located in the vicinity of Beijing was occupied in 1990. The objectives of the IAGBN have been defined by the International Association of Geodesy (IAG), with a global monitoring of gravity variations with time as a major target (Boedecker and Fritzer 1986). A third objectiv of the 1990 gravity project was the strengthening of the Wuhan Calibration System.

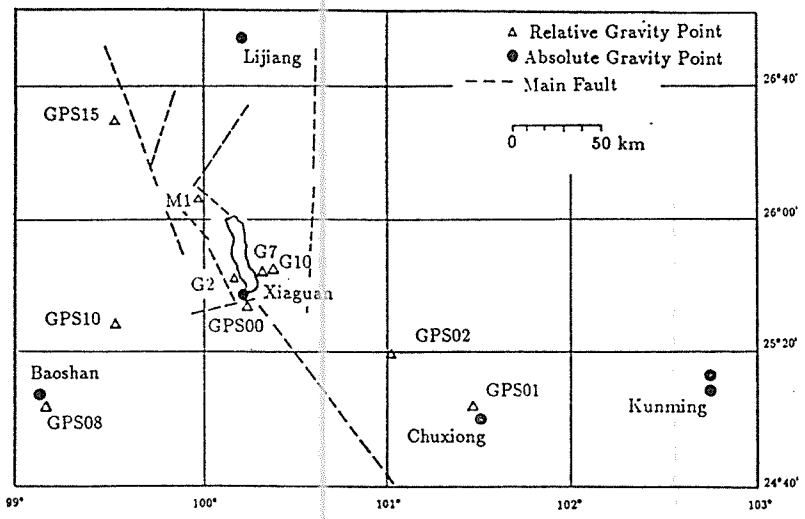


Fig. 2.1 Gravity Base Stations in the WYEPSA

2. Network Design

2.1 Gravity Stations in Kunming,Wuhan and Beijing

Pairs of two absolute points were established in the vicinity of Kunming and Beijing and in the city of Wuhan. As these points are located outside the Yunnan seismic active zone, they serve as reference for future repetition measurements. In addition they improve the existing Wuhan Calibration System (Xu et al. 1988, Nakagawa et al. 1986), and serve for controlling the long-wave calibration parameters of the relative instruments which were employed in the 1990 campaign. By connecting the absolute gravity twin stations through relative gravimetry, the reliability of the absolute gravity determinations could be controlled.

2.2 Gravity Control System in Yunnan

The Yunnan gravity control system consists of a base net, a micro gravity net (further on called micro-net) and a vertical gradient line (further on called gradient-line). The base net covers the whole experimental area. It is based on six absolute points including the two stations in Kunming (Fig. 2.1). Xiaguan (AS6505) is the central station surrounded by three other sites (Baoshan, Chuxiong, Lijiang) about 200 km off. The net was stabilized and densified by relative gravity measurements. This densification includes six stations of the 1988 GPS campaign, with three of them close to absolute gravity stations. Through this connection of the GPS and the gravity network, a common interpretation of geometric and gravimetric changes will be possible after the corresponding repetition surveys.

The absolute points are located in artificial caves which have been built for seismic recordings. An exception is one of the Kunming stations (AS6502). This is an absolute

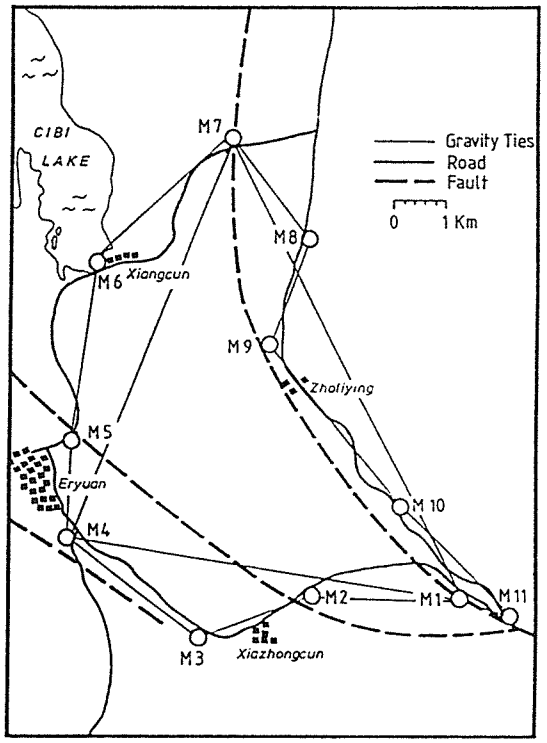


Fig. 2.2 Eryuan Micro Gravity Net

point of the national fundamental gravity network, and it is established on the top of a mountain in the height of about 2500 m.

The Eryuan micro-net shall serve for monitoring relative gravity variations in a local test area crossed by several active faults. It consists of eleven gravity stations (Fig. 2.2), and is connected to the base net by the common point M1. The distances from point to point are 1.0 to 3.7 km. With good traffic conditions a short transportation time allowed a good drift control of the instruments. The maximum gravity difference in the net is about 100 μms^{-2}. This allowed the employment of the IfE electronic feedback systems in the gravimeters.

The Dali vertical gravity gradient line crosses the Erhai Lake depression, and consists of ten stations (Fig. 2.3). Gravity differences between the stations (maximum difference 97 μms^{-2}) and vertical gravity gradients have been observed. This eventually allows to distinguish between mass movements close to the earth's surface and mass shifts in deeper locations. The inter-station distances are 1.0 to 2.4 km, only one tie to a point on an island point is 9.6 km. The eastern and the western part of the line are tied to the base network by stations G2, G6, G7, and G10.

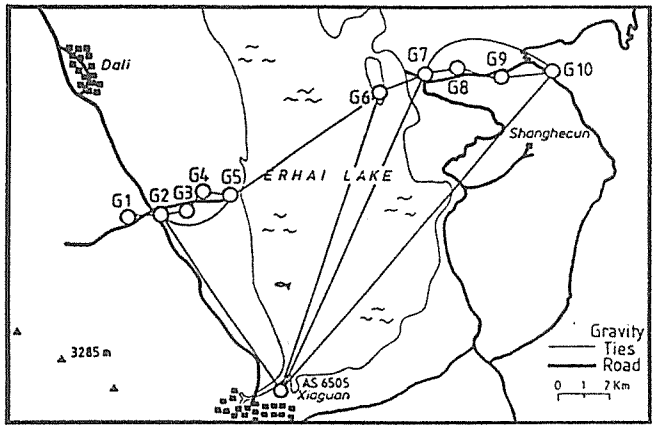


Fig. 2.3 Dali Vertical Gravity Gradient Line

All points of the micro-net and of the gradient-line are monumented by concrete pillars, with the surface level equal to ground level (pillar top: $60 \times 60\ cm^2$, bottom: $90 \times 90\ cm^2$, height: 80 cm).

3. Absolute Gravity Measurements

3.1 The JILAG-3 Absolute Gravimeter System

IfE operates the transportable free-fall absolute gravimeter JILAG-3 (Torge 1989). It was constructed at the Joint Institute for Laboratory Astrophysics (JILA), University of Colorado and National Institute of Standards and Technology, Boulder, by Prof. J. E. Faller and co-workers. Using the Michelson interferometer principle the gravity value is obtained by performing simultaneous distance and time measurements. The observed gravity values are reduced for the effects of earth tides, polar motion and air pressure variations (Torge et al. 1987). Groundwater and soil moisture changes are not taken into account. The observed gravity value refers to points about 0.8 m above floor level and are transfered to the ground by determining the gravity differences with at least two LaCoste&Romberg (LCR) relative gravimeters, equipped with the IfE-feedback system (Schnüll et al. 1984). The accuracy of this reduction is 0.02 μms^{-2} (Röder and Wenzel 1986).

From 1000 to 1500 drops per station distributed over two days a precision of ± 0.01 μms^{-2} is generally achieved. The station accuracy is mainly determined by systematic errors of instrumental character, and by uncertainties of the gravity reductions. From repeated observations on the same stations and from comparisons with the results of other instruments the accuracy of a gravity value is estimated to $\pm 0.05 \ldots 0.10$ μms^{-2}. These figures presuppose a certain seismic and thermic stability of the sites, and convenient transportation conditions for the equipment. With that observation accuracy, vertical crustal movements can be determined with an accuracy of $\pm 2 \ldots 5$ cm.

A first data evaluation is carried out on-line by a HP 200 computer. Here an earth tide routine is implemented which uses a tidal amplitude factor of 1.164 and a zero phase shift, with model errors generally less than 0.03 μms^{-2}. Since 1990, IfE accomplished a post-processing software package for refined data evaluation. In this procedure, all single drop results are corrected for earth tides, using the Cartwright-Tayler-Edden tidal potential development with 505 waves and observed tidal parameters. In addition, a data check for gross errors, produced e.g. by seismic shocks, is included. A drop will be rejected, if the difference between the drop and the mean value of a run (300 drops) exceeds five times the standard deviation.

3.2 Absolute Gravity Measurements in China 1990

During the 1990 campaign in China, different mechanical and electronical damages occurred, mainly caused by rough transportation and the intensive use of the instrument. The necessary repairs have been done by the German team (Dipl.-Ing. M. Schnüll, Dipl.-Ing. L. Timmen) with the assistance of the Chinese colleagues. The campaign could thus be completed within the planned time interval of 46 days. Ten absolute stations were occupied, which is one station more than the original plan considered.

All vertical gradients and local gravity differences were determined by three LCR gravity meters and measured immediately before or after the absolute observations. The instruments used, include G-709 and G-298 of IfE, and G-853 of SSB. The latter is supplied with a feedback system constructed in China.

For post-processing tidal parameters derived from records in Beijing, in Wuhan, and in Kunming were used (appendix 1). All stations in Yunnan Province were corrected with the Kunming data set.

3.2.1 Measurements in Wuhan and Beijing

Two absolute stations in Wuhan and two in the vicinity of Beijing have been occupied with JILAG-3. Each gravity determination includes more than 1100 drops. The results are summarized in Tab. 3.1. A complete listing of the single run results is given in appendix 2. From the drop-to-drop scatter and from the histograms the station quality can be ascertained. As an example Fig 3.1 shows the results of the IAGBN station Baijiatan (AS1003). The drop-to-drop scatter is very low at all stations in China, compared with observations performed in Hannover and elsewhere. This is probably due to the low microseismic noise compared with sites in Europe, and to the stable site locations.

Table 3.1: Results of absolute gravity observations in Beijing and Wuhan, China 1990

Station	*No.*	*Epoch*	$\frac{dg}{dH}$ $\left[\frac{\mu ms^{-2}}{m}\right]$	g $[\mu ms^{-2}]$
Xiangshan	AS1002	5/90	−2.774	9801292.65
Baijiatan	AS1003	5/90	−2.241	9801105.72
Wuhan (Uni)	AS4301	5/90	−3.341	9793488.63
Wuhan (IoS)	AS4302	5/90	−3.237	9793510.16

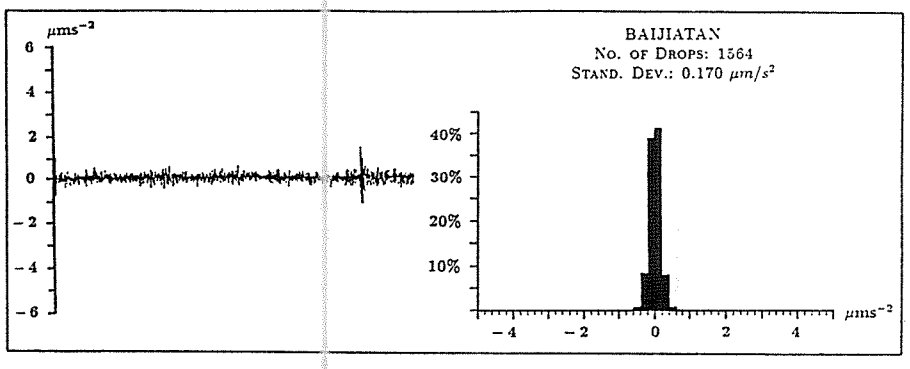


Fig. 3.1 Time sequence and histogram of absolute measurements in Baijiatan

3.2.2 Measurements in the Yunnan Region

The results for the six stations in the Yunnan area including the two Kunming stations are given in appendix 2. In Lijiang (AS6507) JILAG-3 was set up on a pillar about 2 m apart from an absolute point which was established by the Chinese absolute gravity meter NIM-II in 1986 at this pillar. The new point (AS6507) has been centered to the Chinese site.

The standard deviations differ between ±0.008 and ±0.022 μms^{-2} which is due to different environmental and instrumental conditions. High humidity and low temperatures forced us to heat the sites using transportable heaters. Necessary repair-work which included opening of the dropping chamber (loss of its vacuum) eventually influenced the subsequent measurements because of residual air pressure. Instantenous seismic activities increased the standard deviations.

Table 3.2: Results of absolute gravity observations in Yunnan, China 1990

Station	*No.*	*Epoch*	$\frac{dg}{dH}$ $\left[\frac{\mu ms^{-2}}{m}\right]$	g $[\mu ms^{-2}]$
Heilongtan	AS6501	4/90	−2.403	9783477.07
Yemaoshan	AS6502	4/90	−3.472	9782313.37
Chuxiong	AS6503	4/90	−2.442	9783749.13
Xiaguan	AS6505	4/90	−2.438	9783468.01
Baoshan	AS6506	5/90	−2.149	9783878.60
Lijiang	AS6507	5/90	−2.383	9782868.64
Lijiang	AS6517			9782868.45

AS6517 is connected to AS6507 by relative measurements

3.3 Comparison of Field Results with Post-Processed Results

The rejection of outlaying drops at post-processing did not change the results with the exception of AS6505. At this station the first run was strongly disturbed by an earthquake. From seismic records the peaks of the drops could be correlated with an earthquake of magnitude 4.3, about 190 km east of the station. By eliminating 13 drops in one subset (a subset consists of 30 drops) the run was changed by -0.022 μms^{-2} and the final mean by -0.004 $\mu m/s^2$. On the average, three drops per station were rejected (less than 0.1%). The tidal correction post-processing changed the on-line results systematically. On the average the station correction was -0.029 μms^{-2}.

The vertical gravity gradients have been determined in the field by using the data of the two IfE-LCR gravimeters. In the final evaluation G-853 of SSB was included. The differences between field and post-processed results are 0.03 μms^{-2} on the average. For the stations in Yunnan Province the network datum shifted by 0.02 μms^{-2}.

4. Relative Gravity Measurements

4.1 General Objectives

During the China 1990 gravity campaign 1261 relative gravity differences have been observed. 74 additional differences were observed in March and in early April by SSB. The relative measurements can be divided into four groups:

- Measurements between the absolute gravity stations, including the connection of base stations of the micro-net and the vertical gradient line, GPS stations and eccenters to the absolute stations (altogether 28 stations),
- measurements between eleven stations in the micro-net and between the ten gradient-line stations,
- measurement of vertical gravity gradients on the absolute stations and on the gradient-line,
- calibration measurements on the vertical calibration line Wuhan.

The employed instruments were LCR G-298 and G-709 of IfE, operated by R.H. Röder and S. Sander, and G-853 of SSB, mainly operated by Xing Canfei. G-793 and G-854 of SSB were used for the additional measurements in March and April. The IfE instruments are equipped with electronic SRW-feedback systems (measuring range 200 μms^{-2}), and G-853 is equipped with a feedback system built by SSB (measuring range about 30 μms^{-2}). The feedback systems of G-298 and G-709 have been used whenever the gravity differences were within their measuring ranges. To indicate this in the following tables, an 'F' is added to the instrument numbers. The feedback system of G-853 was employed for the measurement of vertical gravity gradients and occasionally for other observations. The feedback systems of G-298 and G-709 have been calibrated on the vertical calibration line of the Gravimeter Calibration System Hannover (Kanngieser et al. 1983) immediately before and after the field campaign. The calibration was checked on the vertical calibration line in Wuhan, where also the feedback of G-853 has been calibrated. This calibration line was established in 1986 in cooperation between IfE and IoS (Xu et al. 1987) as a part of the Gravimeter Calibration System Wuhan (Nakagawa et al. 1986). Measurements performed in this system in 1986 also gave the long and short wave calibration for the mechanical measuring systems of G-298 and G-709, whereas the scale factors for the chinese gravimeters were

determined from measurements between absolute stations in Beijing and Guangzhou in 1986 (G-853 and G-854) and in 1988 (G-793). The linear calibration parameters Y used are:

G-298: $Y = 1.000471$
G-709: $Y = 1.000675$
G-793: $Y = 1.000798$
G-853: $Y = 1.000686$
G-854: $Y = 1.000530$

Parameters x and y for correction of cyclic errors with periods p, expressed in counter units (CU) of the instruments ($1\ CU \approx 10\ \mu ms^{-2}$) are given in table 4.1:

Table 4.1: Periodical calibration parameters

Instrument	p $[CU]$	x $[\mu ms^{-2}]$	y $[\mu ms^{-2}]$
G-298	1.000	−0.0041	0.0100
	7.882	−0.0026	0.0230
	35.47	0.0217	−0.0011
	70.94	0.0132	0.0203
G-709	1.000	−0.0003	−0.0008
	7.333	−0.0026	0.0423
	36.67	0.0311	−0.0168
	73.33	−0.0591	−0.0677

Short wave calibration terms for the Chinese instruments are not available at the moment, but will be taken into account in the future.

Calibrated readings R_{cal} for an instrument are computed from the raw readings R, the readings R_{man} derived by means of the manufacturer's calibration table, the periods p_i and the calibration parameters Y, x_i and y_i according to

$$R_{cal} = R_{man} \cdot Y + \sum_{i=1}^{4} x_i \cdot \cos \frac{R \cdot 2\pi}{p_i} + y_i \cdot \sin \frac{R \cdot 2\pi}{p_i}$$

Linear (L) and quadratic (Q) parameters for the conversion of readings R of the feedback-systems ($volt$) into gravity dimensions (μms^{-2}) are listed in table 4.2. The applied formula is $R_{cal} = R \cdot L + R^2 \cdot Q$.

Table 4.2: Calibration parameters for feedback-systems

Instrument	L $\left[\frac{\mu ms^{-2}}{Volt}\right]$	Q $\left[\frac{\mu ms^{-2}}{Volt^2}\right]$
G-298F	10.6245	$-11.141 \cdot 10^{-3}$
G-709F	9.93313	$-2.256 \cdot 10^{-3}$
G-853F	10.5116	$-19.250 \cdot 10^{-3}$

4.2 Observations

The following long distance gravity observations could be performed in the Yunnan area (see Fig. 2.1): Heilongtan (near Kunming) – Chuxiong, Chuxiong – Xiaguan, Xiaguan – Lijiang and Xiaguan – Baoshan. In connection with these measurements six GPS stations were tied to the absolute sites (see [2.2]). One station of the micro-net (M1) was tied to Xiaguan and Lijiang and four stations of the gradient line (G2, G6, G7, G10) to Xiaguan. All differences between neighbouring stations of the micro-network and the gradient-line have been measured three times each, with three gravimeters applying the measuring scheme 'A→B→A→B→C→B→C→...'. For stabilization, the overlapping ties M1↔M4, M4↔M7, M7↔M1 in the micro-net and G2↔G5, G7↔G10 on the gradient line were observed. The micro-net was connected to the base net by measurements between stations M1 and AS6505 and M1 and AS6507 (via GPS15). For connecting the gradient-line, measurements were performed from the eastern part, the western part and from the island point of the line to the absolute station AS6505 and its eccenter G16 respectively. The twin absolute stations in Kunming, Beijing and Wuhan have been connected to each other and to airport stations in these cities by repeated measurements in triangles (Fig. 4.1). For the determiantion of vertical gravity gradients on the absolute stations and on stations of the gradient line, the differences between ground level and 1.000 meter height above ground have been measured ten times with each of the three gravimeters. The total number of ties which were observed with the different instruments are given in table 4.3. The results for the gradient-line and the micro-net are given in tables 4.4 and 4.5.

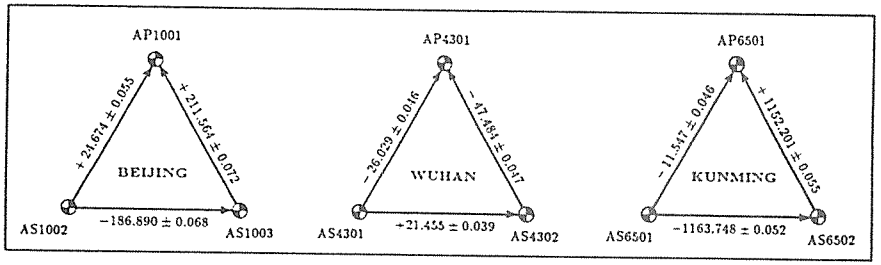


Fig. 4.1 Adjusted gravity differences in Beijing, Wuhan and Kunming

Table 4.3: Number of observed gravity differences with LCR-G-meters

Instrument-Number ....:	298	298F	709	709F	853	853F	793	854
Base network .....:	45	66	47	75	73	24	–	–
Micro-net .....:	–	41	–	41	33	9	22	22
Gradient line (ties) .....:	–	23	–	23	22	1	15	15
Gradient line (gradients) :	–	100	–	101	–	108	–	–
Abs. stations (gradients) :	–	107	–	110	–	118	–	–
Calibration line Wuhan .:	–	30	–	30	–	31	–	–
Subtotal .....:	45	367	47	380	128	291	37	37
Total .....:	1332							

(AP1001→AP6501→AP1001). Wuhan (absolute station) and Beijing (airport) were connected only once (AS4302→AP1001). Table 4.6 shows the results.

Table 4.6: Long range relative gravity measurements

Tie	G-298 $[\mu ms^{-2}]$	G-709 $[\mu ms^{-2}]$	G-853 $[\mu ms^{-2}]$	$Mean_{G-709,G-853}$ $[\mu ms^{-2}]$	JILAG-3 $[\mu ms^{-2}]$
Wuhan-Beijing	7805.87	7807.59	7806.85	7807.22	7807.18
Kunming-Beijing	17850.58	17851.72	17851.62	17851.67	17851.80

Gravity values for the airport stations were derived from adjustments of local networks in the three cities. The results of G-709 and G-853 do not deviate significantly whereas larger discrepancies were found for G-298. Instrumental investigations after the campaign showed a strong airpressure effect for this instrument at short time variations larger than 100 hPa. Consequently, LCR G-298 data for the long range ties were not considered.

5. Adjustment and Comparisons

5.1 Network Adjustment

After pre-processing the relative and the absolute gravity data, a combined adjustment was performed. The absolute observations were introduced into the least squares adjustment with a standard deviation of $\pm$ 0.07 μms^{-2}. For the weighting of the relative data, the standard deviations obtained from the adjustment of the relative networks were used. The final results are listed in tables 5.1 to 5.3. The mean standard deviation of a station is $\pm$ 0.07 μms^{-2}.

5.2 Comparisons

In order to get reliable estimates for the accuracies obtained, some comparisons between relative and absolute measurements have been carried out. In Tab. 5.4 the post-processed absolute measurements and the gravity values calculated by an independent adjustment of the relative observations are given. The RMS discrepancy of $\pm$ 0.12 μms^{-2} indicates that there are no significant differences in the scale of the absolute and the relative network and that the a priori error estimates of $\pm$ 0.07 μms^{-2} for both the results obtained with the absolute and the relative technique are realistic. The gravity differences derived from absolute and relative data between the adjacent absolute points near Beijing, Kunming and in Wuhan show a RMS discrepancy of $\pm$ 0.06 μms^{-2} (Tab. 5.5), which is well within the error estimates.

A comparison with results from observations performed with the Chinese absolute gravimeter (Guo 1990) showed a good agreement in four stations, but large differences occur at the IAGBN station in Beijing (0.3 μms^{-2}) and in Kunming (0.8 μms^{-2}). This has to be investigated further.

The relative networks were processed by a least squares adjustment. In these calculations, one station in each net obtained the fixed value $g = 0.000 \pm 0.000$ μms^{-2}. Thus the results obtained are relative gravity values with relative accuracies, which are not affected by uncertainties in the absolute datum. The adjustment of the micro-net (168 ties) yielded an accuracy better than $\pm$ 0.03 μms^{-2} (Table 4.4). For the gradient-line (150 ties) we obtained a mean standard deviation of $\pm$ 0.06 μms^{-2} (Table 4.5).

Table 4.4: The micro gravity network

Station	Distance $[km]$	Gravity $[\mu ms^{-2}]$	Std.dev. $[\mu ms^{-2}]$
M1	0.0	0.000	0.000
M2	1.8	−25.382	0.024
M3	3.8	−105.597	0.026
M4	6.2	−118.480	0.021
M5	8.5	−126.526	0.026
M6	11.5	−65.418	0.027
M7	13.5	−165.635	0.022
M8	17.2	−66.319	0.027
M9	18.9	−73.629	0.027
M10	21.8	−26.299	0.027
M11	24.0	10.956	0.024
		Quadratic mean:	0.024

Table 4.5: The vertical gravity gradient line

Station	Distance $[km]$	Elevation $[m]$	Gradient $\left[\frac{\mu ms^{-2}}{m}\right]$	Std.dev. $\left[\frac{\mu ms^{-2}}{m}\right]$	g_{floor} $[\mu ms^{-2}]$	Std.dev. $[\mu ms^{-2}]$
G1	0.0	2105	−2.922	0.014	0.000	0.000
G2	1.8	2035	−2.863	0.014	96.747	0.041
G3	2.9	1995	−3.064	0.014	179.524	0.050
G4	3.9	1978	−3.277	0.014	211.340	0.051
G5	5.0	1975	−3.101	0.014	209.095	0.055
G6	14.6	2000	−3.845	0.014	293.733	0.079
G7	17.0	1980	−2.556	0.014	360.670	0.077
G8	18.3	1975	−2.686	0.015	383.205	0.085
G9	19.8	1990	−2.754	0.014	373.794	0.085
G10	21.6	2015	−2.641	0.014	348.933	0.076
					Quadratic mean:	0.065

Long range relative measurements have been performed between Kunming and Wuhan and between Wuhan and Beijing, by aircraft transportation. These measurements serve as control for the used calibration factors, which were determined in 1986. The tie Beijing (airport) – Kunming (airport) could be measured two times

Table 5.1: Adjusted gravity values in the base network

Station	Gravity $[\mu ms^{-2}]$	Std.dev. $[\mu ms^{-2}]$	Location
AS1001	9801292.637	0.052	Beijing Xingshan (Abs.)
AS1003	9801105.739	0.055	Beijing Baijiatan (Abs., IAGBN)
AS1003e	9801105.543	0.056	Beijing Baijiatan (Eccenter)
AP1001	9801317.296	0.058	Beijing airport
AS4301	9793488.652	0.052	Wuhan Univ. (Abs.)
AS4302	9793510.111	0.050	Wuhan IoS (Abs.)
AP4301	9793462.626	0.064	Wuhan airport
AS6501	9783477.065	0.043	Kunming Heilongtan (Abs.)
AS6502	9782313.342	0.050	Kunming Yemaoshan (Abs.)
AS6503	9783479.134	0.048	Chuxiong (Abs.)
AS6505	9783468.081	0.047	Xiaguan (Abs.)
AS6506	9783878.534	0.059	Baoshan (Abs.)
AS6507	9782868.701	0.058	Lijiang (Abs.)
AS6507e	9782868.505	0.060	Lijiang (Eccenter)
AP6501	9783465.540	0.054	Kunming airport
G16	9783478.104	0.049	Xiaguan (Eccenter)
G116	9783954.563	0.066	Baoshan (Eccenter)
GPS00	9783389.373	0.053	
GPS01	9783641.079	0.114	
GPS02	9782435.677	0.081	
GPS08	9783936.300	0.109	
GPS10	9784022.213	0.086	
GPS15	9783053.050	0.086	
Quadratic mean:		0.066	

Table 5.2: Adjusted gravity values in the micro-net

Station	Gravity $[\mu ms^{-2}]$	Std.dev. $[\mu ms^{-2}]$	Location
M1	9783437.826	0.058	Nong Jizhan
M2	9783412.442	0.062	Lian Cheng
M3	9783332.247	0.062	Zhong Cun
M4	9783319.357	0.061	Wu Ziju
M5	9783311.292	0.062	Qi Xiangzhan
M6	9783372.391	0.062	Ci Bi Lake
M7	9783272.198	0.061	Shuei Nichang
M8	9783371.522	0.062	Xiao Ying
M9	9783364.203	0.062	Zhou Liying
M10	9783411.534	0.062	He Dong
M11	9783448.788	0.062	Xin Qiao
Quadratic mean:		0.062	

Table 5.3: Adjusted gravity values on the gradient-line

Station	Gravity $[\mu ms^{-2}]$	Std.dev. $[\mu ms^{-2}]$	Location
G1	9783170.855	0.068	Bai Longmiao
G2	9783267.617	0.060	Zhi Xiao
G3	9783350.407	0.067	Da Wazhuang
G4	9783382.217	0.066	Da Zhuang
G5	9783379.980	0.062	Jiang Shichang
G6	9783464.689	0.057	Hai Dao
G7	9783531.618	0.054	Nan Cun
G8	9783554.197	0.062	Shi Jingcun
G9	9783544.726	0.063	Zuen Zhuang
G10	9783519.886	0.056	Long Tou
Quadratic mean:		0.062	

Tab. 5.4: Comparison of absolute and relative gravity observations in the Yunnan area 1990

Station	No.	Abs. Obs. $[\mu ms^{-2}]$	Rel. Obs. $[\mu ms^{-2}]$	Discrepancy $[\mu ms^{-2}]$
Heilongtan	AS6501	9783477.07	9783477.00	0.07
Yemaoshan	AS6502	9782313.37	9782313.26	0.11
Chuxiong	AS6503	9783749.13	9783749.11	0.02
Xiaguan	AS6505	9783468.01	9783468.13	−0.12
Baoshan	AS6506	9783878.60	9783878.48	0.12
Lijiang	AS6507	9782868.64	9782868.84	−0.20
			RMS:	±0.12

Table 5.5: Comparison of gravity differences between the twin stations determined by relative and by absolute measurements

Location	Abs. Obs. $[\mu ms^{-2}]$	Rel. Obs. $[\mu ms^{-2}]$	Discrepancy $[\mu ms^{-2}]$
Beijing	−186.93	−186.89	−0.04
Wuhan	21.53	21.46	0.07
Kunming	−1163.70	−1163.75	0.05
		RMS:	±0.05

Table 5.6: Comparison of JILAG-3 and NIM absolute measurements

No.	JILAG-3 Epoch	JILAG-3 g $[\mu ms^{-2}]$	JILAG-3 $\frac{dg}{dH}$ $\left[\frac{\mu ms^{-2}}{m}\right]$	NIM Epoch	NIM g $[\mu ms^{-2}]$	NIM $\frac{dg}{dH}$ $\left[\frac{\mu ms^{-2}}{m}\right]$	Δg $[\mu ms^{-2}]$
AS6501	4/90	9783477.07	−2.403	3/86	9783477.04	−2.400	0.03
AS6502	4/90	9782313.37	−3.472	3/86	9782312.58	−3.450	0.79
AS6505	4/90	9783468.01	−2.438	4/86	9783467.90	−2.470	0.11
AS6517[1]	5/90	9782868.45	—	4/86	9782868.47	−2.190	−0.02
AS1002	5/90	9801292.65	−2.774	12/89	9801292.84	−2.774[2]	−0.19
AS1003	5/90	9801105.72	−2.241	3/86	9801105.42[3]	−2.237	0.30

[1] AS6517 is connected to AS6507 by relative observations
[2] IfE gradient used
[3] no air pressure correction applied

6. Conclusion

In the Western Yunnan Earthquake Prediction Study Area, a regional gravity control system has been established in April and May 1990 with an accuracy of better than $\pm$ 0.1 μms^{-2}. A local high precision micro gravity network and a vertical gravity gradient line will permit to detect mass shifts near surface. As the gravity network has been connected to a previously established GPS control net a combined evaluation and interpretation will be possible after the repetition surveys scheduled for 1991 and 1992, resp. and will then especially contribute to absolute and relative height change determination with an accuracy of $\pm$ 5 *cm* (regional) and $\pm$ 2 cm (local).

In addition the large scale calibration system Wuhan and the absolute gravity world net station Beijing have been strengthened at the 1990 campaign. Long wave calibration terms over a range of about 19000 μms^{-2}can be determined now with an accuracy better than $1 \cdot 10^{-5}$.

Acknowledgements

The authors wish to express their gratitude to *Deutsche Forschungsgemeinschaft*, to *Max-Planck-Gesellschaft* and to the *State Seismological Bureau, China* which generously sponsored the project. The hospitality and the valuable help of all institutions, involved in the measurements in China is gratefully acknowledged. *Cand. geod. S. Sander* participated in the field work and in the data evaluation.

REFERENCES

Boedecker, G., Fritzer, TH. (1986): International Absolute Gravity Basestation Network. IAG-SSG 3.87 Status Report March 1986, Veröff. Bayer. Komm. f. d. Int. Erdmessung d. Bayer. Akad. d. Wiss., Astron. - Geod. Arb., Nr. 47, München.

Guo, Y. (1990): Personal communication on results of absolute gravity measurements in China at May 31, 1990.

Kanngieser, E., Kummer, K., Torge, W., Wenzel, H.-G. (1983): Das Gravimeter-Eichsystem Hannover. Wiss. Arb. Fachr. Verm.wesen, Univ. Hannover, Nr. 120.

Lai, X., Shao, Z. (1985): Testing ground for earthquake prediction and its testing plan for research into crustal deformation in Dianxi. Institute of Seismology, State Seismological Bureau, Wuhan.

Nakagawa, I., Shichi, R., Nakai, S., Nakamura, K., Higashi, T., Li, R., Cheng, Y., Wang, D. (1986): International Gravimetric Connection between Japan and China. Bur. Grav. Int., Bull. d'Inf., **59**, 122-128.

Röder, R.H., Wenzel, H.-G. (1986): Relative Gravity Observations at BIPM, Sévres in 1985 and 1986. Bur. Grav. Int., Bull. d'Inf., No. 59, 177-183.

Schnüll, M., Röder, R.H., Wenzel, H.-G. (1984): An improved electronic feedback for LaCoste-Romberg gravity meters. Bur. Grav. Int., Bull. d'Inf., No. 55, 27-36.

Seeber, G., Lai, X. (1989): A GPS Survey in the Yunnan earthquake experimental field – objectives and first results. Pres. to IAG General Meeting Edinburgh, Scotland, 03.–12. August 1989. Proceedings Springer Int. 1990.

Torge, W. (1986): Gravimetry for monitoring vertical crustal movements: potential and problems. Tectonophysics **130**, 385-393.

Torge, W. (1989): Absolute gravimetry as an operational tool for geodynamics research. Proceed. Ron Mather Symp. on Four-dimensional Geodesy, Sydney 1989. Springer-Verlag.

Torge, W., Röder, R.H., Schnüll, M., Faller, J.E. (1987): First results with the transportable absolute gravimeter JILAG-3. Bull. Géodésique, No. 61, 161-176.

Xu, J., Zhu, S., Lui, X., Torge, W., Röder, R.H., Schnüll, M., Wenzel, H.-G. (1988): Vertical gravimeter calibration line Wuhan/China. Bur. Grav. Int., Bull. d'Inf., No. 62, 119-125.

Appendix 1

Local earth tide parameters for Wuhan

Wave group		Amplitude factor	Phase	
001	001	1.000	0.00	$M0S0$
002	128	1.164	0.00	Mf
129	193	1.220	1.15	$Q1$
194	241	1.184	−0.93	$O1$
242	254	1.158	−0.18	$P1$
255	333	1.156	−0.47	$K1$
334	398	1.191	−0.43	$N2$
399	441	1.174	−0.71	$M2$
442	450	1.176	−0.30	$S2$
451	488	1.170	−0.45	$K2$
489	505	1.069	0.22	$M3$

Local earth tide parameters for Beijing

Wave group		Amplitude factor	Phase	
001	001	1.000	0.00	$M0S0$
002	128	1.164	0.00	Mf
129	193	1.196	−0.46	$Q1$
194	241	1.183	0.26	$O1$
242	254	1.163	0.84	$P1$
255	333	1.153	0.39	$K1$
334	398	1.136	0.20	$N2$
399	441	1.180	0.23	$M2$
442	450	1.187	0.29	$S2$
451	488	1.175	0.94	$K2$
489	505	1.030	−3.41	$M3$

Local earth tide parameters for Yunnan

Wave group		Amplitude factor	Phase	
001	001	1.000	0.00	$M0S0$
002	128	1.164	0.00	Mf
129	193	1.179	−0.83	$Q1$
194	241	1.190	−1.50	$O1$
242	254	1.188	−1.21	$P1$
255	333	1.158	−1.12	$K1$
334	398	1.173	−0.77	$N2$
399	441	1.176	−0.73	$M2$
442	450	1.176	−0.07	$S2$
451	488	1.180	0.52	$K2$
489	505	1.074	1.26	$M3$

Appendix 2

Results of absolute gravity observations in China 1990

WUHAN (Institute of Seismology, AS4302)

Run	date	drops	$g_{h=0.822\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900520	291	9793507.485	0.365	9793510.15
2	900520	291	9793507.506	0.353	9793510.17
3	900520	289	9793507.515	0.353	9793510.18
4	900521	291	9793507.508	0.406	9793510.17
5	900521	291	9793507.486	0.436	9793510.15
		1453		Mean:	9793510.16
					$s = \pm 0.013$
					$\bar{s} = \pm 0.006$

WUHAN (University, AS4301)

Run	date	drops	$g_{h=0.832\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900522	291	9793485.913	0.319	9793488.69
2	900522	279	9793485.915	0.355	9793488.69
3	900522	284	9793485.821	0.219	9793488.60
4	900522	287	9793485.764	0.333	9793488.54
		1141		Mean:	9793488.63
					$s = \pm 0.073$
					$\bar{s} = \pm 0.037$

XIANGSHAN (Beijing, AS1002)

Run	date	drops	$g_{h=0.829\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900531	290	9801290.339	0.163	9801292.64
2	900531	289	9801290.343	0.148	9801292.64
3	900531	290	9801290.358	0.153	9801292.66
4	900531	290	9801290.367	0.321	9801292.67
5	900531	290	9801290.361	0.164	9801292.66
		1421		Mean:	9801292.65
					$s = \pm 0.012$
					$\bar{s} = \pm 0.005$

BAIJIATAN (Beijing, AS1003)

Run	date	drops	$g_{h=0.821\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900528	114	9801103.893	0.182	9801105.73
2	900529	288	9801103.929	0.127	9801105.77
3	900529	291	9801103.907	0.149	9801105.75
4	900529	290	9801103.911	0.139	9801105.75
5	900529	291	9801103.820	0.123	9801105.66
6	900530	290	9801103.850	0.249	9801105.69
		1564		Mean:	9801105.72
					$s = \pm 0.041$
					$\bar{s} = \pm 0.017$

HEILONGTAN (KUNMING, AS6501)

Run	date	drops	$g_{h=0.823\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900421	287	9783475.119	0.145	9783477.10
2	900421	287	9783475.074	0.139	9783477.05
3	900422	290	9783475.080	0.169	9783477.06
4	900422	144	9783475.086	0.149	9783477.06
		1008		Mean:	9783477.07
					$s = \pm 0.020$
					$\bar{s} = \pm 0.010$

YEMAOSHAN (KUNMING, AS6502)

Run	date	drops	$g_{h=0.823\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900425	290	9782310.484	0.129	9782313.34
2	900425	290	9782310.490	0.198	9782313.35
3	900425	289	9782310.540	0.131	9782313.40
4	900425	290	9782310.527	0.145	9782313.38
		1159		Mean:	9782313.37
					$s = \pm 0.028$
					$\bar{s} = \pm 0.014$

CHUXIONG (AS6503)

Run	date	drops	$g_{h=0.824\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900427	291	9783747.131	0.549	9783749.14
2	900427	262	9783747.146	0.246	9783749.16
3	900427	290	9783747.140	0.199	9783749.15
4	900427	290	9783747.177	0.206	9783749.19
5	900428	290	9783747.023	0.245	9783749.04
6	900428	291	9783747.081	0.212	9783749.09
		1714		Mean:	9783749.13
					$s = \pm 0.054$
					$\bar{s} = \pm 0.022$

XIAGUAN (AS6505)

Run	date	drops	$g_{h=0.830\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900430	276	9783465.986	0.264	9783468.01
2	900430	291	9783465.987	0.189	9783468.01
3	900430	291	9783465.986	0.201	9783468.01
4	900430	291	9783466.010	0.139	9783468.03
5	900430	291	9783466.012	0.110	9783468.04
6	900531	290	9783465.952	0.109	9783467.98
		1730		Mean:	9783468.01
					$s = \pm 0.021$
					$\bar{s} = \pm 0.008$

BAOSHAN (AS6506)

Run	date	drops	$g_{h=0.822\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900508	262	9783876.856	0.197	9783878.62
2	900508	290	9783876.865	0.209	9783878.63
3	900508	289	9783876.848	0.184	9783878.61
4	900508	290	9783876.849	0.220	9783878.62
5	900508	291	9783876.746	0.170	9783878.51
6	900508	287	9783876.827	0.168	9783878.59
		1709		Mean:	9783878.60
					$s = \pm 0.045$
					$\bar{s} = \pm 0.018$

LIJIANG (AS6507)

Run	date	drops	$g_{h=0.831\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900504	289	9782866.708	0.110	9782868.69
2	900504	290	9782866.647	0.140	9782868.63
3	900504	287	9782866.662	0.128	9782868.64
4	900504	291	9782866.648	0.105	9782868.63
5	900504	291	9782866.651	0.167	9782868.63
		1448		Mean:	9782868.64
					$s = \pm 0.026$
					$\bar{s} = \pm 0.012$

13th Meeting of the International Gravity Commission

Toulouse, September 10 - 14, 1990

Presented Paper

G.Boedecker

Terrain Effects from Series Developments Using FFT-Methods

0. Introduction

In physical geodesy, the impact of the topographic masses on quantities like gravity vector (for gravimetric reduction, deflection interpolation etc.) or the potential is required. Frequently, the total topography is split into a layer of constant thickness through some point P at the topographic surface and the deviation of the real topographic surface in the area giving the terrain effect, thus admitting series developments and consequently the application of faster numerical methods such as Fast Fourier Transform. Increased topographic data density and precision require investigations in higher order approximations of the topography, effects of the curvature of the earth etc.

1. Series developments for the terrain effect

The gravitational potential of a mass element is, according to Newton

$$V = G\varrho \frac{1}{r} dv \tag{1-1}$$

where

- V gravitational potential
- G gravitational constant
- ϱ density in volume element dv
- r distance

Introducing local cartesian coordinates we have

$$r = (x^2 + y^2 + z^2)^{\frac{1}{2}}, \tag{1-2}$$

thus from (1-1) we have

$$V = G\varrho \left(x^2 + y^2 + z^2\right)^{-\frac{1}{2}} dx\, dy\, dz \tag{1-3}$$

We divide the total topography into the ("Bouguer-")-plate and the terrain as shown in figure 1.

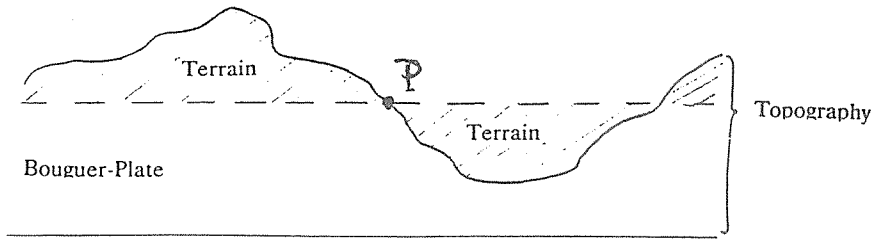


Fig. 1: Topography and Terrain

If convenient, we shall use $\ell^2 = x^2 + y^2$, $\Delta h = h - h_p$, where h_p – height of point and h – height of topography, and $\alpha = \text{arc tan } \frac{\Delta h}{\ell}$. Integration of (1-3) over Δh yields

$$V_1 = G\varrho \left\{ \ell n \left[\frac{\sqrt{\ell^2 + \Delta h^2}}{\ell} + \frac{\Delta h}{\ell} \right] \right\} dx\, dy \tag{1-4}$$

which may be visualized as the potential of a vertical mass line; the index for V simply indicates the different meaning with respect to (1-3). In this study we further anticipated a constant density.

Series development of (1-4) with respect to Δh yields:

$$V_2 = G \cdot \varrho \left\{ \frac{\Delta h}{\ell} - \frac{\Delta h^3}{6\ell^3} + \frac{3\Delta h^5}{40\ell^5} - \ldots \right\} dx\, dy \tag{1-5}$$

Setting $\alpha = \text{arc tan } \frac{\Delta h}{\ell}$ and using the expression

$$E_V = \frac{V_2 - V_1}{V_1} \cdot 100 \tag{1-6}$$

we have the relative error of the series approximation (1-5), which depends on α and — of course — on the degree of series expansion. The result is shown in figure 2 for the linear and third and fifth order polynomial. The error of the "weight function" depends only on height angle α, not on distance ℓ.

The differentiation of (1-4) and (1-5) respectively with respect to the vertical yields the expressions to be used for the gravimetric terrain reductions. We have

$$\frac{\partial V_1}{\partial z} = V_{z,1} = G \cdot \varrho \left\{ \left(\ell^2 + \Delta h^2\right)^{-\frac{1}{2}} - \ell^{-1} \right\} dx\, dy \tag{1-7}$$

and

$$V_{z,2} = G \cdot \varrho \left\{ -\frac{\Delta h^2}{2\ell^3} + \frac{3\Delta h^4}{8\ell^5} - \frac{5\Delta h^6}{16\ell^7} + \ldots \right\} dx\, dy \tag{1-8}$$

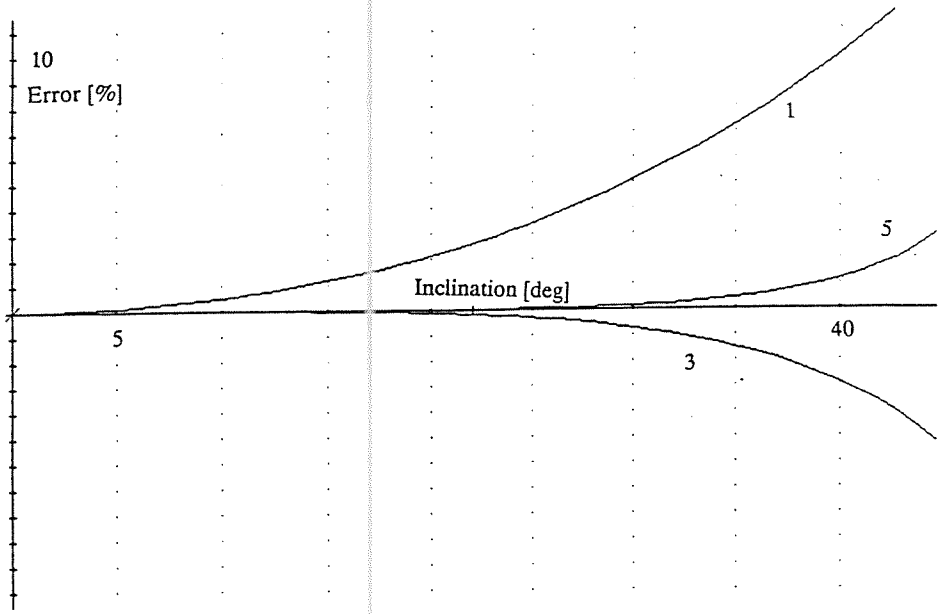


Fig. 2 Error of a series expansion of the gravitational potential of the terrain as a function of the inclination

As above we compute the relative error

$$E_g = \frac{V_{z2} - V_{z1}}{V_{z1}} \cdot 100 \tag{1-9}$$

for various degrees of the development of (1-8), cf. figure 3.
Likewise, for the horizontal components we have

$$\frac{\partial V_1}{\partial \left\{ \begin{smallmatrix} x \\ y \end{smallmatrix} \right\}} = V_{\left\{ \begin{smallmatrix} x \\ y \end{smallmatrix} \right\},1} = G \cdot \varrho \left\{ -\frac{\left\{ \begin{smallmatrix} x \\ y \end{smallmatrix} \right\} \cdot \Delta h}{(\ell^2 + \Delta h^2) \cdot \ell^2} \right\} dx\, dy \tag{1-10}$$

or

$$V_{\left\{ \begin{smallmatrix} x \\ y \end{smallmatrix} \right\},2} = G \cdot \varrho \left\{ \frac{\left\{ \begin{smallmatrix} x \\ y \end{smallmatrix} \right\} \Delta h}{\ell^3} + \frac{\left\{ \begin{smallmatrix} x \\ y \end{smallmatrix} \right\} \Delta h^3}{2\ell^5} - \frac{3 \left\{ \begin{smallmatrix} x \\ y \end{smallmatrix} \right\} \Delta h^5}{8\ell^7} + \ldots \right\} dx\, dy \tag{1-11}$$

Again, we compute the relative error; it is depicted in figure 4.
The physical interpretation of the first term of (1-5) is obvious. it is identical with the horizontal condensation of the terrain to the plane through point P; the same interpretation

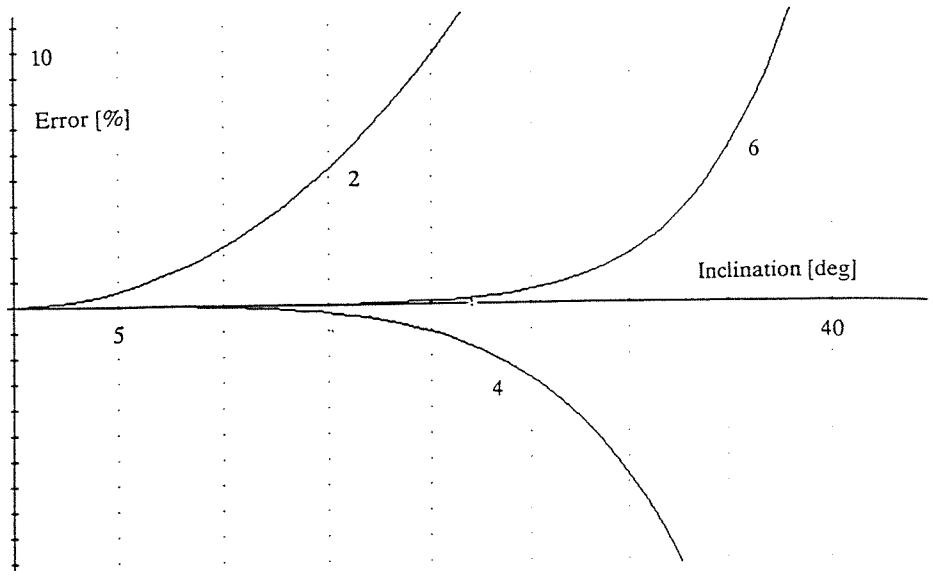


Fig. 3 Error of a series expansion of the gravimetric terrain effect as a function of the inclination

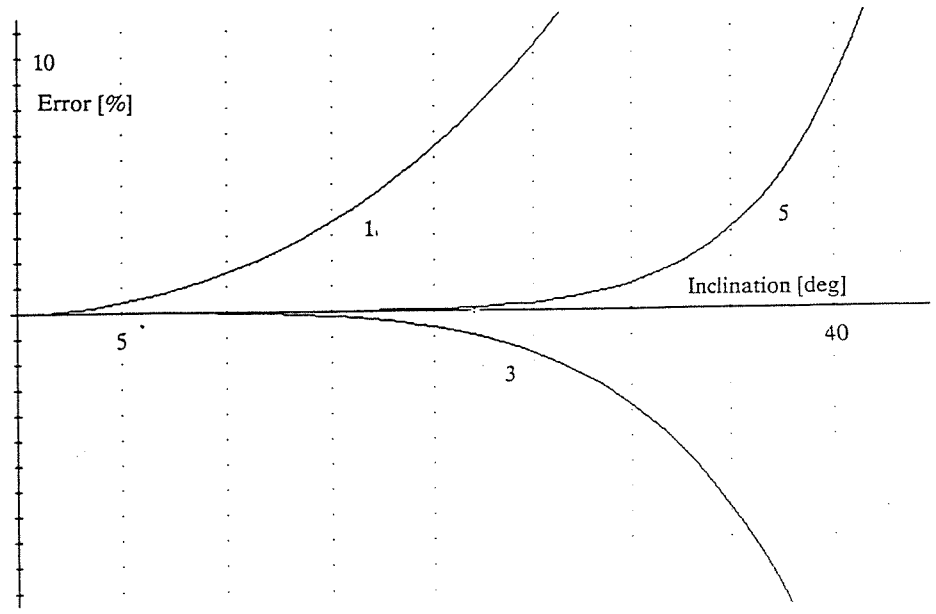


Fig. 4 Error of a series expansion for the terrain-induced deflection of the vertical as a function of the inclination

holds for the first term of (1-11). The first term of (1-8) is equivalent to the usual gravimetric terrain correction formula, cf. MORITZ (1984, p. 415), which for FFT-evaluation also had been used by SIDERIS (1984, p. 46) or FORSBERG (1984, p. 44). It is called "linear approximation". Here we have added higher order approximations and generalized the error investigation of e. g. FORSBERG (1984, p. 46ff.).

2. Application of Fast Fourier Transform (FFT) Methods

The basis in textbooks (e. g. PRESS et al. 1987) is usually given for (one-dimensional) time domain, where the convolution theorem reads

$$g * h = \int_{-\infty}^{\infty} g(t-\tau)\, h(\tau)\, d\tau \tag{2-1a}$$

$$g * h \Leftrightarrow G(f)\, H(f) \tag{2-1b}$$

where

t	point in time
τ	time lag with respect to t
g,h	(complex-valued) functions in time domain
f	frequency
$G(f)$	$= \int_{-\infty}^{\infty} g(t)\, e^{2\pi i f t}\, dt = \mathcal{F}(g)$, $\mathcal{F}(\cdot)$ Fourier transform
$g(t)$	$= \int_{-\infty}^{\infty} G(f) e^{-2\pi i f t}\, df = \mathcal{F}^{-1}(G)$ $\mathcal{F}(\cdot)$ inverse Fourier transform
$\Leftrightarrow$	pair of Fourier transform and its inverse
G,H	spectra of functions g, h

Since for the Fourier transform of gridded data the numerical Fast Fourier transform (FFT-) method is very efficient, it makes sense to transform data to spectral domain, where integration reduces to mere multiplication and backtransform the result, if also the result is desired on a grid.

For the details of the derivation from the above basic formulae to the algorithm, the reader is referred to SIDERIS (1984) and PRESS et al. (1987).

The formulae (1-4) and (1-7) for the computation of terrain effects are not in the form of (2-1a) ready for application of the convolution theorem. Instead, we have to use the series expansion (1-5) and (1-8), which have to be modified slightly: for the 3rd degree development of the potential (1-5) we have using $\Delta h = h - h_p$:

$$V_3 = G \cdot \varrho \cdot \left\{ \frac{h_p^3}{6\ell^3} - \frac{h_p^2\, h}{2\ell^3} + \frac{h_p\, h^2}{2\ell^3} - \frac{hp}{\ell} - \frac{h^3}{6\ell^3} + \frac{h}{\ell} \right\} \tag{2-2}$$

$$V_3 \approx V_2$$

In the terms 1 and 4, $\frac{1}{6\ell^3}$ and $\frac{1}{\ell}$ resp. are to be integrated analytically once for the whole area, the other four terms are evaluated by FFT along the following lines: To be FFT-transformed are the functions $\frac{1}{\ell^3}$, $\frac{1}{\ell}$, h, h^2, h^3. By taking the proper products in frequency domain, inverse transform and adding the terms we get V_3. In order to save computer time, we make use of the fact that the above five functions are real-valued, whereas the FFT always anticipates complex-valued functions. Thus we can put one function to the real part of an input array and a second function to the imaginary component of the same complex input array. For this reason, only 3 FFT and 3 inverse FFT computations are needed. Thus the 3rd degree approximation will be much better than the linear one and still the computation is much faster compared to using the strict formula (1-4) and classical numerical integration.

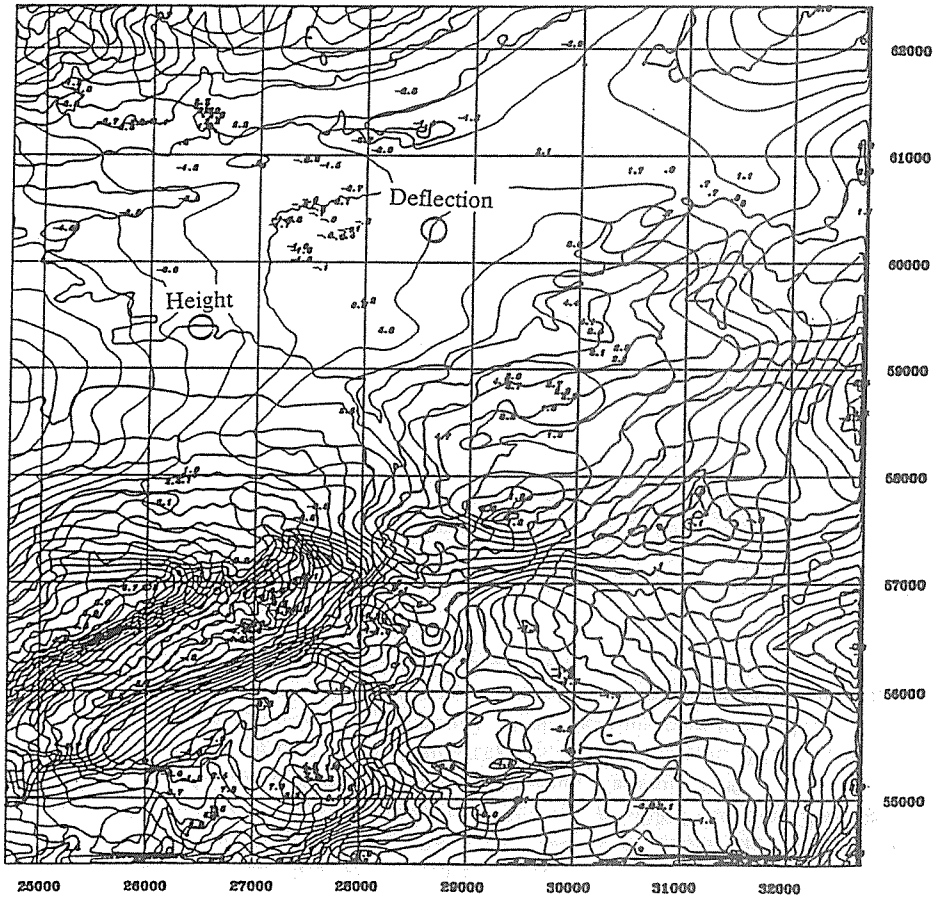


Fig. 5 Example for the FFT-computation of topographic deflections of the vertical (Alpine foreland, grid spacing 50 m, extension 8 km, height-isolines 100m, North deflection isolines 1arcsec.
Scale 1:50 000

An example is given in figure 5, showing the North derivative of the gravitational potential of the topography in linear approximation (topographic deflections of the vertical). These were computed from a 50 m by 50 m height grid with about dm-accuracy in the Alpine foreland.

3. Curvature of the Earth's Surface

Because of the hight quality and density of the data points and because of the higher degree series expansions, also minor disturbing effects have to be investigated. The curvature of the Earth enters in two ways: The above formulae refer to an orthogonal coordinate system where the z-axis is orthogonal to the height reference surface and the x-y-plane passes through the point P under investigation at the topographic surface of the Earth, i. e. it is tangent to the parallel of the reference surface through point P and deviates at some distance d by

$$D \approx \frac{d^2}{R} \tag{3-1}$$

where R is the radius of the Earth. This amounts to

D	[km]	10	30	50	100
d	[m]	8	71	196	785

As derived in BOEDECKER 1975, we have to take into account this horizon depression by using

$$\delta g_{\text{ter}} = f\left(|h - h_P - D|\right) - f(D) \tag{3-2}$$

if f here denotes the terrain effect computation formula. This procedure cares for the balance of the real topographic surface to the height of P. In our test area with height variations of some 1000 m and in an outer radius of 10 km, the effect of the horizon depression was below $0.02 \cdot 10^{-5}$ ms^{-2} and therefore negligable. Further, the coordinates used were GAUSS-KRÜGER-coordinates (like UTM, 3°-stripes). Again, the effect was negligable.

4. Conclusions

Increased terrain data density for the computation of terrain effects in physical geodesy and geophysics requires faster algorithms like FFT. The series developments necessary for this purpose permit to maintain high precision, if higher order terms are utilized. The article presents a concise error analysis for the potential and its first derivatives. The effects of the Earth's curvature have to be taken care of. The limiting factor now probably comes from the rock densities.

5. References

BOEDECKER, G.: *An Economically Working Method for Computing the Gravimetric Terrain Correction.* J. Geophys. **41**, pp. 513–521, 1975

FORSBERG, R.: *A Study of Terrain Reductions, Density Anomalies and Geophysical Inversion Methods in Gravity Field Modelling.* OSU rep. # **355**, Columbus/Ohio 1984

MORITZ, H.: *Advanced Physical Geodesy.* Wichmann, Karlsruhe 1980

PRESS, W. H.; FLANNERY, B. P.; TEUKOLSKY, S. A.; VETTERLING, W. T.: *Numerical Recipes — The Art of Scientific Computing.* Cambridge University Press 1987

SIDERIS, M.: *Computation of Gravimetric Terrain Corrections Using Fast Fourier Transform Techniques.* UCSE rep. # **20007**, Calgary 1984

REGIONAL GRAVITY MAPS AND PROJECTS IN AFRICA, SOUTH AMERICA, SOUTH-EAST ASIA AND EUROPE

J.D. Fairhead

THE AFRICAN GRAVITY PROJECT (AGP)

P. Chevalier

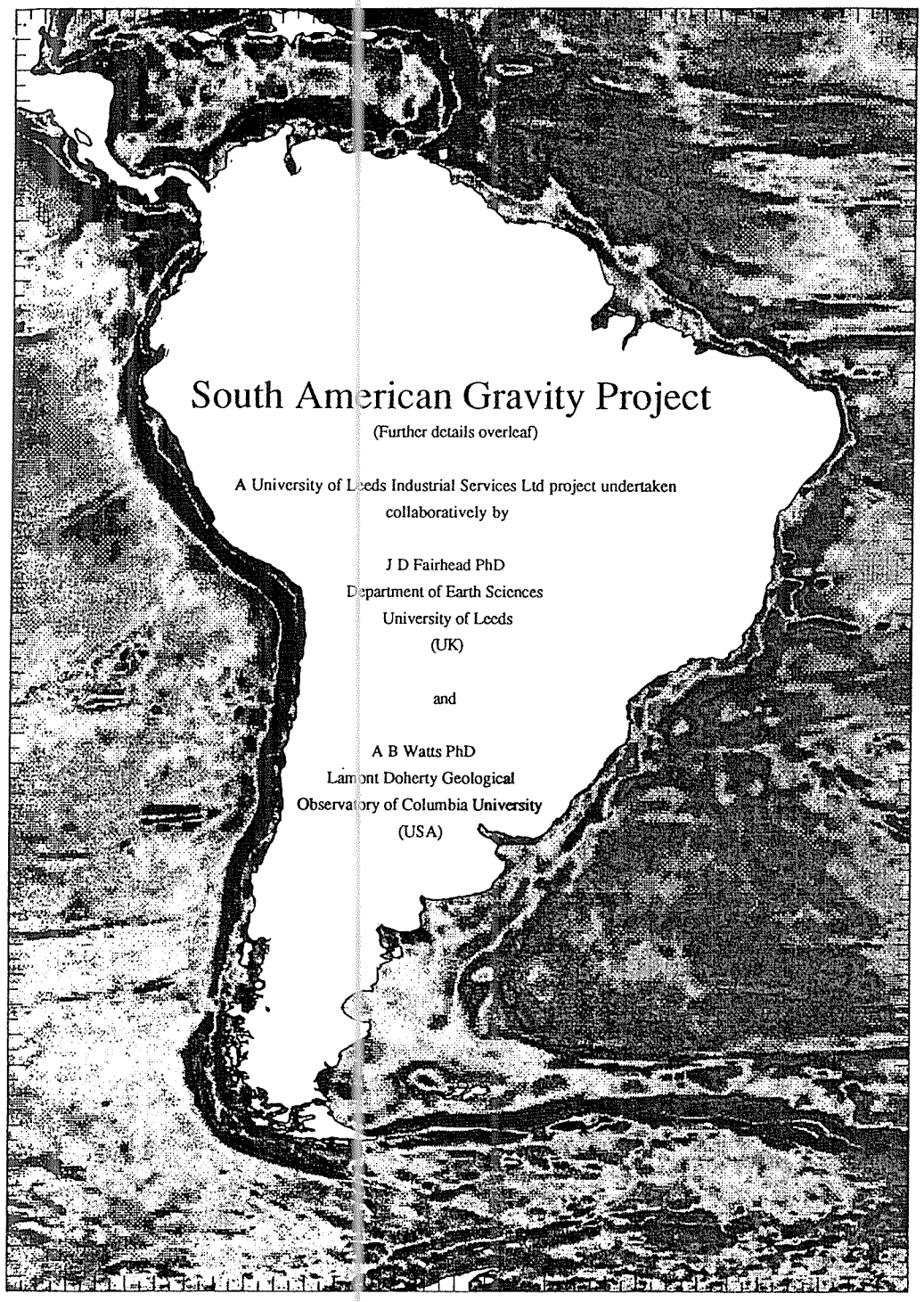
THE SOUTH AMERICAN GRAVITY PROJECT (SAGP)

I. Windle

The following four papers summarize the activities presented by the authors listed above in the framework of the four projects.

J.D. Fairhead's presentation was an overview of all projects, while P. Chevalier and I. Windle communications dealt with more technical aspects and with the results obtained already in AGP and SAPG, also with prospects in other areas of the world.

N.D.L.R.



South American Gravity Project

PROJECT SUMMARY

The South American Gravity Project is a joint venture between the University of Leeds (UK) and Lamont Doherty Geological Observatory of Columbia University (USA) sponsored by:

Agip, Amoco, Arco, BP, Conoco, Exxon, Marathon, Mobil, Petrobras, Shell, Texaco and Unocal.

The project is designed to gather the maximum proprietary and open file gravity data available for the whole of the South American continent and its offshore continental margin over a 3 year period, April 1988 - April 1991. These data will be reprocessed to a common datum and the Bouguer, free air and topography (bathymetry) data resampled onto a 5' x 5' grid (approximately 10 x 10 km). These gridded data sets will be used to produce colour Bouguer & free air anomaly maps at various scales using modern computing (Sun-4 & Intergraph) and colour plotting (Versatec) systems.

PROJECT PRODUCTS

a) **Computer Generated Colour Maps** at scales of 1:10,000,000 and 1:5,000,000 and 1:2,000,000 the last contoured at 5 mGal (50 g.u.) intervals with gravity station distribution shown.

b) **Technical Reports** on a country by country basis giving details of each survey used, data reduction, proprietary rights and ownership of data.

c) **Magnetic Data Tapes** containing the regularised 5' x 5' grid of interpolated free air, Bouguer and topography (bathymetry) values and locations of all point by point data used.

SPONSORSHIP

In addition to the 12 original sponsors listed, late sponsors are permitted to join the project at a premium. After April 1989, late sponsors will be restricted to those who are able and willing to contribute substantial data coverage to the project.

For further details of the South American Project, please contact Dr J Derek Fairhead, Department of Earth Sciences, University of Leeds, LS2 9JT (UK). Office telephone (0532) 422407 or via ULIS address below.

University of Leeds Industrial Services Ltd (ULIS)
175 Woodhouse Lane, LEEDS, West Yorkshire, LS2 9JT, England
Telephone (0532) 333444 Telex 556473 UNILDS G Fax (0532) 429234

AFRICAN GRAVITY PROJECT (1986 - 1988)

COMMERCIAL RELEASE OF PRODUCTS

Dr J D Fairhead
Dept of Earth Sciences
Leeds University
Leeds
LS2 9JT

Telephone: (44) 532 422407
Facsimile: (44) 532 429234
Telex: 556473 UNILDS G

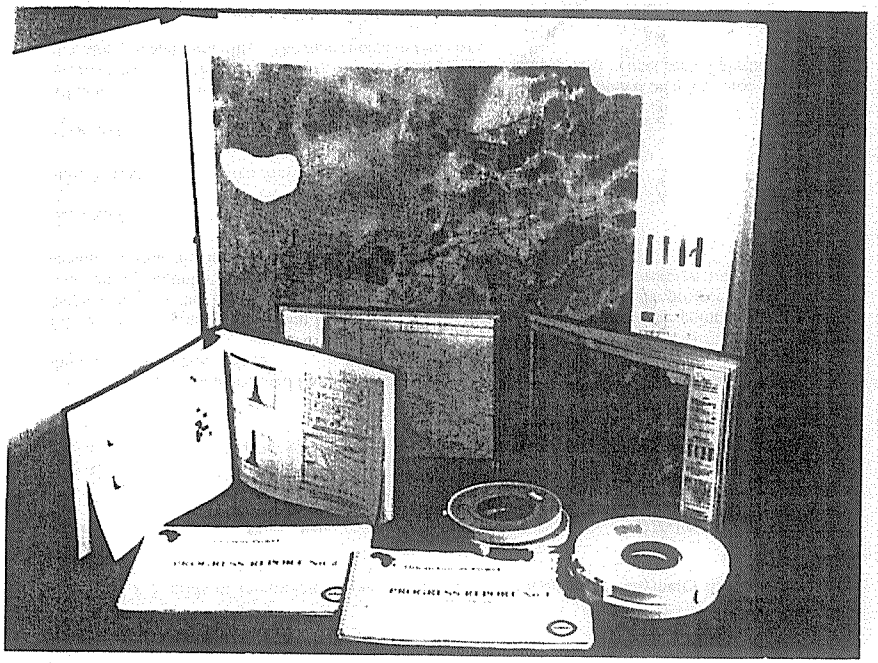
A project that has compiled over 750,000 land and 1,500,000 marine gravity values in and about Africa. The results of this project are now available for wider use within the oil industry as a regional geophysical tool to investigate frontier exploration areas.

All enquiries to Dr J D Fairhead

University of Leeds Industrial Services Ltd (ULIS)
175 Woodhouse Lane, LEEDS, West Yorkshire, LS2 9JT, England
Telephone (0532) 333444 Telex 556473 UNILDS G Fax (0532) 429234

AFRICAN GRAVITY PROJECT
COMMERCIAL RELEASE OF PRODUCTS

Products of the African Gravity Project (AGP) will be available for immediate delivery as of 1 September, 1990. The products represent the regional gravity coverage of Africa and its continental margins in the form of digital gridded data sets, map atlases and technical reports. The products provide a new regional exploration tool to evaluate continental tectonic and basement controls on sedimentary basins within Africa and along its continental margins.

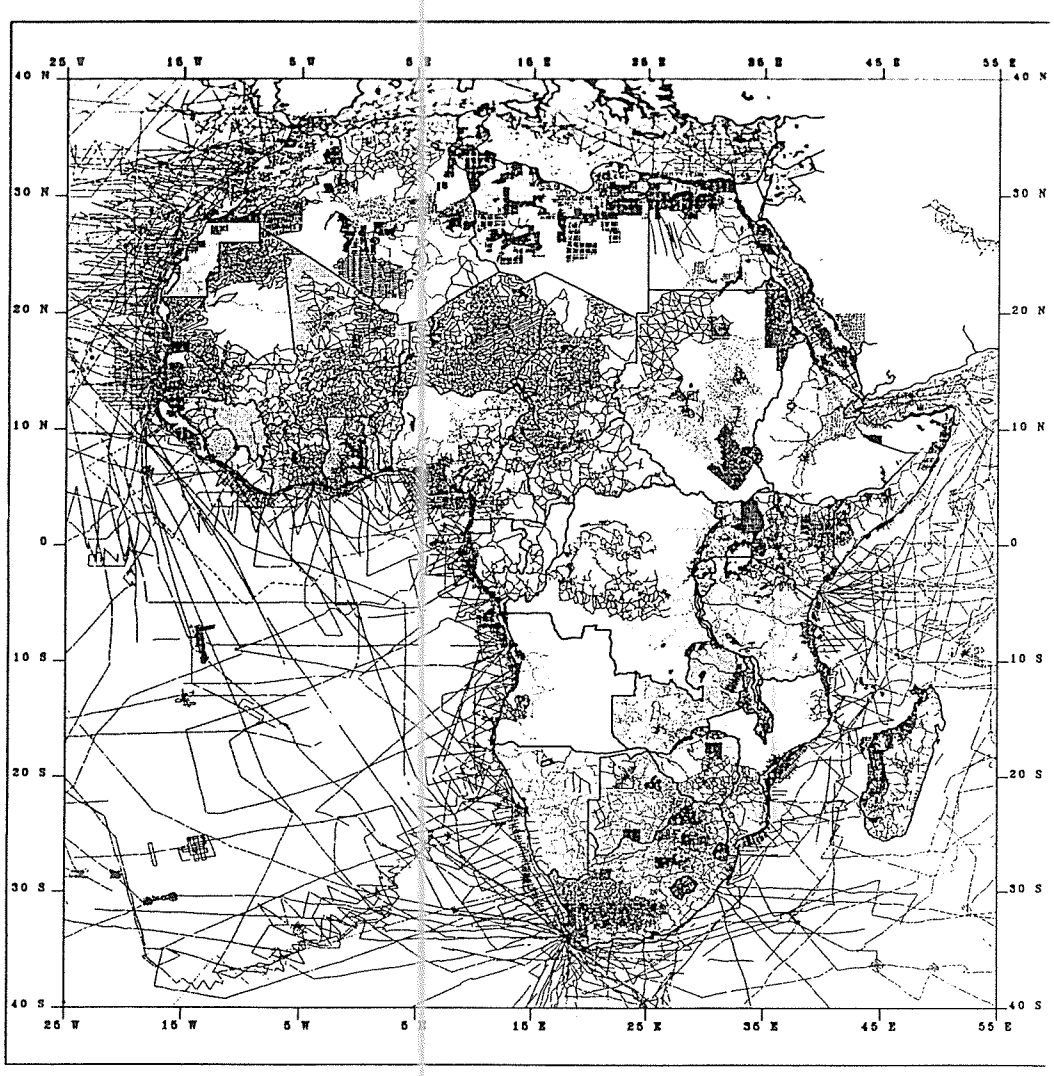


Products of the African Gravity Project

AGP Sponsors: Agip, Amoco, Arco, BHP, BP, Chevron, Conoco, Exxon, Mobil, Marathon, Phillips, Placid, Shell, Texaco, Total and Unocal.

DATA COVERAGE

The coverage of data is shown in the diagram below for the rectangular area 25°W to 55°E and 40°S to 40°N. Except for Madagascar, land areas outside Africa have not been considered in this study. The data provided from oil industry, geological surveys, universities, individuals and institutes were in excess of 750,000 for land and 1,500,000 for the marine areas.



DATA PROCESSING PARAMETERS

Anomaly values have been adjusted to the IGSN71 gravity datum and processed using the 1967 International Gravity Formula (IGF67). The free air correction was 0.3086 mGal m^{-1} and the Bouguer reduction densities of 2.67 g/cc (land) and 1.64 g/cc (marine) were used. No terrain corrections were calculated but if supplied they were used.

Marine data of various vintages and spatial coverage were adjusted by least squares methods using ship track intersections. The final solution was constrained by reliable surveys tied to land base stations. The continuity of the land and marine data were checked at numerous coastal locations about Africa in areas of low anomaly gradient. The internal consistency of the data is high and closely matches the Seasat derived field, with the marine data having the higher spatial resolution.

To reduce bias in the interpolated 5' x 5' grid node values caused by the variable station coverage, spatial weighted mean anomaly values were calculated within each 2.5' x 2.5' square for both the marine and land data sets. These smoothed values (pigeon hole values) were used with a modified minimum curvature technique to generate the 5' x 5' grids and associated flag files.

Full details of the processing sequence are given in the technical report.

PRODUCTS

1) **Digital Data** (9 files)

Digital 5' x 5' grids of interpolated Bouguer, free air and topography/bathymetry data are as follows.

File	Flag File	Onshore	Offshore
File 1	(File 5)	Bouguer	Bouguer
File 2	(File 6)	Bouguer	Free Air
File 3	(File 7)	Free Air	Free Air
File 4	(File 8)	Topography	Bathymetry

Files 5 to 8 represent associated flag files indicating the distance about each grid node containing three 2.5' pigeon hole values.

File 9 contains gravity data point locations, flags H, B, F, indicates whether the point data has heights, and whether Bouguer and free air anomaly values were available to the project together with survey, country and source codes to provide GIS facilities and cross referencing to our technical documentation.

Optional Extras

Standard Intergraph design files of the twenty one 1:2 million scale maps.

2) **Map products**

All map products have been generated from the 5' x 5' digital grids and plotted on a Versatec 200 nibs/inch electrostatic colour plotter. All Versatec plots are encapsulated in heat sealed plastic to give strength and durability. The maps come in two sizes:

Large Map Atlas (size ~A0)

1:2 million scale series - twenty one maps showing Bouguer (onshore) and free air (offshore) contoured at 5 mGals and colour filled at 10 mGal intervals. Station locations, coastlines and national boundaries are superimposed on the maps.

1:5 million scale series - fifteen maps subdivided into three map sets showing:

a) Bouguer (onshore), free air (offshore) with marine free air data beyond the continental edge replaced by Seasat derived free air data (after Haxby) contoured at 10 mGal and colour filled at 20 mGal intervals.

b) Bouguer onshore and offshore with contours and colouring the same as (a).

c) Overlay maps showing station distribution.

Small Map Atlas (size ~A3)

This atlas is an easy to handle reference book with the twenty one maps featured in the large map atlas reduced to 1:5 million scale. The station locations form a separate set of overlay maps.

Optional Extras

Wall posters showing shaded relief plots of Africa and global view of Africa hemisphere (centred on 0°, 0°) with AGP data inset within Geosat derived free air anomaly map of the oceans (after Haxby). The latter is shown at reduced size on the front cover without legend.

3) **Technical Report**

This document describes the reduction and reprocessing of land and marine gravity data into a coherent data set. The major part of the document is devoted to technical details of each survey used in this study on a country by country basis. Details on status of data (i.e. confidentiality) and ownership are given.

CONFIDENTIALITY OF DATA AND PRODUCTS

Data

No point data will be released since the majority of the data sets used are either proprietary or have restrictions on their distribution. These data often contain higher resolution of the gravity field than shown by our products and thus their commercial value remains intact. Sufficient details are provided to enable identification of owners.

Products

All products are supplied in accordance with a confidentiality agreement. All products have copyright restrictions.

PRICE

The complete product (excluding optional extras) comprises of:

1 set of magnetic tapes (specify tape format)
2 large map atlases
2 small map atlases
2 technical documents

Price available on request. No part products are available.

For further details contact:

Dr J D Fairhead
Dept of Earth Sciences
University of Leeds
Leeds
LS2 9JT
UK

Telephone: (44) 532 422407
Fax: (44) 532 429234
Telex: 556473 UNILDS G

SOUTH EAST ASIA GRAVITY PROJECT

A collaborative project proposed by the University of Leeds Industrial Services Ltd

involving

Dr J D Fairhead
Dept of Earth Sciences
Leeds University
Leeds
LS2 9JT
Telephone: (44) 532 422407
Facsimile: (44) 532 429234
Telex: 556473 UNILDS G

Prof A B Watts
Dept of Earth Sciences
University of Oxford
Parks Road
Oxford OX1 3PR
UK
Telephone: (44) 865 272000
Facsimile: (44) 865 272072

Dr G Balmino
Bureau Gravimetrique International
CNES
18, avenue Edouard Belin
31055 Toulouse Cedex
France
Telephone: (33) 61 33 28 89
Facsimile: (33) 61 27 31 79
Telex: CNES 531081 F

Correspondence to be addressed to Dr J D Fairhead

University of Leeds Industrial Services Ltd (ULIS)
175 Woodhouse Lane, LEEDS, West Yorkshire, LS2 9JT, England
Telephone (0532) 333444 Telex 556473 UNILDS G Fax (0532) 429234

(Sponsors of the pre-commitment stage are: Agip, BHP, BP, Conoco, Enterprise Oil, JNOC, Marathon, Mobil, Shell, Texaco & Unocal)

1 PROJECT SUMMARY

The pre-commitment stage (April 1990 - March 1991) of the South East Asia Gravity Project (SEAGP) is designed to establish links with national organisations and international oil companies throughout SE Asia and Australasia to determine the amount and availability of land and marine gravity data in the region that SEAGP can expect to compile. SEAGP will commence in April 1991 and will follow the completion of the highly successful African and South American Gravity Projects which have brought together all available gravity data from international and national oil companies, national organisations, institutes and universities. SEAGP has the same aim as these projects and will integrate all available land and marine gravity data for the area 45°S to 45°N and 60°E to 180°E (see cover picture) into a single digital database. The database will be used to generate a 5' x 5' grid (~10 km x 10 km) of interpolated Bouguer, free air and topography/bathymetry values for the region. Point gravity data will be normally treated as confidential and not passed to Sponsors. The region of study will extend to and include New Zealand, China, Mongolia and Afghanistan if data are available. Areas of poor marine gravity coverage will be infilled with the free air gravity field derived from GEOSAT. Areas of good marine gravity coverage will have a better spatial resolution at shorter wavelengths than GEOSAT. Thus marine gravity will play an important and continuing role in exploration for the foreseeable future.

The results of the project will give a regional perspective to sedimentary basins and their relations to plate tectonic processes. The South East Asia/Australasia region is a distinct and complex plate tectonic environment exhibiting major gravity relief and harbouring major oil reserves. This is a frontier area with major oil reserves still to be discovered. Gravity, although its interpretation is non unique, is playing an ever increasing role as a basic exploration tool in frontier areas and provides an initial and on-going means of evaluating the geometry and structural controls on sedimentary basins especially in their transition from land to marine environments.

2 PRODUCTS

During the three year project Sponsors will be provided with a phased release of the following products.

a) **Digital grids** (5' x 5') of interpolated Bouguer, free air gravity and bathymetry/topography.

b) **Digital listing** of all data point locations (not their height or gravity).

c) **Digital technical database** giving details of surveys used and their ownership.

d) **Colour gravity maps** at 1:2 million and 1:5 million scales for the region constructed from the 5' x 5' grid at 5 mGals showing location of gravity stations used.

e) **Technical report** indicating data processing parameters and bibliography of data sources used in the study on a country by country basis.

3) SPONSORS

In late 1990 all interested oil companies will be invited to join the SEAGP in April 1991 as full Sponsors. The sponsorship cost will be announced in late 1990 and will be in the region of £25,000 to £30,000 per year for three years. Final costs will be subject to availability of gravity data in SE Asia and the number of Sponsors. Oil companies who have joined the project at the pre-commitment stage will have a price advantage in the first year of the project over those Sponsors who did not join at the pre-commitment stage. **All companies wishing to be considered as Sponsors should fill in the attached reply form so that project proposals can be sent in due course.**

4) ASSOCIATE MEMBERS & DATA TRADERS

Associate Membership is free of charge to national organisations who are able to release gravity data into the project. In return the Associate Member will receive, at no cost, the gravity maps, digital data and technical documentation of the gravity database for its country and adjacent undisputed marine areas. For example, the South American Gravity Project has linked with the majority of the national oil companies in South America via Associate Membership Agreements to bring together over forty years of archived gravity surveys for digitising and reprocessing into a unified database. SEAGP has already made formal links with BMR (Australia) to integrate and reprocess all its land and marine data. At the end of the project the database will provide the opportunities for the collaborators to link with Associate Members to partake in a PhD/Post Doctorate based research programme which the Sponsors will be invited to fund as an independent follow-on project.

Non sponsoring international oil companies and contractors are encouraged to enter Trade Agreements whereby they will release their archived gravity data in return for receiving certain project products covering an expanded area containing their data. The project will provide good international exposure of available data sets and space will be made available for contractors to advertise their speculative surveys in the Technical Report.

5) CONFIDENTIALITY

All gravity data handled by the project are treated as confidential and not passed to Sponsors or any third party without the written approval of the owner. Oil company gravity data retains its commercial value since the interpolated 5' x 5' grid can only resolve gravity anomalies greater than about 20 km.

6) COLLABORATORS

The three collaborating groups have worked in close cooperation on previous projects on Africa and South America and will be combining a wide range of experience in processing land, marine and satellite-derived gravity data.

i) University of Leeds Industrial Services Ltd (ULIS) is a wholly University owned marketing and development company, set up by the University of Leeds to utilise the expertise and facilities of the University in the industrial and commercial field. The experience ULIS has gained during the oil industry sponsored African and South American Gravity Projects (AGP and SAGP) will help with the initial arrangements and subsequent running of SEAGP. ULIS will manage all financial, contractual and legal aspects of the project.
Department of Earth Sciences (University of Leeds) The UK part of the project will be managed by Dr J Derek Fairhead and Dr Graham W Stuart who have managed the successful AGP and SAGP since 1986. Through these projects Leeds has installed state-of-the-art CAD systems including Intergraph and Sun networks linked to digitising and colour Versatec plotting facilities. These computing systems are operated by experienced staff in software development, data handling and colour plotting.

ii) Department of Earth Sciences (University of Oxford) Prof Watts has been a collaborator in both the AGP and SAGP whilst based at Lamont-Doherty Geological Observatory (USA). Prof Watts has now moved to the University of Oxford (UK) where a new processing centre for marine gravity data has already been set up and will be involved in the marine data acquisition and reprocessing.

iii) BGI, (Bureau Gravimétrique International) is one of the offices of FAGS (Federation of Astronomical and Geophysical Services). It is also the executive office of the International Gravity Commission of section III of the International Association of Geodesy. The main task of BGI is to collect, store and validate Earth gravity field data and to redistribute them on request. BGI has experience in managing large computerised databases and in validating surface gravity measurements, for which its staff has developed its own software.

The participation of BGI in the project will mostly consist of providing data from its database, in acquiring data from new sources via its extensive links in SE Asia and in validating land gravity observations.

The BGI part of the project will be managed by Dr Georges Balmino and colleagues.

SOUTH EAST ASIA GRAVITY PROJECT

Reply form

Name: .....

Company: .....

Address: .....

.....

.....

.....

.....

Telephone: .....

Telex: .....

Facsimile: .....

By ticking the appropriate box shown below, please register your interest in becoming:

1) Potential Sponsor ☐ Associate Member* ☐ Trader+ ☐

** Restricted to national organisations*
+ Normally non-sponsoring oil company

2) Do you have gravity data (onshore and offshore) you can supply to project? Yes ☐ No ☐

3) Please send map showing data coverage.

4) Are data on magnetic tape? Yes ☐ No ☐

5) Are data confidential? Yes ☐ No ☐

6) Are data open file? Yes ☐ No ☐

7) Please provide other names and addresses (plus telephone, fax and telex numbers) of other sources of gravity data in your country.

.....

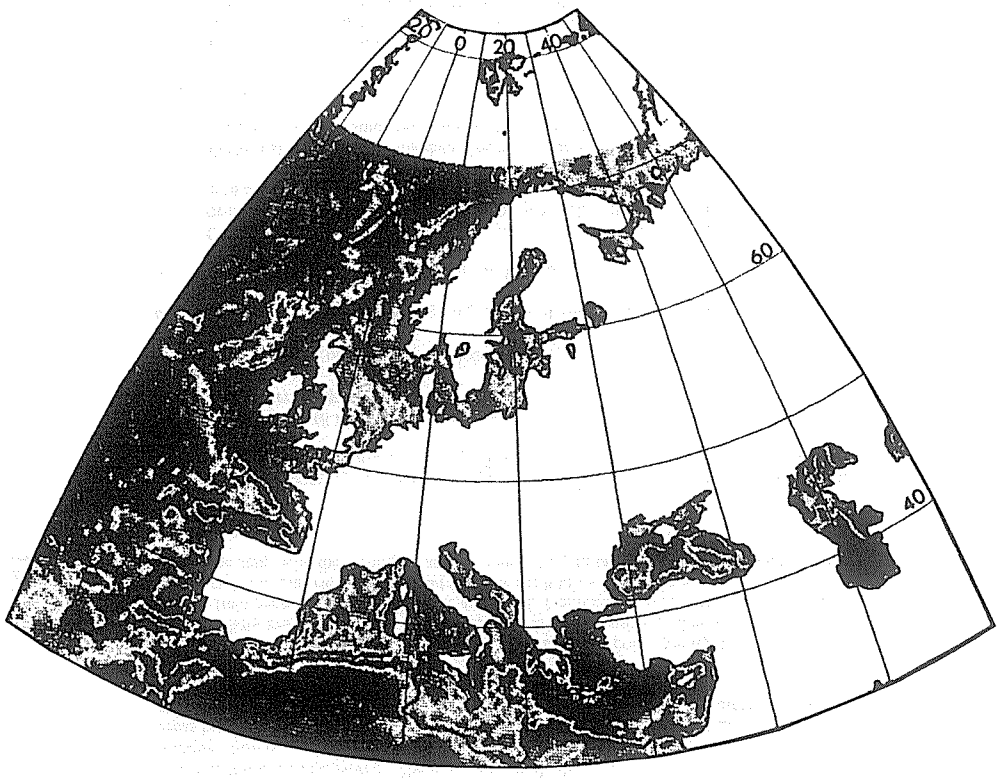
.....

.....

Please return form to: Dr J D Fairhead, Dept of Earth Sciences, Leeds University, Leeds LS2 9JT, UK. Telephone: (44) 532 422407, Fax: (44) 532 429234, Telex: 556473 UNILDS G

WEST-EAST EUROPEAN GRAVITY PROJECT

(Enhancing oil and gas exploration in Eastern Europe as far east as the Urals)



Proposal by

Dr J D Fairhead
University of Leeds Industrial Services Ltd
175 Woodhouse Lane
Leeds
LS2 3AR
UK

Telephone: (44) 532 422407
Facsimile: (44) 532 429234
Telex: 556473 UNILDS G

University of Leeds Industrial Services Ltd (ULIS)
175 Woodhouse Lane, LEEDS, West Yorkshire, LS2 9JT, England
Telephone (0532) 333444 Telex 556473 UNILDS G Fax (0532) 429234

WEST-EAST EUROPEAN GRAVITY PROJECT

(Enhancing oil and gas exploration in Eastern Europe as far east as the Urals)

Proposal by

Dr J D Fairhead
University of Leeds Industrial Services Ltd
175 Woodhouse Lane
Leeds
LS2 3AR
UK

Telephone: (44) 532 422407
Facsimile: (44) 532 429234
Telex: 556473 UNILDS G

in collaboration with

Dr M Kogan
Institute of Physics of the Earth
B Grouzinskaya 10
Moscow 123242
USSR

Telephone: (7) 095 2544136
Telex: 411196 IFZAN SU

Dr G Balmino
Bureau Gravimetrique International
CNES
18, avenue Edouard Belin
31055 Toulouse Cedex
France

Telephone: (33) 61 33 28 89
Facsimile: (33) 61 27 31 79
Telex: CNES 531081 F

COVER PICTURE Shows the proposed study area which includes the whole of Western and Eastern Europe as far east as the Urals. The oceans and seas as far north as 72°N show the free air gravity data derived from GEOSAT satellite altimeter data (after Haxby) and North Africa shows part of the Bouguer gravity map of the African Gravity Project.

WEST-EAST EUROPEAN GRAVITY PROJECT

1 PROJECT SUMMARY

WEEGP will commence in April 1991 and will follow the completion of the highly aclaimed African and South American Gravity Projects which have brought together all available gravity data from international and national oil companies, national organisations, institutes and universities. WEEGP has the same aim as these projects and will integrate all available land and marine gravity data for the area 35°S to 84°N and 25°W to 60°E (see cover picture) into a single digital database. The database will be used to generate a 8 km x 8 km grid of interpolated Bouguer, free air and topography/bathymetry values for the region. Point gravity data will be treated as confidential and not passed to Sponsors. The region of study will extend from the Mediterranean to the Arctic, and from Iceland to the Urals. Turkey and Syria will only be included if data become available.

The results of this project will give a regional perspective of sedimentary basins for the whole of the European plate for the first time, thereby permitting the evaluation of plate tectonic processes on the evolution of these basins. Western Europe, in particular the North Sea area, is a major oil producing province whereas Eastern Europe, including the Soviet Union as far east as the Ural mountains, remains a frontier exploration area with the potential of major oil reserves still to be discovered. The gravity method, although having limitations in that its interpretation is non-unique, is playing an increasing role as a basic exploration tool in frontier areas by providing an initial (as well as on-going) means of evaluating the geometry and structure of sedimentary basins. This is especially true for the transitional areas from land to marine environments.

The collaborators envisage that as a result of this project the point gravity data will become commercially available to sponsors in preference to non-sponsors so that the high resolution gravity field over descrete basins can be evaluated. Negotiations with Soviet/Russian authorities for the rights to digitise point data and generate the 8 km x 8 km grid for this project are at an advantage stage with the signing of an agreement likely to take place before the end of 1990.

2 PRODUCTS

During the three year project (1991-1994) sponsors will be provided with a phased release of the following products for the area covered by 35°S to 84°N and 25°W to 60°E (see cover picture).

a) **Digital grids** (8 km x 8 km) of interpolated Bouguer, free air gravity and bathymetry/topography.

b) **Digital listing** of all data point locations (not their height or gravity).

c) **Digital technical database** giving details of surveys used and their ownership.

d) **Simplified digital geology** map of Eastern Europe.

e) **Colour gravity maps** at 1:1 million and 1:4 million scales for the region constructed from the 8 km x 8 km grid and contoured at 5 mGals showing location of gravity stations used and national boundaries.

f) **Technical report** indicating data processing parameters and bibliography of data sources used in the study on a country by country basis.

3) SPONSORS

In late 1990 all interested oil companies will be invited to join WEEGP in April 1991 as full sponsors. The sponsorship cost will be announced in September/October 1990. The start date and cost per sponsor are still subject to negotiations with Eastern European countries and the Soviet Union. **All companies wishing to be considered as Sponsors should fill in the attached reply form so that the final project proposal can be sent in due course.**

4) ASSOCIATE MEMBERS & DATA TRADERS

Associate Membership is free of charge to national organisations who are able to release gravity data into the project. In return the Associate Member will receive, at no cost, the gravity maps, digital data and technical documentation of the gravity database for its country and adjacent undisputed marine areas as well as a large scale colour gravity map for the whole of the project area. For example, the South American Gravity Project has linked with the majority of the national oil companies in South America via Associate Membership Agreements to bring together over forty years of archived gravity surveys for digitising and reprocessing into a unified database.

Non sponsoring international oil companies and gravity contractors are encouraged to enter Trade Agreements whereby they will release their archived gravity data in return for receiving certain project products covering an expanded area containing their data. The project will provide good international exposure of available data sets and space will be made available for contractors to advertise their speculative surveys in the Technical Report.

5) CONFIDENTIALITY

All gravity data handled by the project are treated as confidential and not passed to Sponsors or any third party without the written approval of the owner. National gravity datasets will retain their commercial value since the interpolated 8 km x 8 km grid can only resolve gravity anomalies with wavelengths greater than 16 km.

6) COLLABORATORS

Two of the three collaborating groups (Leeds and BGI) have worked in close cooperation on previous projects on Africa and South America and will be combining their wide range of experience in processing land, marine and satellite-derived gravity data with that of the Institute of Physics of the Earth, Moscow.

i) University of Leeds Industrial Services Ltd (ULIS) is a wholly University owned marketing and development company, set up by the University of Leeds to utilise the expertise and facilities of the University in the industrial and commercial field. The experience ULIS has gained during the oil industry sponsored African and South American Gravity Projects (AGP and SAGP) will help with the initial arrangements and subsequent running of WEEGP. ULIS will manage all financial, contractual and legal aspects of the project.
Department of Earth Sciences (University of Leeds) The UK part of the project will be managed by Dr J Derek Fairhead who has managed the successful AGP and SAGP since 1986. Through these projects Leeds has installed state-of-the-art CAD systems including Intergraph and Sun networks linked to digitising and colour Versatec plotting facilities. These computing systems are operated by experienced staff in software development, data handling and colour plotting.
Department of Earth Sciences (University of Oxford) Prof Watts has been a collaborator in both the AGP and SAGP whilst based at Lamont-Doherty Geological Observatory (USA). Prof Watts has now moved to the University of Oxford (UK) where a new processing centre for marine gravity data has already been set up and will be involved in the marine data acquisition and reprocessing.

ii) Institute of Physics of the Earth (IPE), Moscow The USSR part of the project will be managed by Dr M G Kogan, Head of the IPE Laboratory of the Global Gravity Field. Dr Kogan previously collaborated with Lamont-Doherty Geological Observatory (USA) in managing the Pacific and South Atlantic Gravity Projects, which resulted in a series of gravity field maps being published by the Geological Society of America and the Hydrographic Office of the USSR. Within the framework of WEEGP, a new computing system will be established in Moscow to be run jointly by IPE and the Ministry of Geology of the USSR, in order to reprocess and incorporate the gravity data covering the European part of the USSR.

iii) Bureau Gravimétrique International (BGI) is one of the offices of FAGS (Federation of Astronomical and Geophysical Services). It is also the executive office of the International Gravity Commission of section III of the International Association of Geodesy. The main task of BGI is to collect, store and validate Earth gravity field data and to redistribute them on request. BGI has experience in managing large computerised databases and in validating surface gravity measurements, for which its staff has developed its own software.

The participation of BGI in the project will mostly consist of providing data from its database, in acquiring data from new sources via its extensive links in West and East Europe and in validating land gravity observations.

The BGI part of the project will be managed by Dr Georges Balmino and colleagues.

WEST-EAST EUROPEAN GRAVITY PROJECT

Reply form

Name: .....

Company: .....

Address: .....

.....

.....

.....

.....

Telephone: .....

Telex: .....

Facsimile: .....

By ticking the appropriate box shown below, please register your interest in becoming:

1) Potential Sponsor ☐ Associate Member* ☐ Trader+ ☐

** Restricted to national organisations*
+ Normally non-sponsoring oil company

2) Do you have gravity data (onshore and offshore) you can supply to project? Yes ☐ No ☐

3) Please send map showing data coverage.

4) Are data on magnetic tape? Yes ☐ No ☐

5) Are data confidential? Yes ☐ No ☐

6) Are data open file? Yes ☐ No ☐

7) Please provide other names and addresses (plus telephone, fax and telex numbers) of other sources of gravity data in your country.

.....

.....

.....

Please return form to: Dr J D Fairhead, Dept of Earth Sciences, Leeds University, Leeds LS2 9JT, UK. Telephone: (44) 532 422407, Fax: (44) 532 429234, Telex: 556473 UNILDS G

COMPARISON OF GRAVIMETRIC, ALTIMETRIC AND SATELLITE TRACKING DATA ON THE EARTH'S GLOBAL GRAVITY FIELD

P.P.Medvedev
Soviet Geophysical Committee, USSR, Moscow

V.V.Bojkov, V.F.Galazin, G.V.Demjanov,
E.L.Makedonski, O.M.Ostach, L.P.Pellinen, V.A.Taranov
Geodetic Survey of the USSR, USSR, Moscow

Abstract

Harmonic geopotential coefficients in the GEM-T2 gravity model (within the harmonics included in the GEM-L2 model) and mean Faye anomalies for 1654 equal-area 5°-blocks are jointly adjusted. 823 of those anomalies are determined from gravimetric data collected by Geodetic Survey of the USSR and 831 are obtained from combination of altimetric /2/ and the above gravimetric data. Information about 5°-anomaly corrections for different regions and for the whole earth surface is presented. The RMS 5°-anomaly correction equals to ±3.9 mGal. The highest accuracy has been achieved for the USSR territory (the scheme of 5°-anomalies on this territory is presented) and for ocean area where altimetric information was used. The maximal systematic errors were detected within Antarctica and Africa and the maximal random errors were found for Antarctica and Asia (the USSR excluding). The list of the normalized coefficients of the spherical harmonic expansion of adjusted Faye anomalies up to 36th degree is given.

Introduction

Let the part of the general Earth's gravity field represented by spherical harmonics with degree up to 20-36 be the global gravity field. They are harmonics that are obtained by satellite tracking and therefore they can be deduced from the analyses of their orbit perturbations. Mean free air gravity anomalies (Faye anomalies on land) for 1654 equal-area 300 x 300 miles (5° x 5° at the Equator) blocks /3,9/ are in good correspondence with the above described harmonics. Such anomalies may be obtained from gravimetric data as well as from satellite altimetric data on the ocean surface.

Further results of the comparative analysis of various data on global gravity field of the Earth by the Geodetic Survey of the USSR is presented. Mean 5°-anomalies based on the recent gravity surveys with accuracy estimations of these anomalies for the USSR territory are presented below. The preliminary combined adjustment of all data used has been accomplished. As the result a gravitational model presented by the Faye anomaly spherical harmonics expansion up to 36th degree is given.

Initial data

Satellite tracking data. We used the gravitational model of Goddard Space Flight Center GEM-T2 /5/ that includes all harmonic geopotential coefficients up to 36th degree and some of their values up to 50th degree. A significant increase in the number of harmonics as compared with the previous models obtained from analysis of the satellite tracking data can be explained mainly by the use of the RMS apriori values of harmonic geopotential coefficients as the additional information applied within the least squares collocation method. As the result, high degree coefficients in the GEM-T2 model are essentially diminished, and it is difficult to use them when comparing independent gravimetric and altimetric data. Therefore, we used only such harmonic coefficients that were previously included in the GEM-L2 model (all coefficients up to 20th degree and some coefficients up to 30th degree). They are weakly slightly distorted by undesirable effects of the least squares collocation method.

Gravimetric data. Mean Faye (free-air) 5°-block anomalies were computed using gravimetric data collected by Geodetic Survey of the USSR in the form of mean 1° x 1° values. Obtained values (Antarctida and Greenland excluding) are reduced in the case of the incomplete gravity coverage of 5°-blocks to mean heights (depths) of these blocks using obtained statistical dependency of mean 1°-anomalies and heights (depths) within a 5°-block. If the gravity coverage of a 5°-block was smaller than 30% we used the least squares collocation method to obtain the Δg-values. This method was also used to predict the Δg-values for 5°-block containing no 1° x 1° data with

the aid of 5°-anomalies for the neighbour blocks. The apriori RMS errors M_g were computed for all 5°-blocks based on previously obtained apriori estimations of the 1°-anomaly RMS errors. Additionally we took in account the errors of representation for the block where the least squares collocation method was used.

The most precise Δg - values were obtained for 5°-blocks within the USSR territory and partly for neighboured seas (Fig. 1). We used the available mean 5' x 7.5' Faye anomalies computed on the land by the method of indirect interpolation as the sum of modified Bouguer anomaly (simple Bouguer anomaly plus terrain correction) and Bouguer reduction. The analysis of mean 5' x 7.5' and 1° x 1° Faye anomalies errors was carried out with consideration of systematic effects due to the errors in the control gravity nets and topographic maps used. From this analysis the M_g-values were computed. The $\Delta\bar{g}$ - values corresponding to the Geodetic reference system 1980 and the M_g-values for the USSR territory are presented in Figure 1.

Altimetric data. Free-air anomalies obtained by Balmino /2/ for the 15' x 15' grid with the aid of altimetric data mainly from Seasat ones are used. We obtained the $\Delta\bar{g}$-values for 831 5°-blocks the centers of which are extended more than for 500 km off continents or great islands.

We compared the $\Delta\bar{g}$-values obtained from Balmino data as well as those published by Rapp /8/ who used altimetric data from the GEOS 3. Additionally we used the $\Delta\bar{g}$-values obtained from gravimetrical data for the well gravimetrically studied areas in the Atlantic north of the Equator and in the Pacific north of the +25°-parallel. The mean M_g-values were estimated for each of three sets of data considering their sets as independent:

Balmino $\pm$ 1.7 mGal,
Rapp $\pm$ 2.2 mGal,
gravimetry $\pm$ 3.0 mGal.

The RMS differences in Balmino and Rapp $\Delta\bar{g}$-estimates for other ocean areas are equal to $\pm$2.6 mGal that verify qualitatively the above estimates. The value $M_g = \pm 1.7$ mGal was assumed for the most of $\Delta\bar{g}$-values after Balmino /2/. However we increased the M_g-values up to 5 mGal for sea 5°-blocks, situated within the very anomalous areas with ridges, island arcs and trenches.

Taking into account the comparatively high accuracy of gravimetric data for some ocean regions we assumed finally the mean weight $\Delta\bar{g}$-values from gravimetric and altimetric data. Considering some possible systematic errors of the assumed $\Delta\bar{g}$-values we take the minimal M_g - estimation as being 2 mGal.

Combined adjustment of various data.

Two variants of Preliminary Combined adjustment of the g-values and the harmonic geopotential coefficients for the GEM-T2 model were accomplished fitting two sets of normalized coefficients of gravity anomaly expension into spherical harmonics ($\bar{a}_{nk}$, $\bar{b}_{nk}$) where n is the degree and k is the order of coefficients: one obtained from the $\Delta\bar{g}$-anomalies and the other derived from the above harmonic geopotential coefficients. The RMS errors of the $\bar{a}_{nk}$, $\bar{b}_{nk}$ were assumed for the first variant according to data in /5/ and for the second variant according to the GEM-T1 model /4/.

As the result of the correlate adjustment the corrections of the satellite values ($\bar{a}_{nk}$, $\bar{b}_{nk}$) and the mean anomalies $\bar{g}$ were obtained. The smaller determined RMS errors of values are obtained for the second variant. Therefore, below we present the results for this variant. Table 1 shows maximal and minimal values of corrections V to the $\Delta\bar{g}$ - anomalies, as well as mean values V and RMS values M_V of these corrections for various regions of the Earth's surface, in particular for 831 blocks in the open ocean where altimetric data were used. As one can see, at the Earth's surface as a whole mean correction $\bar{V}$ equals to -0.12 mGal. It is a very satisfactory result. However a significant discordance of the $\bar{V}$ - values about 1 mGal was discovered in the estimations made for 831 blocks and that for the rest relevant blocks. Since such a discordance has not been discovered in the previous comparison of the altimetric and gravimetric data for the open ocean, one can ascribe the mentioned error to the systematic

errors of the assumed $\Delta\bar{g}$ -values in Antarctica and Africa.

The apriori RMS M_g - errors for various regions and for the entire Earth are also presented in Table 1. These errors as a rule, are a bit higher than M_V. However M_V - values for Europe (the USSR excluding), North America and, in particular, for the USSR and ocean areas, where altimetric data were used, the obtained M_V -values are much smaller than the M_g values. This fact as well as the occurrence of small values in the above regions indicates the high precision of the assumed gravimetric and altimetric data.

However, M_V -value is much greater than M_g in Asia (the USSR excluding). It is interesting that in this region, as well as in the Western America V -values in the zones of rough topography are (predominantly) positive probably due to ignoring the terrain correction though theoretically, the necessity of this correction has been proved /1,6/. Ten of the largest V corrections with the absolute value above 20 mGal (4 values in Antarctica, 4 in Central Asia, one in the Andes as well as in Greenland) can be sharply distinguished among other corrections.

The corrected $\Delta\bar{g}$ - values for the USSR territory are enclosed in brackets in Figure 1.

The coefficients ($\bar{a}_{nk}$, $\bar{b}_{nk}$) obtained from the adjusted $\Delta\bar{g}$ - values are presented in Table 2 in mGal up to 36th degree. These coefficients may be applied in the Earth's gravity field studies in spite of the distortion of high degree coefficients due to the use of gravity anomalies averaged by greater blocks /7/. Low degree coefficients are practically fitted to the GEM-T2 model. As for the high degree coefficients their RMS-errors are smaller than 0.14 mGal.

This corresponds to the RMS errors of normalized harmonic geopotential coefficients about $14 \cdot 10^{-8}/(n-1)$. These errors are smaller than those of the greater part of the coefficients for the GEM-T2 model if $n > 20$.

Investigations for establishing weights of gravimetric as well as altimetric and tracking satellite information are proposed for the future.

Литература

1. Пеллинен Л.П. Влияние топографических масс на вывод характеристик гравитационного поля Земли. - Труды ЦНИИГАиК, вып.145, М., 1962, 23-42.
2. Balmino G. File of worldwide oceanic gravity anomalies (15 x 15°) Bureau Gravimetrique International. Toulouse, 1985.
3. Kaula W.M. Tests and combination of satellite determinations of gravity field with gravimetry. JGR. 1966. 71 N 22, 5303-5314.
4. Marsh J.G. et al. A new gravitational model for the Earth from satellite tracking data: GEM-T1. J.Geophys.Res., 93, 66, pp. 6169-6215, 1988.
5. Marsh J.G. et al. The GEM-T2 gravitational model. NASA Technical Memorandum 100746, Goddard Space Flight Center, 1989.
6. Moritz H. On the use of the terrain correction in solving Molodensky's problem. Rep. 108. Dep. Geod. Sci., Ohio State Univ., 1968.
7. Rapp R.H. Comparison of potential coefficient determinations with 5° and 1°-anomalies. Rep. 300. Dep. Geod. Sci., Ohio State Univ., 1980.
8. Rapp R.H. Global anomaly and undulation recovery using GEOS-3 altimeter data. Rep. 285. Dep. Geod. Sci., Ohio State Univ., 1979.
9. Rapp R.H. The formation and analysis of a 5° equal area block terrestrial gravity field. Rep. 178. Dep. Geod. Sci., Ohio State Univ., 1972.

Table 1

Statistics of 5°-gravity anomaly corrections (in mGal)

Region	Number of 5°-blocks	Correction V Max	Correction V Min	V	M_V	M_g
USSR	67	+0.4	-1.2	-0.1	±0.3	±0.5
Europe (USSR excluding)	26	+3.1	-3.4	-1.0	-1.0	2.7
Asia (USSR excluding)	105	+49.2	-27.5	+0.6	8.1	5.6
North America	73	++8.9	-4.6	+0.4	2.1	3.4
South America	64	+25.7	-12.1	+1.4	5.9	6.5
Australia	26	+6.1	-9.1	-0.2	2.6	2.8
Africa	95	+15.6	-14.1	-2.6	5.0	5.3
Arctica	59	+25.0	-11.2	-1.0	5.0	4.2
Antarctica	111	+22.0	-49.2	-5.3	8.9	9.5
Transition land-sea region	197	+15.8	-7.4	+1.3	3.5	4.0
Oceans (combination of altimetric and gravimetric data)	831	+7.0	-4.4	+0.35	1.0	2.2
Whole earth surface	1654	+49.2	-49.2	-0.12	3.9	4.1

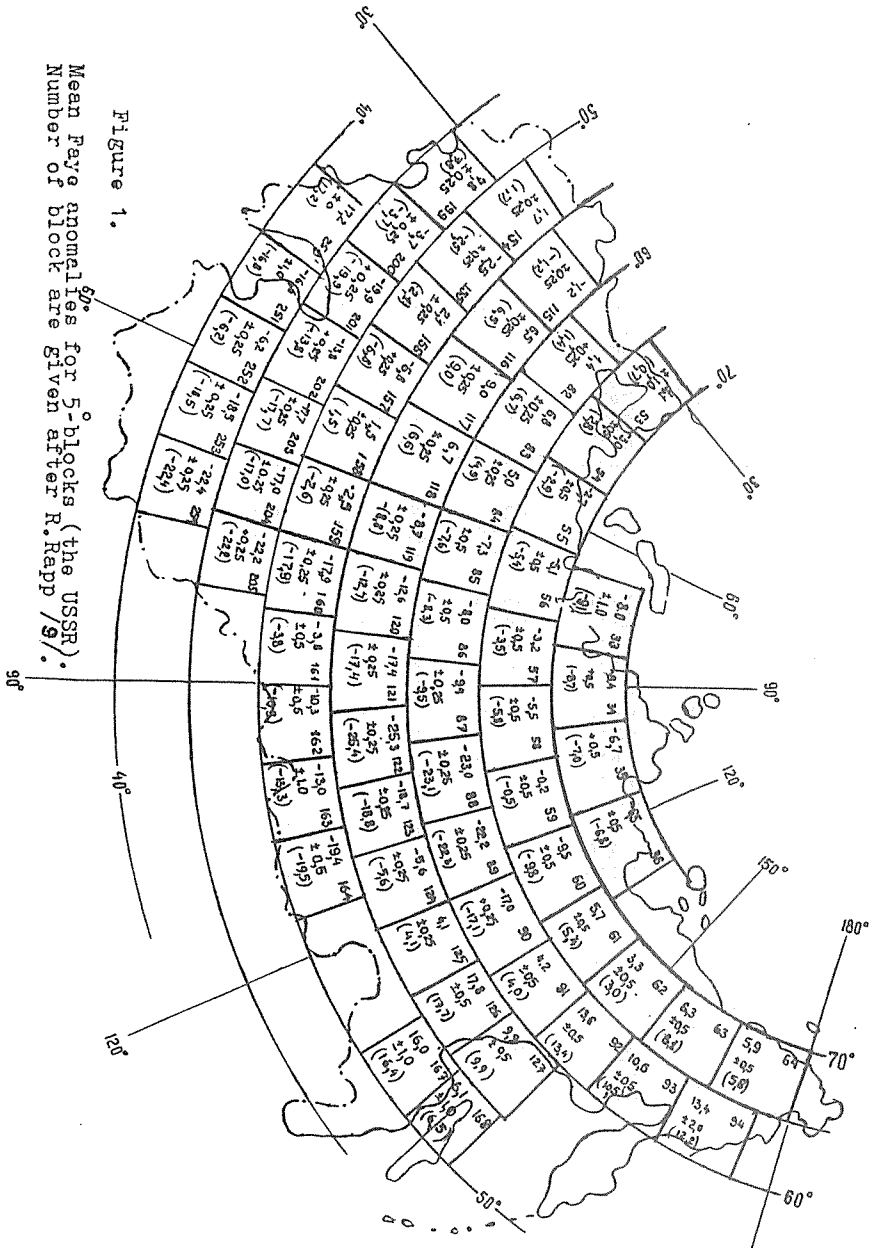


Figure 1.

Mean Faye anomalies for 5°-blocks (the USSR). Number of block are given after R.Rapp /9/.

Normalized coefficients of the Faye-anomalies expansion into spherical harmonics (mGal) Table 2

n	$\bar{a}_{n0}$	n	$\bar{a}_{no}$	n	$\bar{a}_{no}$	n	$\bar{a}_{no}$
1	0.00	2	0.00	3	1.88	4	-0.75
5	0.27	6	-0.74	7	0.53	8	0.33
9	0.22	10	0.44	11	-0.52	12	0.41
13	0.49	14	-0.30	15	0.03	16	-0.07
17	0.26	18	0.01	19	-0.06	20	0.39
21	0.15	22	-0.19	23	-0.36	24	0.10
25	0.13	26	0.04	27	0.23	28	-0.17
29	-0.15	30	-0.20	31	0.12	32	-0.19
33	0.10	34	-0.26	35	0.42	36	-0.17

n	k	$\bar{a}_{nk}$	$\bar{b}_{nk}$	n	k	$\bar{a}_{nk}$	$\bar{b}_{nk}$	n	k	$\bar{a}_{nk}$	$\bar{b}_{nk}$
1	1	0.00	0.00	2	1	0.00	0.00	3	1	3.98	0.49
4	1	-1.58	-1.40	5	1	-0.24	-0.36	6	1	-0.38	0.13
7	1	1.63	0.58	8	1	0.16	0.40	9	1	1.08	0.13
10	1	0.70	-1.21	11	1	0.17	-0.36	12	1	-0.48	-0.59
13	1	-0.57	0.46	14	1	-0.14	0.29	15	1	0.24	0.12
16	1	0.36	0.41	17	1	-0.51	-0.24	18	1	0.04	-0.51
19	1	-0.23	0.22	20	1	0.25	-0.10	21	1	-0.17	0.78
22	1	0.33	0.00	23	1	0.23	0.39	24	1	0.08	-0.15
25	1	0.07	-0.11	26	1	-0.11	-0.09	27	1	0.15	-0.10
28	1	-0.07	0.04	29	1	0.12	-0.16	30	1	-0.21	0.09
31	1	0.15	-0.40	32	1	-0.01	0.04	33	1	0.08	-0.05
34	1	0.01	-0.08	35	1	-0.24	0.13	36	1	0.19	0.20
2	2	2.39	-1.37	3	2	1.77	-1.21	4	2	1.02	1.95
5	2	2.57	-1.27	6	2	0.25	-1.84	7	2	1.86	0.55
8	2	0.43	0.42	9	2	0.24	-0.27	10	2	-0.67	-0.45
11	2	0.22	-0.99	12	2	0.20	0.27	13	2	0.60	-0.64
14	2	-0.49	-0.04	15	2	-0.29	-0.43	16	2	-0.26	0.40
17	2	-0.16	0.26	18	2	-0.09	0.08	19	2	0.44	-0.01
20	2	0.33	0.34	21	2	0.14	0.25	22	2	-0.33	-0.12
23	2	-0.21	-0.24	24	2	0.10	0.25	25	2	0.22	0.13
26	2	-0.03	0.03	27	2	0.07	-0.06	28	2	-0.09	-0.15
29	2	0.07	0.01	30	2	-0.07	-0.10	31	2	0.06	0.05
32	2	0.18	-0.06	33	2	-0.15	0.06	34	2	-0.02	0.06
35	2	-0.28	0.35	36	2	0.00	-0.01				
3	3	1.42	2.78	4	3	2.91	-0.60	5	3	-1.78	-0.85
6	3	0.28	0.04	7	3	1.47	-1.23	8	3	-0.09	-0.58
9	3	-1.17	-0.64	10	3	-0.03	-1.36	11	3	-0.31	-1.34
12	3	0.52	0.23	13	3	-0.22	1.02	14	3	0.50	0.15
15	3	0.54	0.40	16	3	-0.39	-0.46	17	3	0.20	0.21
18	3	0.12	-0.07	19	3	-0.07	0.18	20	3	0.15	0.37
21	3	0.20	0.41	22	3	0.22	0.29	23	3	-0.32	-0.13
24	3	0.05	-0.20	25	3	-0.15	-0.14	26	3	0.23	0.21
27	3	-0.06	0.10	28	3	0.25	0.12	29	3	0.15	-0.23
30	3	-0.07	-0.16	31	3	-0.03	-0.29	32	3	-0.04	0.04
33	3	0.03	0.22	34	3	0.11	-0.17	35	3	0.05	0.08
36	3	-0.11	-0.51								
4	4	-0.55	0.91	5	4	-1.16	0.20	6	4	-0.44	-2.31
7	4	-1.61	0.72	8	4	-1.65	0.44	9	4	-0.10	0.16
10	4	-0.85	0.63	11	4	-0.25	-0.70	12	4	-0.72	-0.08
13	4	-0.08	-0.08	14	4	0.07	-0.12	15	4	-0.43	-0.03
16	4	0.59	0.61	17	4	-0.03	0.27	18	4	0.87	-0.01
19	4	0.34	-0.10	20	4	0.09	-0.27	21	4	-0.09	0.28
22	4	0.08	0.21	23	4	-0.12	0.23	24	4	-0.06	0.17
25	4	0.37	0.04	26	4	0.41	-0.23	27	4	0.28	0.10
28	4	-0.06	0.35	29	4	-0.31	-0.06	30	4	0.04	0.10
31	4	0.16	-0.43	32	4	-0.09	0.00	33	4	0.00	0.16
34	4	-0.01	0.16	35	4	-0.14	-0.02	36	4	0.04	-0.04
5	5	0.67	-2.63	6	5	-1.31	-2.64	7	5	0.01	0.11
8	5	-0.14	0.59	9	5	-0.17	-0.43	10	5	-0.44	-0.45
11	5	0.38	0.51	12	5	0.41	0.18	13	5	0.68	0.64
14	5	0.33	-0.27	15	5	0.03	0.15	16	5	-0.06	0.02
17	5	-0.06	-0.08	18	5	-0.05	0.39	19	5	0.04	0.22
20	5	-0.10	0.06	21	5	0.11	-0.02	22	5	-0.19	0.17
23	5	0.07	0.00	24	5	-0.03	-0.16	25	5	-0.07	-0.11
26	5	0.11	-0.12	27	5	0.48	0.11	28	5	0.30	-0.01
29	5	-0.22	0.30	30	5	0.02	-0.20	31	5	0.17	0.02
32	5	0.39	-0.01	33	5	0.07	0.11	34	5	0.07	0.03
35	5	-0.26	-0.15	36	5	-0.29	0.07				
6	6	0.05	-1.16	7	6	-2.11	0.90	8	6	-0.44	2.13
9	6	0.52	1.75	10	6	-0.29	-0.69	11	6	0.02	0.25
12	6	0.02	0.43	13	6	-0.34	0.05	14	6	-0.27	0.11
15	6	0.32	-0.62	16	6	-0.03	-0.43	17	6	-0.17	-0.48
18	6	0.23	-0.07	19	6	0.06	0.36	20	6	0.20	0.08
21	6	-0.08	0.00	22	6	0.06	-0.11	23	6	-0.26	0.21
24	6	-0.14	-0.16	25	6	0.33	0.03	26	6	0.40	0.12
27	6	0.41	0.06	28	6	0.12	0.09	29	6	0.11	0.00
30	6	-0.09	0.19	31	6	-0.08	-0.27	32	6	-0.13	-0.37
33	6	-0.02	-0.11	34	6	0.36	0.09	35	6	0.17	-0.19
36	6	0.15	-0.03								
7	7	-0.01	0.14	8	7	0.47	0.52	9	7	-0.96	-0.73
10	7	0.08	0.01	11	7	0.02	-0.79	12	7	-0.19	0.44
13	7	-0.02	0.01	14	7	0.32	0.08	15	7	0.74	0.06
16	7	-0.08	-0.16	17	7	0.51	-0.14	18	7	0.06	0.03

19	7	-0.13	-0.21	20	7	-0.24	0.06	21	7	-0.10	0.25
22	7	0.13	0.13	23	7	-0.17	0.00	24	7	0.16	-0.12
25	7	0.11	-0.14	26	7	0.27	-0.21	27	7	-0.39	0.22
28	7	0.28	0.28	29	7	-0.38	0.09	30	7	0.21	-0.30
31	7	-0.14	0.04	32	7	0.14	-0.24	33	7	-0.26	0.01
34	7	0.18	-0.14	35	7	-0.12	0.23	36	7	0.00	0.06
8	8	-0.81	0.81	9	8	1.48	-0.05	10	8	0.38	-0.82
11	8	-0.06	0.21	12	8	-0.24	0.17	13	8	-0.13	-0.10
14	8	-0.39	-0.23	15	8	-0.38	0.26	16	8	-0.36	0.03
17	8	0.38	0.10	18	8	0.49	-0.02	19	8	0.41	-0.13
20	8	0.05	0.04	21	8	-0.23	0.02	22	8	-0.43	0.23
23	8	-0.03	0.07	24	8	0.17	-0.16	25	8	0.37	-0.06
26	8	0.08	0.05	27	8	0.02	-0.18	28	8	-0.02	0.09
29	8	-0.21	0.05	30	8	-0.21	0.14	31	8	0.10	-0.07
32	8	0.35	0.10	33	8	-0.03	0.12	34	8	0.07	0.28
35	8	0.12	0.28	36	8	0.17	0.06				
9	9	-0.38	0.76	10	9	1.07	-0.35	11	9	-0.39	0.43
12	9	0.41	0.21	13	9	0.23	0.48	14	9	0.35	0.30
15	9	0.13	0.57	16	9	-0.26	-0.46	17	9	0.02	-0.33
18	9	-0.31	0.47	19	9	0.11	-0.02	20	9	0.36	0.05
21	9	0.32	0.18	22	9	0.27	0.08	23	9	0.04	-0.14
24	9	-0.27	-0.11	25	9	-0.51	0.30	26	9	0.00	0.00
27	9	0.21	0.24	28	9	-0.01	-0.09	29	9	-0.06	0.19
30	9	-0.14	-0.10	31	9	0.18	0.26	32	9	0.11	-0.25
33	9	0.23	-0.02	34	9	0.06	-0.14	35	9	0.05	0.04
36	9	-0.16	-0.24								
10	10	0.84	-0.15	11	10	-0.49	-0.24	12	10	-0.10	0.36
13	10	0.45	-0.39	14	10	0.49	-0.03	15	10	0.10	0.12
16	10	-0.20	0.08	17	10	-0.06	0.25	18	10	0.10	-0.02
19	10	-0.47	-0.19	20	10	-0.50	-0.18	21	10	-0.17	0.05
22	10	0.16	0.23	23	10	0.13	0.05	24	10	0.33	0.25
25	10	-0.05	0.10	26	10	-0.27	-0.24	27	10	-0.12	0.13
28	10	0.11	0.24	29	10	0.34	0.11	30	10	-0.03	-0.39
31	10	0.05	-0.21	32	10	0.20	-0.09	33	10	-0.06	-0.13
34	10	-0.14	0.11	35	10	0.01	0.25	36	10	0.01	0.01
11	11	0.48	-0.56	12	11	0.10	-0.05	13	11	-0.48	0.00
14	11	0.23	-0.53	15	11	0.00	0.25	16	11	0.22	-0.07
17	11	-0.24	0.14	18	11	-0.14	0.04	19	11	0.22	0.22
20	11	0.30	-0.25	21	11	0.20	-0.54	22	11	-0.01	-0.33
23	11	0.32	0.41	24	11	0.24	0.57	25	11	0.11	0.12
26	11	0.01	0.03	27	11	0.15	-0.35	28	11	-0.15	-0.11
29	11	-0.12	0.07	30	11	-0.22	0.17	31	11	0.13	0.26
32	11	0.04	0.15	33	11	0.03	-0.10	34	11	-0.16	0.18
35	11	-0.21	-0.03	36	11	0.09	0.07				

12	12	-0.05	-0.10	13	12	-0.36	0.99	14	12	0.09	-0.41
15	12	-0.39	0.15	16	12	0.28	0.09	17	12	0.34	0.21
18	12	-0.45	-0.29	19	12	-0.01	0.00	20	12	-0.13	0.19
21	12	-0.04	0.21	22	12	0.12	-0.10	23	12	0.25	-0.33
24	12	0.17	-0.27	25	12	-0.25	0.16	26	12	-0.24	-0.06
27	12	-0.22	-0.02	28	12	-0.03	0.21	29	12	-0.02	-0.08
30	12	0.39	-0.34	31	12	-0.08	0.06	32	12	-0.23	0.30
33	12	0.15	0.25	34	12	0.07	0.10	35	12	0.04	-0.18
36	12	-0.15	-0.36								
13	13	-0.73	0.80	14	13	0.40	0.58	15	13	-0.40	-0.06
16	13	0.19	0.02	17	13	0.27	0.32	18	13	-0.12	-0.57
19	13	-0.14	-0.48	20	13	0.50	0.10	21	13	-0.32	0.23
22	13	-0.34	0.39	23	13	-0.19	-0.05	24	13	-0.06	0.09
25	13	0.24	-0.28	26	13	-0.04	0.09	27	13	-0.06	-0.01
28	13	0.11	0.03	29	13	-0.07	-0.17	30	13	0.28	0.14
31	13	0.21	0.01	32	13	0.25	0.02	33	13	0.02	0.01
34	13	-0.17	0.20	35	13	-0.15	0.24	36	13	-0.04	0.06
14	14	-0.64	-0.05	15	14	0.10	-0.35	16	14	-0.30	-0.56
17	14	-0.21	0.19	18	14	-0.14	-0.20	19	14	-0.08	-0.24
20	14	0.25	-0.26	21	14	0.39	0.17	22	14	0.18	0.16
23	14	0.09	-0.11	24	14	-0.36	-0.09	25	14	-0.36	0.16
26	14	0.07	0.08	27	14	0.21	0.25	28	14	-0.21	-0.18
29	14	-0.18	-0.16	30	14	0.11	0.05	31	14	-0.10	-0.10
32	14	-0.05	0.05	33	14	0.24	0.13	34	14	0.03	0.13
35	14	0.00	-0.06	36	14	-0.16	0.07				
15	15	-0.27	-0.12	16	15	-0.19	-0.46	17	15	0.08	0.08
18	15	-0.65	-0.17	19	15	-0.28	-0.21	20	15	-0.36	0.00
21	15	0.27	0.22	22	15	0.46	0.10	23	15	0.33	0.09
24	15	0.07	-0.19	25	15	0.00	-0.16	26	15	0.00	-0.01
27	15	-0.16	-0.09	28	15	-0.26	0.05	29	15	-0.26	-0.05
30	15	0.01	-0.03	31	15	0.15	-0.11	32	15	0.25	-0.07
33	15	-0.07	-0.17	34	15	-0.05	0.07	35	15	-0.38	0.07
36	15	0.09	0.13								
16	16	-0.46	0.03	17	16	-0.48	0.04	18	16	0.15	0.13
19	16	-0.32	-0.09	20	16	-0.27	-0.01	21	16	0.06	-0.14
22	16	0.00	-0.04	23	16	0.11	0.28	24	16	0.11	-0.03
25	16	-0.04	-0.18	26	16	0.14	0.02	27	16	0.16	-0.06
28	16	0.00	-0.31	29	16	-0.04	-0.42	30	16	-0.35	-0.01
31	16	-0.14	0.21	32	16	0.03	0.10	33	16	0.17	0.22
34	16	-0.05	-0.14	35	16	-0.07	-0.21	36	16	0.11	-0.16
17	17	-0.48	-0.23	18	17	0.08	0.02	19	17	0.55	-0.28
20	17	0.08	-0.19	21	17	-0.08	-0.08	22	17	0.13	-0.33
23	17	-0.05	-0.16	24	17	-0.31	-0.01	25	17	-0.32	-0.16
26	17	-0.12	0.04	27	17	-0.07	0.16	28	17	0.14	0.10

29	17	0.16	-0.12	30	17	-0.01	-0.26	31	17	0.01	0.07
32	17	-0.05	0.22	33	17	-0.21	0.30	34	17	-0.06	0.12
35	17	-0.16	-0.27	36	17	0.18	-0.14				
18	18	0.10	-0.18	19	18	0.60	-0.08	20	18	0.08	0.08
21	18	0.52	-0.13	22	18	0.32	-0.18	23	18	0.12	-0.15
24	18	0.10	-0.07	25	18	0.02	-0.15	26	18	-0.29	0.02
27	18	-0.06	-0.01	28	18	0.08	-0.29	29	18	-0.10	-0.04
30	18	-0.18	-0.01	31	18	-0.04	0.03	32	18	0.23	0.01
33	18	-0.18	0.07	34	18	-0.28	-0.12	35	18	-0.18	-0.15
36	18	0.06	0.18								
19	19	-0.03	0.22	20	19	-0.05	0.14	21	19	-0.42	0.19
22	19	0.18	-0.07	23	19	0.02	0.13	24	19	-0.20	-0.01
25	19	0.12	0.19	26	19	0.00	0.24	27	19	0.05	0.05
28	19	0.27	0.22	29	19	-0.04	0.18	30	19	-0.06	0.17
31	19	-0.04	-0.04	32	19	-0.05	-0.04	33	19	0.06	-0.06
34	19	-0.07	0.05	35	19	-0.12	-0.16	36	19	-0.06	-0.14
20	20	0.15	-0.27	21	20	-0.26	0.16	22	20	-0.15	0.42
23	20	0.24	0.05	24	20	-0.11	0.11	25	20	0.00	-0.11
26	20	-0.01	-0.27	27	20	-0.17	-0.05	28	20	0.08	0.04
29	20	-0.09	0.16	30	20	-0.13	0.17	31	20	-0.21	0.24
32	20	0.05	0.05	33	20	0.07	-0.13	34	20	0.09	-0.18
35	20	0.10	-0.09	36	20	-0.13	0.02				
21	21	0.16	-0.09	22	21	-0.49	0.31	23	21	0.26	0.31
24	21	-0.03	0.44	25	21	0.19	0.17	26	21	0.07	0.05
27	21	0.07	-0.17	28	21	0.20	-0.09	29	21	0.04	-0.08
30	21	-0.14	0.02	31	21	-0.10	0.07	32	21	-0.09	0.00
33	21	-0.09	-0.08	34	21	-0.06	-0.01	35	21	0.19	-0.10
36	21	0.20	-0.16								
22	22	-0.30	0.06	23	22	-0.43	0.08	24	22	0.03	-0.17
25	22	-0.15	0.23	26	22	-0.14	0.17	27	22	0.03	-0.07
28	22	-0.04	0.05	29	22	0.24	-0.02	30	22	-0.04	-0.11
31	22	-0.02	0.03	32	22	-0.12	-0.03	33	22	-0.25	-0.25
34	22	-0.07	-0.10	35	22	-0.06	-0.11	36	22	0.02	0.05
23	23	-0.02	-0.36	24	23	-0.10	-0.02	25	23	0.24	-0.14
26	23	-0.01	0.30	27	23	0.01	-0.13	28	23	0.14	-0.04
29	23	0.04	0.03	30	23	0.07	-0.07	31	23	0.07	0.20
32	23	0.14	0.01	33	23	0.03	-0.10	34	23	-0.01	-0.30
35	23	-0.01	-0.17	36	23	0.17	-0.17				
24	24	0.16	0.06	25	24	0.15	0.00	26	24	0.02	0.28
27	24	-0.07	-0.01	28	24	0.02	-0.25	29	24	-0.04	0.07
30	24	0.07	0.01	31	24	-0.12	0.04	32	24	-0.27	0.18
33	24	0.08	-0.05	34	24	0.09	0.02	35	24	0.20	0.12
36	24	0.18	0.00								
25	25	0.02	0.13	26	25	0.13	-0.01	27	25	0.20	0.15
28	25	-0.16	-0.47	29	25	0.12	0.05	30	25	-0.04	-0.12
31	25	-0.22	-0.10	32	25	-0.24	0.08	33	25	0.01	-0.25
34	25	-0.07	-0.21	35	25	0.07	0.16	36	25	0.12	0.28
26	26	0.14	-0.02	27	26	-0.10	-0.09	28	26	0.12	0.19
29	26	0.11	0.02	30	26	-0.02	0.25	31	26	-0.11	0.07
32	26	0.00	-0.12	33	26	0.14	-0.05	34	26	0.12	-0.32
35	26	-0.07	0.03	36	26	0.03	0.16				
27	27	0.31	0.12	28	27	-0.17	-0.07	29	27	0.04	0.02
30	27	-0.11	0.35	31	27	0.01	0.18	32	27	-0.22	-0.07
33	27	-0.14	0.05	34	27	0.16	-0.11	35	27	0.14	-0.18
36	27	0.02	0.19								
28	28	0.12	-0.04	29	28	0.06	0.10	30	28	-0.14	-0.07
31	28	0.34	0.12	32	28	-0.10	-0.09	33	28	0.00	-0.19
34	28	-0.01	-0.31	35	28	0.10	-0.26	36	28	-0.08	0.00
29	29	0.31	-0.21	30	29	-0.09	0.13	31	29	-0.26	0.05
32	29	0.09	-0.01	33	29	-0.29	0.05	34	29	0.07	-0.11
35	29	0.22	0.03	36	29	0.00	-0.04				
30	30	-0.05	0.32	31	30	-0.01	-0.06	32	30	-0.11	-0.13
33	30	-0.08	-0.30	34	30	-0.46	0.03	35	30	0.05	-0.01
36	30	-0.13	-0.05								
31	31	-0.21	0.03	32	31	-0.09	-0.11	33	31	0.18	0.08
34	31	-0.16	0.04	35	31	0.03	0.01	36	31	-0.24	0.10
32	32	0.34	0.04	33	32	0.16	-0.15	34	32	0.10	-0.10
35	32	-0.03	-0.08	36	32	0.34	-0.14				
33	33	0.04	0.19	34	33	0.11	0.04	35	33	0.26	-0.17
36	33	0.17	-0.05								
34	34	-0.24	-0.11	35	34	-0.04	-0.05	36	34	-0.06	0.03
35	35	-0.12	-0.13	36	35	0.08	-0.19				
36	36	0.10	0.02								

PRECISE GRAVIMETRIC OBSERVATIONS AT BELOMORSK DURING THE FULL SOLAR ECLIPSE ON JULY 22, 1990

A.V.Kopayev, V.K.Milukov, V.N.Rudenko, V.D.Yushkin

Sternberg State Astronomical Institute
of Moscow State University
13 Universitetsky prosp.
V-234 Moscow 119899 USSR

Abstract

Precise gravimetric observations carried out with the help of thermostatized Sodin-GT-gravimeter during full solar eclipse on July 22, 1990 at Belomorsk, Karelia didn't demonstrate the existence of anomalouos gravitational effect on the accuracy level 5 mcGal with 95 % confidence.

Our group took participation in international gravimetric-astrophysical expedition for observation of the full solar eclipse in Belomorsk (USSR) near the seacost of the White Sea ($\varphi = 64^{o}$, $\lambda = 47^{o}$) which was choosen due to its location in full solar eclipse area and appropriate living and observational conditions.

The group was equipped by one thermostatized Sodin-gravimeter for recording gravity variations and fully automatized and computerized torsion-balance-gradiometer for permanent recording horizontal gravity gradients in order to distinguish between the local geodynamical effects and larger scale phenomena.

The gravimetric part of expedition included also the italian team (C. Gantar, G.Santorato) equipped by computerized LCR-D gravimeter, chinese team with Saxl pendulum and another soviet team with paraconical pendulum.

The main goal of expedition was to measure as far as possible precisely variations of gravity field parameters in order to try to check the hypothesis of gravitation shielding.

The gravimetric devices were placed on the pillars inside of isolated rooms of hotel's basement with a temperature variations only about 0.5^{o}C during a day.

The readings from Sodin-gravimeter were taken each 0.5 hour during 3 days (July 20-22) for the control of the drift and stability. The drift was found to be about 50 mcGal/day. More detailed observations were carried out from 4:00 to 8:00 on July 22 (the time of the first contact of eclipse was 5:02, the time of full phase was 5:53 - 5:55, the time of the last contact was 6:48) and for the control during the same period on July 21. The precision of single reading was found to be about 5 mcGal.

The observations with gradiometer were carried out in the same interval on July 20 - 22 with readings frequency 0.5 hour and on July 21-22 from 4:00 to 8:00 with readings frequency 2 min. In parallel the temperature variations with an precision 0.01^{o}C were recorded.

The preliminary processing of gravimetric data included smoothing spline-approximation of records and comparison with calculated tide curves. We may state that our data don't confirm the existence of anomalous effect in gravity variations with an amplitude more than 5 mcGal on the confidence level 0.95 (see fig.). We are going to make more detailed analisys with adding data of gradiometer and to compare it with results of our italian colleagues.

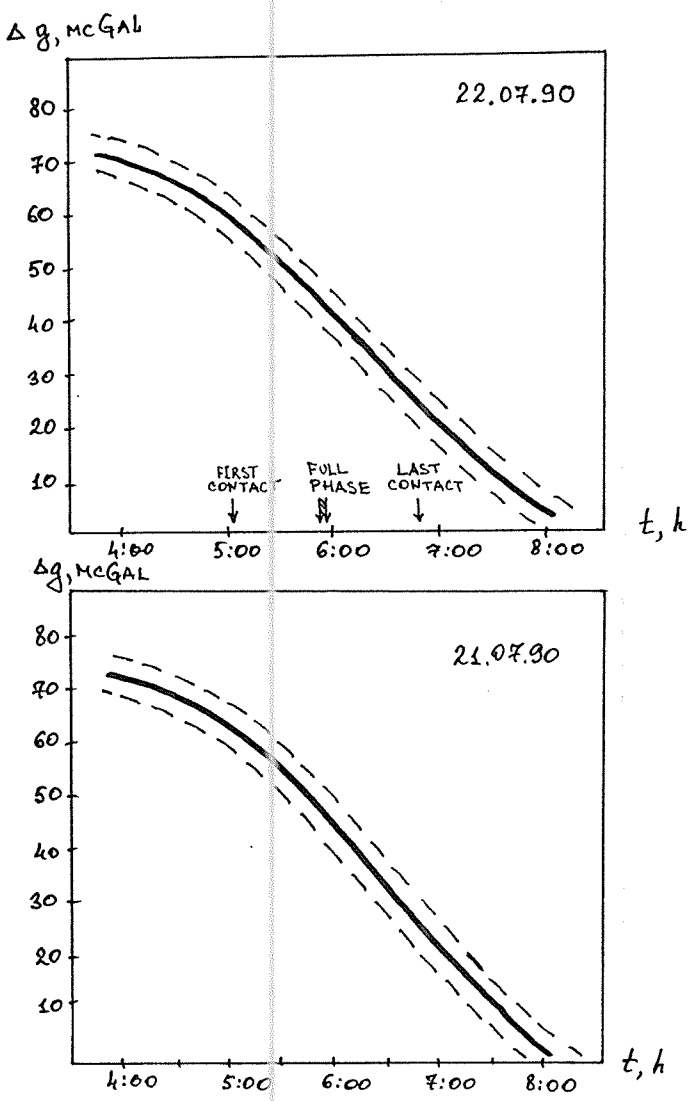


Fig. Graphs of smoothed dependence of the gravity on time during the solar eclipse and one day before it.

RELATIVE GRAVITY MEASUREMENTS AT THE 3RD INTERNATIONAL COMPARISON OF ABSOLUTE GRAVIMETERS

M. Becker, B. Bernard, Y. Boulanger, G. Corrado, J. Faller, J. Fried, E. Groten, H. Hanada, K. Lindner, B. Meurers, G. Peter, R. Röder, D. Ruess, L. Timmen, B. Toro, S. Tsuruta, W. Zürn

Abstract

Relative gravimeter measurements at the 3rd International Comparison of Absolute Gravimeters in Paris 1989 were needed for the connection of the different sites and for the determination of vertical gradients at each site. 12 LaCoste gravimeters, 10 of which equiped with electrostatic feedback were employed in the campaign. Vertical gradients and gravity differences are estimated with an accuracy of about 1 μgal.

Introduction

The intercomparison of absolute gravimeters is performed in few years intervals in order to check the apparatusses for systematic errors and to test their performance in a special environment. To be sure that all instruments are observing the same "g"-value these comparisons are preferably made at one time at one location, namely the BIPM in Paris-Sevres. In order to compare the absolute values obtained at different pillars of the same building, relative measurements of the small gravity differences are needed. Moreover today's absolute gravimeters still need the input of the vertical gradient of gravity at the observation sites. These two tasks were realized in a campaign at BIPM from Nov. 23th to Nov. 27th, 1989, organized by the IAG-Special Study Group 3.110 "Local Gravity Field Variation" of Prof. E. Groten. These local observations of rather small gravity differences under controlled and stable environmental conditions are furthermore an ideal tool to a valuation of the 'State of the Art' of relative gravimetry with respect to purely instrumental accuracies.

Design and Performance of Observations

For the campaign 8 Institutions with 12 Gravimeters were willing to participate, see Appendix A. Based on the experiences of previous comparisons the observations were made in a kind of 3-D network-mode, considering the points at a certain height which should be used for vertical gradient determination as points in the network. Fig. 1 shows the 5 pillars used for absolute measurements. At each pillar 3 points in 0.05, 0.85 and 1.25 m height above the floor are chosen. As each pillar a tripod was installed permanently so that all ties at each of the different height levels as well as between different height levels could be observed. The schedule of measurements is given in the appendix.

At every height the instruments were carefully aligned to magnetic north in order to reduce magnetic effects.

Data Reduction and Adjustment

The data reduction was made using the standard procedures and calibration values supplied by the owner of the instruments. Tidal corrections were computed using the empirical values for amplitude and phase determined by the ICET in Bruxelles. In order to keep the a priori height corrections as small as possible, the average height of all gravity meter sensors was used as height reference at each site. This turned out to be 0.05, 0.85 and 1.25 m at every point.

The adjustment was made using a robust estimation technique developed for high precision gravimetry. By iteratively re-weighted least squares solutions the effects of observations with large residuals are minimized. For details see (Becker, 1989). In this way all original observations are included in the adjustment, but those which may be gross-errors or erroneous in some way are labelled so that distortion of the parameters to be estimated is reduced. Table 1 gives a review of both the least squares and the Robust M-estimation results.

		least squares		Robust M-estimate		
Instr.	observations	m_o (μgal)	m(Δg) (μgal)	m_0 (μgal)	m(Δg) (μgal)	max.change in g (μgal)
D 9	192	4.2	2.2	4.1	2.1	0.8
D17	120	11.7	7.0	8.0	5.4	10.4
D43	120	6.5	4.0	5.6	3.6	3.2
D60	123	6.9	4.7	5.8	4.0	2.0
D136	117	9.6	6.2	3.4	5.0	3.9
G156	120	3.8	2.3	3.6	2.2	1.2
G249	120	4.9	3.0	4.8	2.9	0.7
G258	133	3.8	2.2	3.6	2.1	0.7
G298	54	6.9	4.3	5.9	3.9	1.7
G305	155	5.2	3.4	4.6	3.1	4.3
G625	142	5.4	3.0	4.9	2.7	2.7
G709	36	12.2	9.2	6.3	5.0	13.0
Combined	1432	7.2	1.4	5.9	1.0	2.3

Table 0 Results of Least Squares and Robust - M Estimation (m_0=Mean Square error of unit weight, m(Δg) = m.s.e. of adjusted gravity difference)

It can be seen, that the estimated gravity differences for those instruments with gross-errors change by several microgals. Obviously one would eliminate some of these observatins "by hand" beforehand, but the robust estimation procedure as applied here does this automatically and based on statistically determined limits. All results presented in the sequel are computed by the Robust-M-estimates.

Results

Results for combined and single adjustments are given in Table 2 to 5. Due to the large number of observations the formal accuracy is about 1 μgal for the ad-

justed gravity differences. Single instruments obtained 2 to 5 μgal for the adjusted differences. Fig. 2 shows the range of the gravity differences and fig. 3 the summary of the comparison of single instrument versus combined adjustment. Most differences are in the range of +- 2 to 5 μgal, but there is a considerable number of instruments with larger discrepancies of up to 10 μgal. This may indicate that there are some systematic effects in some instruments, especially because the largest deviations occur at the points in .8 and 1.2 m height.
We introduced on trial scale factors for some of the feedback instruments to verify that the calibration factors used are correct, but no significant reduction of the discrepancies could be obtained.

COMBINED ADJUSTMENT

Station	Number	G-value	[μgal]
A (0.05 m)	9000	0.0	0.0
A1(0.05 m)	9100	-0.01099	+-0.0007
A2(0.05 m)	9200	0.00536	+-0.0007
A3(0.05 m)	9300	-0.07270	+-0.0008
A8(0.05 m)	9800	0.55938	+-0.0008
A (0.85 m)	9008	-0.24964	+-0.0009
A1(0.85 m)	9108	-0.25790	+-0.0009
A2(0.85 m)	9208	-0.24301	+-0.0009
A3(0.85 m)	9308	-0.31100	+-0.0009
A8(0.85 m)	9808	0.35451	+-0.0009
A (1.25 m)	9012	-0.37041	+-0.0009
A1(1.25 m)	9112	-0.37805	+-0.0009
A2(1.25 m)	9212	-0.36636	+-0.0010
A3(1.25 m)	9312	-0.42690	+-0.0010
A8(1.25 m)	9812	0.25712	+-0.0010

Table 1 Results of combined Adjustment [mgal]

Tables 2 to 5 Results of Single Adjustments [mgal]

Site	Instrument D 9		D17		D43	
9000	0.0	0.0	0.0	0.0	0.0	0.0
9100	-0.00981	+-0.0014	-0.01377	+-0.0038	-0.01562	+-0.0028
9200	0.00536	+-0.0014	0.00041	+-0.0041	0.00485	+-0.0029
9300	-0.07149	+-0.0017	-0.06885	+-0.0038	-0.07948	+-0.0029
9800	0.56159	+-0.0019	0.56154	+-0.0037	0.55837	+-0.0031
9008	-0.25293	+-0.0018	-0.24396	+-0.0052	-0.25114	+-0.0033
9108	-0.25780	+-0.0018	-0.24614	+-0.0045	-0.26774	+-0.0037
9208	-0.24537	+-0.0019	-0.24020	+-0.0049	-0.24814	+-0.0036
9308	-0.31213	+-0.0020	-0.29983	+-0.0051	-0.31988	+-0.0037
9808	0.35659	+-0.0023	0.35780	+-0.0050	0.34935	+-0.0035
9012	-0.36882	+-0.0019	-0.37070	+-0.0046	-0.37990	+-0.0031
9112	-0.38103	+-0.0020	-0.38800	+-0.0052	-0.38986	+-0.0033
9212	-0.36503	+-0.0019	-0.37453	+-0.0051	-0.37172	+-0.0032
9312	-0.42447	+-0.0021	-0.42867	+-0.0048	-0.43558	+-0.0034
9812	0.25838	+-0.0022	0.26146	+-0.0047	0.25721	+-0.0038

Site	Instrument D60		D136		G156	
9000	0.0	0.0	0.0	0.0	0.0	0.0
9100	-0.01015	+- 0.0025	-0.00931	+-0.0030	-0.01080	+-0.0016
9200	0.00692	+- 0.0029	0.01041	+-0.0033	0.00661	+-0.0016
9300	-0.07145	+- 0.0027	-0.06943	+-0.0037	-0.07420	+-0.0017
9800	0.55736	+- 0.0027	0.56594	+-0.0040	0.56150	+-0.0017
9008	-0.25099	+- 0.0025	-0.24694	+-0.0035	-0.24921	+-0.0020
9108	-0.25852	+- 0.0027	-0.25313	+-0.0036	-0.25713	+-0.0022
9208	-0.24328	+- 0.0030	-0.23774	+-0.0034	-0.24241	+-0.0021
9308	-0.31081	+- 0.0027	-0.30970	+-0.0040	-0.31134	+-0.0020
9808	0.35988	+- 0.0031	0.35885	+-0.0041	0.35249	+-0.0021
9012	-0.36918	+- 0.0042	-0.37768	+-0.0055	-0.36900	+-0.0019
9112	-0.37309	+- 0.0047	-0.36915	+-0.0062	-0.37658	+-0.0019
9212	-		-0.36720	+-0.0070	-0.36302	+-0.0019
9312	-0.42298	+- 0.0050			-0.42439	+-0.0021
9812	0.25156	+- 0.0042			0.25967	+-0.0022

Site	Instrument G249		G258		G298	
9000	0.0	0.0	0.0	0.0	0.0	0.0
9100	-0.01017	+-0.0023	-0.01140	+-0.0015	-0.01198	+-0.0037
9200	0.00446	+-0.0022	0.00534	+-0.0016	0.00094	+-0.0039
9300	-0.07876	+-0.0022	-0.07431	+-0.0017	-0.07447	+-0.0039
9800	0.55508	+-0.0022	0.55698	+-0.0016	0.55336	+-0.0039
9008	-0.24911	+-0.0027	-0.24973	+-0.0018	–	
9108	-0.26128	+-0.0028	-0.26010	+-0.0018	–	
9208	-0.24686	+-0.0027	-0.24204	+-0.0020	–	
9308	-0.31650	+-0.0028	-0.31270	+-0.0018	–	
9808	0.34758	+-0.0027	0.35183	+-0.0018	–	
9012	-0.36913	+-0.0026	-0.36998	+-0.0019	-0.36834	+-0.0038
9112	-0.37790	+-0.0030	-0.37722	+-0.0019	-0.37284	+-0.0037
9212	-0.36380	+-0.0029	-0.36864	+-0.0021	-0.36836	+-0.0037
9312	-0.42790	+-0.0026	-0.42925	+-0.0021	-0.42990	+-0.0041
9812	0.25061	+-0.0026	0.25527	+-0.0021	0.26103	+-0.0037

Site	Instrument G305		G625		G709	
9000	0.0	0.0	0.0	0.0	0.0	0.0
9100	-0.00601	+-0.0020	-0.01340	+-0.0024	-0.01526	+-0.0049
9200	0.01052	+-0.0021	0.00391	+-0.0022	0.00347	+-0.0054
9300	-0.06438	+-0.0020	-0.07298	+-0.0023	-0.07678	+-0.0050
9800	0.56461	+-0.0019	0.56074	+-0.0022	0.54739	+-0.0052
9008	-0.24206	+-0.0024	-0.25256	+-0.0027	–	
9108	-0.25790	+-0.0025	-0.25843	+-0.0030	–	
9208	-0.23434	+-0.0025	-0.24524	+-0.0029	–	
9308	-0.30476	+-0.0024	-0.30682	+-0.0028	–	
9808	0.35879	+-0.0023	0.35721	+-0.0027	–	
9012	-0.36869	+-0.0023	-0.36925	+-0.0027	-0.37267	+-0.0055
9112	-0.37125	+-0.0025	-0.37745	+-0.0029	-0.38055	+-0.0050
9212	-0.35705	+-0.0026	-0.36652	+-0.0027	-0.36867	+-0.0056
9312	-0.42273	+-0.0025	-0.42282	+-0.0027	-0.43390	+-0.0051
9812	0.25580	+-0.0025	0.26154	+-0.0027	0.24910	+-0.0050

Tables 6 to 9 Differences in the ties to Sevres A [mgal]

S I T E	Comb.- D 9	Comb.-D17	Comb.-D43	Comb.-D60
9000	0	0	0	0
9100	-0,0012	0,00278	0,00463	-0,0008
9200	0	0,00495	0,00051	-0,0016
9300	-0,0012	-0,00385	0,00678	-0,0013
9800	-0,0022	-0,00216	0,00101	0,002
9008	0,0033	-0,00560	0,00100	0,0013
9108	-0,0001	-0,01176	0,00980	0,0006
9208	0,0024	-0,00281	0,00513	0,0003
9308	0,0011	-0,01117	0,00880	-0,0002
9808	-0,0021	-0,00329	0,00516	-0,0054
9012	-0,0016	0,00029	0,00949	-0,0012
9112	0,003	0,00995	0,01181	-0,005
9212	-0,0013	0	0,00530	–
9312	-0,0024	0,00177	0,00868	-0,0039
9812	-0,0013	-0,00430	0,00000	0,0056

S I T E	Comb.-D136	Comb.-G156	Comb.-G249	Comb.-G258
9000	0	0	0	0
9100	-0,0017	0,0001	-0,000	0,00046
9200	-0,0051	-0,0009	0,0009	0
9300	-0,0033	0,0017	0,0061	0,0016
9800	-0,0066	-0,002	0,0043	0,0024
9008	-0,0027	-0,0007	-0,0005	-0,0001
9108	-0,0048	-0,0005	0,0034	0,0022
9208	-0,0053	0	0,0038	-0,0010
9308	-0,0013	0,0004	0,0050	0,0017
9808	-0,0043	0,0022	0,0069	0,0027
9012	0,0073	-0,0012	-0,0013	0,00042
9112	-0,0089	-0,0012	-0,0001	-0,0008
9212	0,0008	-0,0032	-0,0026	0,0023
9312	–	-0,0020	0,00	0,0024
9812	–	-0,0020	0,0065	0,0019

S I T E	Comb.-G298	Comb.-G305	Comb.-G625	Comb.-G709
900	0	0	0	0
9100	0,001	-0,005	0,0024	0,0043
9200	0,0044	-0,0052	0,0015	0,0019
9300	0,0018	-0,0083	0,0003	0,0041
9800	0,006	-0,0052	-0,0014	0,012
9008	–	-0,0076	0,0029	–
9108	–	0	0,0005	–
9208	–	-0,0087	0,0022	–
9308	–	-0,0062	-0,0042	–
9808	–	-0,0043	-0,0027	–
9012	-0,0021	-0,0017	-0,0012	0,0023
9112	-0,0052	-0,0068	-0,0006	0,0025
9212	0,002	-0,0093	0,0002	0,0023
9312	0,003	-0,0042	-0,0041	0,007
9812	-0,0039	0,0013	-0,0044	0,008

Vertical Gradients

Vertical gradients can be obtained by using the gravity differences at the 3 different heights. Table 10 shows the values computed by use of the results of the combined adjustment. Besides the well known fact that the gradient is considerably different at the different sites, also a more or less systematic increase of the vertical gradient with increasing height could be determined. The non-linearities are fitted by a polynomial and the coefficients are also listed in tab. 10. The coefficient of the quadratic term is in the range of 2 to 10 $\mu gal/m^2$. This means, that the differences to a mean linear gradient may be up to 8 μgal in this parabolic fit. This value should obviously be used for interpolation between measured points only and not for extrapolation.

Site	0.05-0.85 m	0.05-1.25 m	a_0 [μgal]	a_1 [$\mu gal/m$]	a_2 [$\mu gal/m^2$
A	-312.05	-308.67	15.96	-319.61	8.44
A1	-308.63	-305.89	4.73	-314.83	6.88
A2	-310.46	-309.76	20.98	-312.03	1.74
A3	-297.87	-295.16	15.18	-303.97	6.77
A8	-256.09	-251.88	572.63	-265.55	10.51

Polynomial: $g(h)=a_0 + a_1 * h + a_2\ h*h$

Table 10 Vertical Gradients in $\mu gal/m$ and Polynomial Approximation

Horizontal gradients in room 1 with 3 adjacent stations are below about 5 $\mu gal/m$

Comparison To Results Of Previous Relative Measurements.

We use the values of the summary in (Röder and Wenzel, 1986) where the results published in the original papers of the literature list given below are collected.

For gravity differences only the sites A0 and A3 can be compared. Care must be taken with the numbering and the names of the points. In room 1 there is one pillar where 3 gravity-points are marked. They are, from north to south : Sevres A, Sevres A0 and Sevres A1. In the previous campaigns Sevres A0 was used and labelled Sevre A1. Now Sevres A and Sevres A1 were used. Therefore the difference A to A0 must be known. Fortunately D9 measured the difference in an extra set of observations and the result is 2.7 μgal +- 2.2 μgal. The difference to be compared to the previous values is A0 to A3 = -75.41 μgal +- 2.20 μgal as adjusted in the combined adjustment. Table 11 gives the gravity difference for the different epochs.

Epoch	Gravity Difference [μgal]	Remarks
1976	- 90.1 +- 7.	Cannizzo et. al.
1977	- 90.6 +- 0.6	Marson
1978	- 91.0 +- 7.	Poitevin
1981	- 79.6 +- 1.5	Int. Comp. 1981, excentric on A3
1981	- 72.0 +- 1.9	Int. Comp. 1981, reduced to A3 according to Röder and Wenzel, 1986
1985	- 70.6 +- 0.4	Int. Comp. 1985
1986	- 68.2 +- 0.6	Röder and Wenzel 1986
1989	- 75.4 +- 2.2	Int. Comp. 1989, this study

Table 11 Comparison of Gravity Difference A0 - A3 in Time

It seems that considering the errors of the adjusted values there is no significant change in the difference A0 to A3 since 1981. The same holds true for the vertical gradient if compared for the different epochs since 1977, see tab. 12. For the 1989 value we used the gradient deduced for measurements between 0.05 and 1.0 m from the polynomial approximation. Because we do not know the exact heights of the earlier determinations, an error of about 1.5 μgal may occur due to the nonlinearity of the gradient. However, if the excentricity as determined by Röder and Wenzel (1986) is taken into account, and disregarding the observations of Ogier (1986), the standard deviation of the 5 values since 1981 is only 1.2 μgal.

From the comparison of these results it looks like the gravity difference Sevres A0 to Sevres A3 as well as the vertical gradient at A3 being stable with a possible bigger change before 1981.

Epoch	Gradient A3 [μgal/m]	Remark
1977	- 273. +- 3.	Cannizzo et. al. 1977
1980	- 273. +- 7.	Sakuma
1981	- 283.6 +- 1.6	Int. Comp. 1981, excentric
1981	- 294.1 +- 2.5	Int. Comp. 1981, reduced to A3 according to Röder and Wenzel, 1986
1984	- 274.8 +- 1.9	Ogier, 1986
1985	- 295.3 +- 1.2	Int. Comp. 1985
1985	- 296.9 +- 4.6	Ogier, 1986
1986	- 294.8 +- 1.2	Röder and Wenzel, 1986
1989	- 296.8 +- 0.7	Int. Comp. 1989, this study

Table 12 Comparison of Vertical Gravity Gradient at Station A3 in Time

Conclusion

In the relative measurements at the 3rd International Comparison of Absolute Gravimeters a homogenous accuracy of about 1 μgal could be obtained for gravity differences and consequently for the gravity gradients over given intervals. In spite of the fact that all known systematic error sources were considered and and 10 out of 12 instruments were equipped with electrostatic feedback, discrepancies between instruments still may reach 10 μgal in some ties. Only instruments with optimal adjustment, up to date calibration of feedback and/or periodical errors and tested for the perfection of their magnetic shielding should be used in combination with absolute gravimeters. Otherwise the measured absolute value may suffer from errors introduced by the reduction to a reference marker by relative instruments. So if less instruments are used the number of observations should be increased and measurements be made at different times and conditions in order to get some averaging of errors and to detect gross errors.

There is no indication of differential gravity changes at BIPM over the last 8 years if the improved results of the different campaigns since 1981 are compared.

Acknowledgement: We gratefully acknowledge the help and hospitality of Prof. Sakuma and the staff of BIPM.

Literature

Becker, M. and E. Groten, 1983 : Relative Gravimeter Measurements at the 1981 Absolute Gravimeter Campaign in Paris Sèvres. BGI, Bulletin d'Informations NO. 52, 86-96, Toulouse 1983

Becker, M., 1985 : Relative Gravimeter Measurements at the 1985 Absolute Gravimeter Campaign in Sèvres - Preliminary Results, BGI, Bulletin d'Informations No. 57, 46-71, Toulouse 1985

Becker, M., 1989 : Adjustment of Microgravimetric Measurements for Detecting Local and Regional Vertical Displacements, Paper presented at the 125. IAG General Assembly, Edinburgh, 1989

Boulanger, J.D., G.P. Arnautov and S.N. Scheglov, 1983 : Results of Comparison of Absolute Gravimeters. Sèvres, 1981. BGI, Bulletin d'Informations NO. 52, 99-124, Toulouse 1983

Boulanger, Yu., J. Faller and E. Groten (Editors), 1986 : Results of the Second International Comparison of Absolute Gravimeters in Sèvres 1985. BGI, Bulletin d'Informations, Toulouse 1986

Cannizzo, L., G. Cerutti, I. Marson, 1978 : Absolute-Gravity Measurements in Europe. Il Nuovo Cimento, Vol. IC, N.1, 1978

Ogier, M., 1986 : Nouvelle détermination du gradient vertical de presenteur sur le piller A3 du B.I.P.M. a Sèvres (Hauts-de-Seine). Bureau de Recherches Géologiques et Minières, 1986

Röder, R.H., M. Schnüll and H.-G. Wenzel, 1985 : Gravimetry with an Electrostatic Feedback System. BGI, Bulletin d'Informations No. 57, 72-81, Toulouse 1985

Röder, R.H., and H.-G. Wenzel, 1986 : Relative Gravity Observations at BIPM, Sevres in 1985 and 1986. BGI, Bulletin d'Informations No. 59, 177-183, Toulouse, 1986

Schnüll, M., R.H. Röder and H.-G. Wenzel, 1984 : An Improved Electronic Feedback for LaCoste-Romberg Gravity Meters. BGI, Bulletin d'Informations No. 55, 27-36, Toulouse 1984

APPENDIX

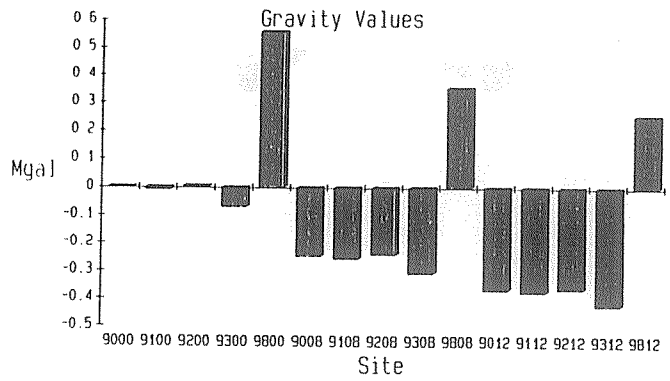
PARTICIPANTS, OBSERVERS AND INSTRUMENTS AT SÈVRES, NOV. 23 TO NOV. 27, 1989

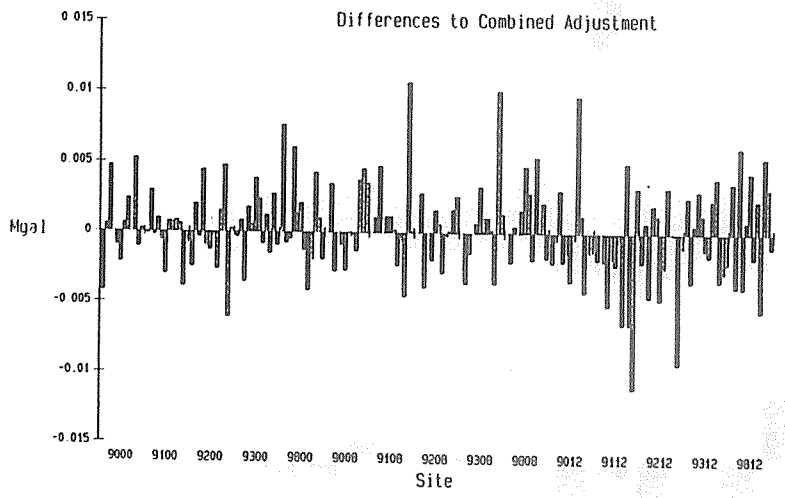
1. Institut für Meteorologie und Geophysik,	D9	Hannover Feedback
Universität Wien, Dr. Meurers, Dr. D. Ruess	G625	Hannover Feedback
2. Geodetic Research and Development Laboratory,	D17	LaCoste Feedback
National Geodetic Survey, Rockville,	D43	LaCoste Feedback
Dr. G. Peter, J. Fried, B. Bernhard		
3. Dipartimento Di Scienze Della Terra,	D60	
Universita Degli Studi Di Roma		
"La Sapienzia", Dr. B. Toro		
4. Geodätisches Institut, Universität Karlsruhe,	G156	Hannover Feedback
Dr. K. Lindner, Dr. W. Zürn	G249	Hannover Feedback
5. Dipartimento Di Geofisica E Vulcanologia,	D136	LaCoste Feedback
Universita Degli Studi Di Napoli, Dr. G. Corrado		
6. Institut für Physikalische Geodäsie,	G258	Darmstadt Feedback
TH Darmstadt, Dr. M. Becker		
7. Institut für Erdmessung,	G298	Hannover Feedback
Universität Hannover, R. Röder, L. Timmen	G709	Hannover Feedback
8. National Astronomical Observatory, Mizusawa	G305	
Dr. H. Hanada, S. Tsuruta		

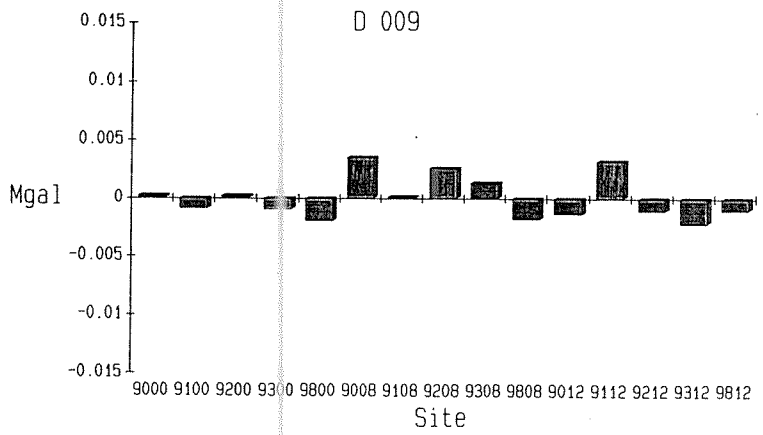
CALIBRATION FACTORS USED

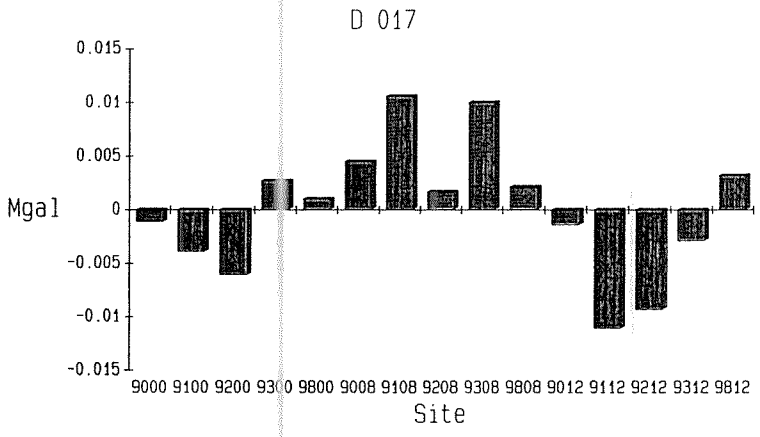
Instr.	ΔH	FEEDBACKSYSTEM-SCALE-FACTOR Linear	Quadratic	Calibration-factor
D09	0.15	1.116787	0.000756117	–
D17	0.15	1.38272	0.0000	1.3665
D43	0.15	1.26463	–	1.238864
D60	0.15	no feedback		1.0799
D136	0.15	– 1.15607	–	–
G156	0.153	1.05017	0.000767	–
G249	0.147	1.063505	– 0.001087	–
G258	0.15	– 1.05826	0.004483	–
G298	0.16	1.057901	– 0.0002235667	–
G305	0.14	no feedback	–	1.06085
G625	0.15	1.02018	0.0219417	–
G709	0.16	0.9918554	– 0.000173219	–

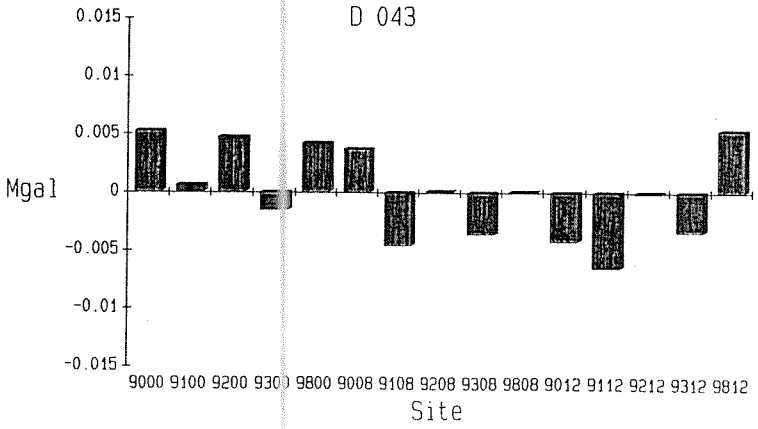
(ΔH = height difference of top of gravimeter to beam)

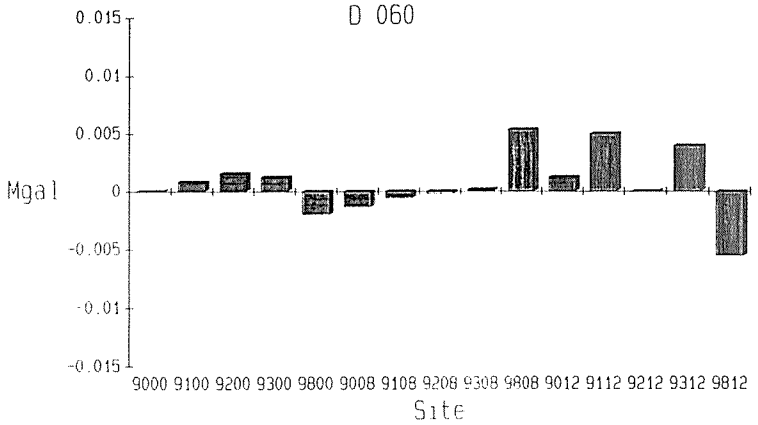


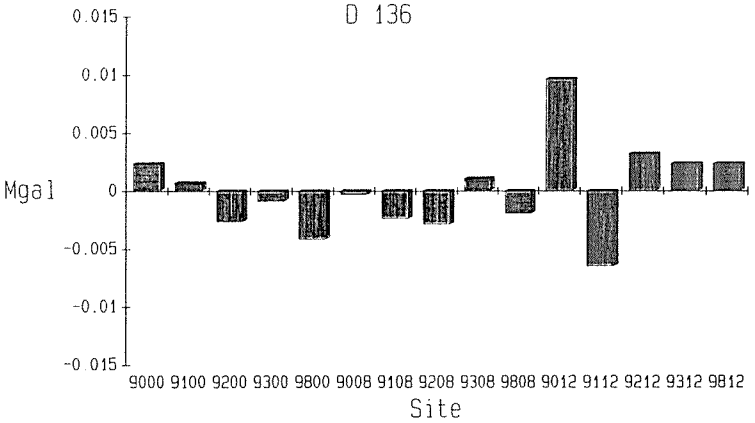


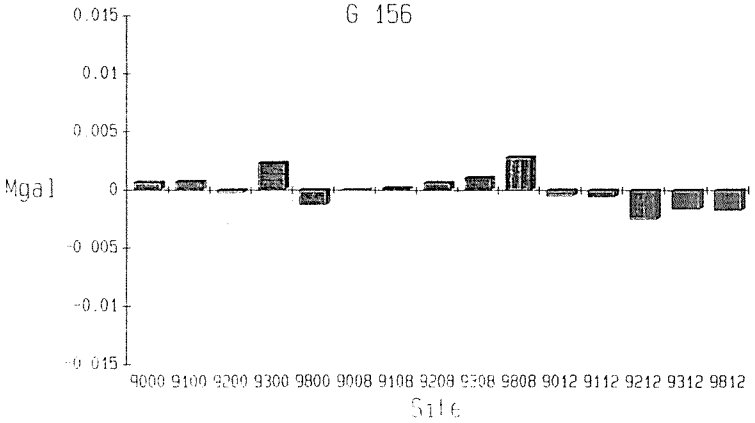

D 009
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Mgal
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site

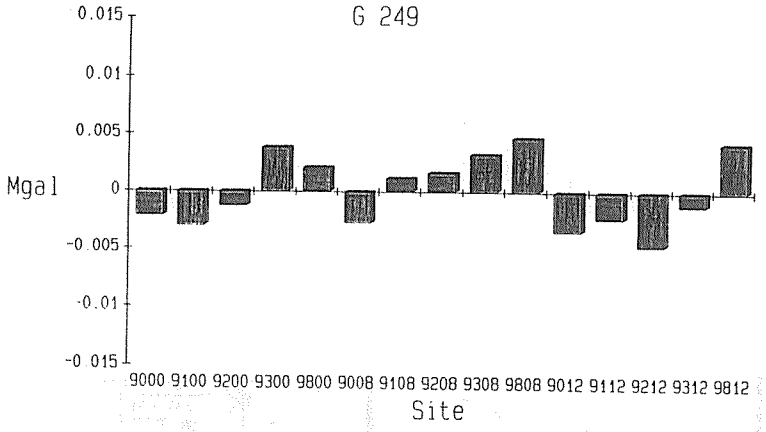

D 017
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Mgal
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site

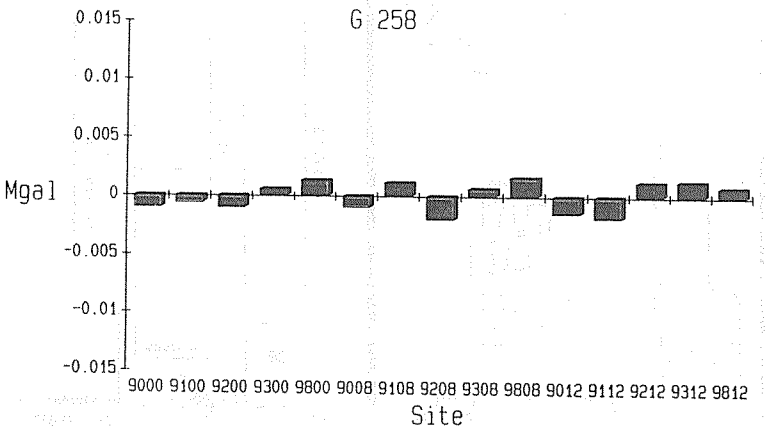

D 043
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Mgal
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site

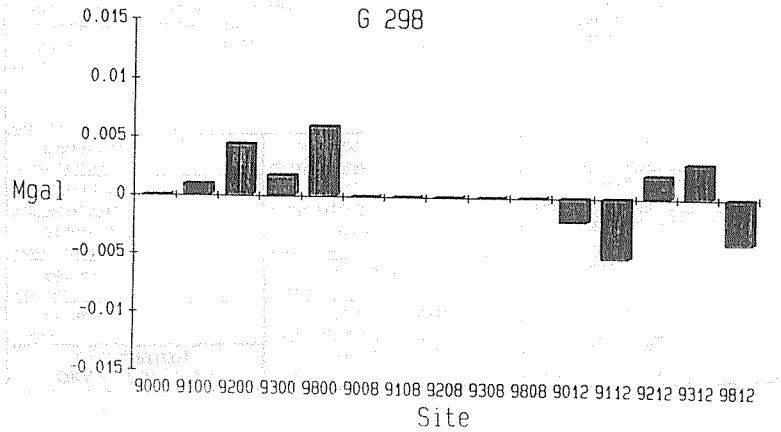

D 060
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Mgal
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site

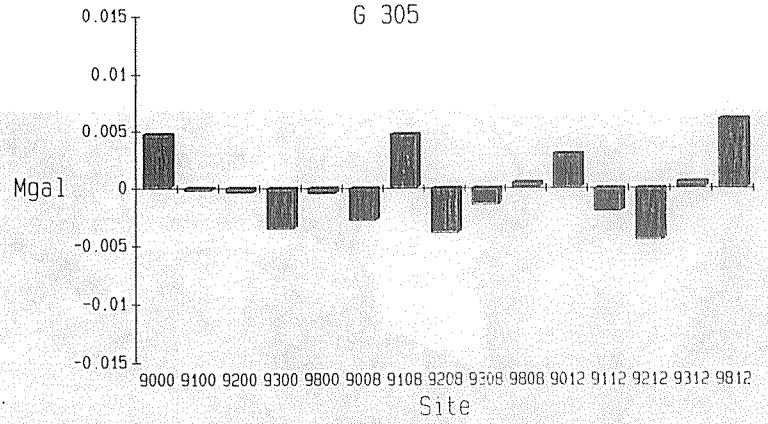

D 136
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Mgal
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site

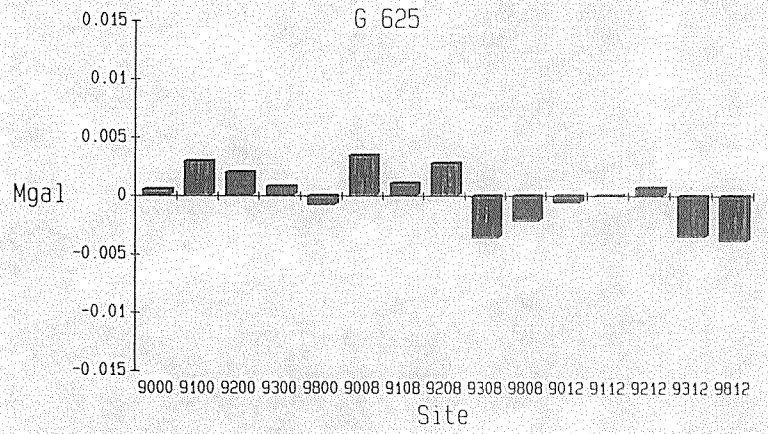

G 156
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Mgal
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site

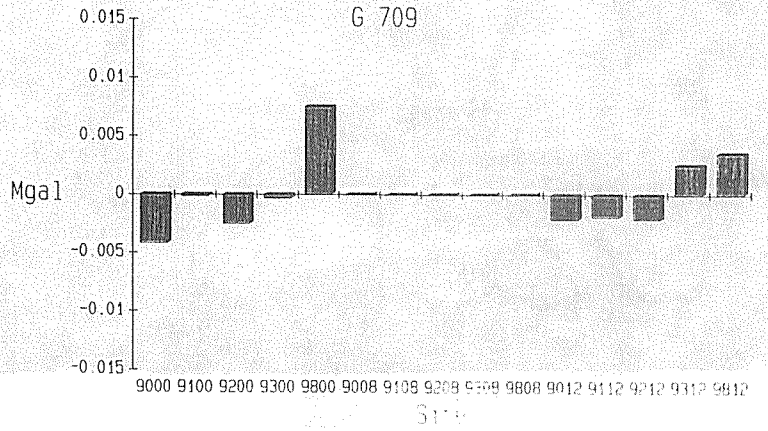

G 249
Mgal
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site


G 258
Mgal
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site


G 298
Mgal
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site


G 305
Mgal
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site


G 625
Mgal
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812
Site


G 709
Mgal
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
9000 9100 9200 9300 9800 9008 9108 9208 9308 9808 9012 9112 9212 9312 9812

GRAVITY STATION DESCRIPTION	STATION TYPE	STATION DESIGNATION
	Absolute Site	Paris A
COUNTRY	STATE/PROVINCE	CITY
France	Hauts-de-Seine	Sevres
LATITUDE	LONGITUDE	ELEVATION
48° 49!8 N	2° 13!2 E	65.93 meters
GRAVITY STATION MARK	AGENCY SOURCE	INSCRIPTION
Aluminum Plate	BIPM	Sevres Point A
POSITION REFERENCE	POSITION SOURCE	SOURCE DESIGNATION
Publication	IGC	Paris A
ELEVATION REFERENCE	ELEVATION SOURCE	SOURCE DESIGNATION
Publication	IGC	Paris A

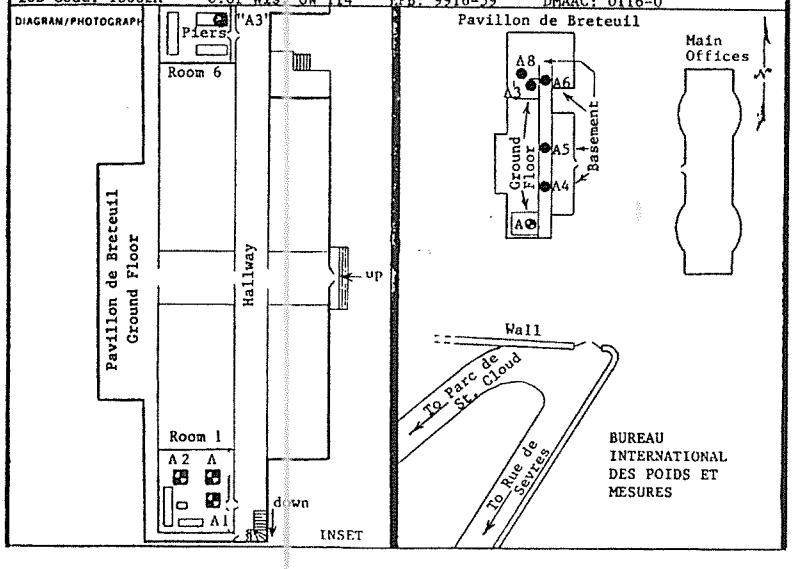
POSITION/ELEVATION REMARKS

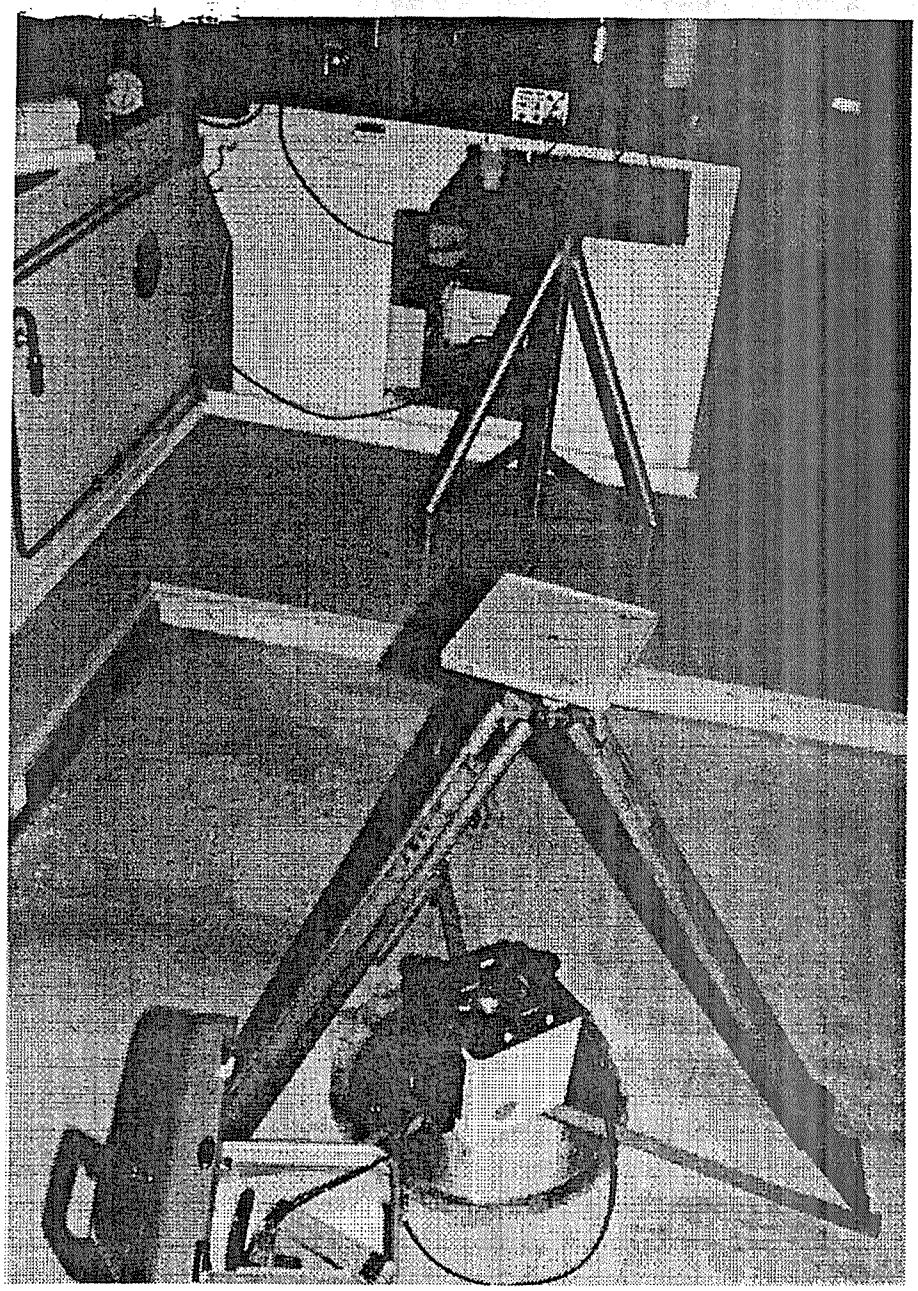
DESCRIPTION

The station is about three kilometers southwest of the city limits of Paris in Sevres at the Bureau International des Poids et Mesures (in the Parc de St. Cloud). Observations were made in the Pavillon de Breteuil, ground floor, in Room 1 (the southernmost room). The station is 1.2 meters west of the innermost set of doors, on the concrete pier which is 0.1 meters below the floor level.

IGB Code: 18082A U.of Wis: GW 114 EPB: 9916-59 DMAAC: 0116-0

DIAGRAM/PHOTOGRAPH





Schedule of Relative Measurements

Measurement Nr.	Instrument Nr.				
	R1	R2	R3	R4	R5
1	A0/0	A10/0	A9/0	A8/0	A3/0
2	A0/8	A10/8	A9/8	A8/8	A3/8
3	A10/0	A9/0	A8/0	A3/0	A0/0
4	A10/8	A9/8	A8/8	A3/8	A0/8
5	A9/0	A8/0	A3/0	A0/0	A10/0
6	A9/8	A8/8	A3/8	A0/8	A10/8
7	A8/0	A3/0	A0/0	A10/0	A9/0
8	A8/8	A3/8	A0/8	A10/8	A9/8
9	A3/0	A0/0	A10/0	A9/0	A8/0
10	A3/8	A0/8	A10/8	A9/8	A8/8
11	A0/8	A10/8	A9/8	A8/8	A3/8
12	A0/0	A10/0	A9/0	A8/0	A3/0
13	A3/8	A0/8	A10/8	A9/8	A8/8
14	A3/0	A0/0	A10/0	A9/0	A8/0
15	A8/8	A3/8	A0/8	A10/8	A9/8
16	A8/0	A3/0	A0/0	A10/0	A9/0
17	A9/8	A8/8	A3/8	A0/8	A10/8
18	A9/0	A8/0	A3/0	A0/0	A10/0
19	A10/8	A9/8	A8/8	A3/8	A0/8
20	A10/0	A9/0	A8/0	A3/0	A0/0
21	A0/8	A10/8	A9/8	A8/8	A3/8
22	A9/8	A8/8	A3/8	A0/8	A10/8
23	A3/8	A0/8	A10/8	A9/8	A8/8
24	A10/8	A9/8	A8/8	A3/8	A0/8
25	A8/8	A3/8	A0/8	A10/8	A9/8
26	A10/0	A9/0	A8/0	A3/0	A0/0
27	A3/0	A0/0	A10/0	A9/0	A8/0
28	A9/0	A8/0	A3/0	A0/0	A10/0
29	A0/0	A10/0	A9/0	A8/0	A3/0
30	A8/0	A3/0	A0/0	A10/0	A9/0

Remarks :

1. total 30 readings à 10 minutes ≙ 5 h

2. Repetition at day 2

3. Gradients from site AN/0 to AN/12, clockwise change of the 5 relative gravimeters on the 5 stations.

RESULTS OF THE 3rd INTERNATIONAL COMPARISON OF ABSOLUTE GRAVIMETERS IN SEVRES

Yu. D. Boulanger

Soviet Geophysical Committee, Moscow, USSR

The full results of the Comparison Campaign had to be rederived due to the late withdrawal of the BIPM contribution (see footnote at the end of this page). The complete report and associated pages will appear in the next issue of the Bulletin d'Information. (G. Balmino)

As a result of the 2nd International Comparison of Absolute Gravimeters in Sèvres 1985, notable systematic errors were observed in the measured gravity values. Taking into consideration this circumstance, a resolution was adopted at the meeting of the International Gravity Commission during the XIX General Assembly of the International Association of Geodesy (Vancouver, 1987) to the effect that such comparisons should be continued and carried out systematically, if possible every 3-4 years. For this purpose the Working Group 6, IGC, "Comparison of Absolute Gravimeters" was set up with Pr. Yu.D. Boulanger as Convener. It was also suggested to hold the next comparison in the autumn of 1988. The tentative participants were Austria, Canada, China, Finland, Germany, BIPM (Sèvres), Italy, Japan, USA and USSR.

The first WG6 meeting took place in Paris on 22-23 June 1988, where it became apparent that in 1988 in many countries the absolute gravimeters would not be ready as yet for comparison. Pr. P. Giacomo, Director of BIPM at that time, invited the next comparison to Sèvres in the end of 1989, which was accepted with gratitude. Moreover, Pr. E. Groten and Dr. M. Becker have kindly agreed to undertake the accomplishment of the relative measurements necessary for setting up a microgravimetric network and for the determination of vertical gradients over the pillars.

Since BIPM cannot receive simultaneously ten instruments, it was decided to carry out this comparison by two groups : the first group in the last decade of November, and the second group in the first decade of December 1989. In the interval between them, it was recommended to make measurements with relative gravimeters.

The second WG6 meeting, which took place on 23-24 November 1989, in Sèvres just before the beginning of the observations, discussed and finally adopted the observation program for both absolute and relative gravimeters. The order was established of processing of observations and concrete dates of its accomplishment. A wish was expressed to publish a full report on observations in Bull. d'Inf. after their discussion at the XIII IGC meeting in Toulouse in September 1990. The preparation of the materials for publication and their generalisation was entrusted to Yu.D. Boulanger, J. Faller and E. Groten.

However, not a single country presented its results by the fixed deadline (end of February 1990), and the materials were received with great delay and at different dates. I received the last additional corrections to the data in the second half of June, making it necessary to recalculate the summarising Tables and to introduce corrections into the final results of comparison three times.

At the same meeting, three scientific papers were presented by Pr. A. Sakuma (France), Pr. J. Faller (USA), and Dr. L. Vitushkin (USSR) on further prospects of development of absolute gravity determinations concurrently with the determination of vertical gradients, with a subsequent discussion.

As planned previously, ten countries took part in the comparison : Austria, Canada, China, Finland, Germany, BIPM*, Italy, Japan, USA and USSR. The observations were successful : the maximal differences was recorded between the BIPM instrument (980 925 963.5 ± 5.8 mcgal) and the instrument from the USSR (980 925 986.9 ± 4.4 mcgal), i.e. 23.1 ± 7.4 mcgal.

For the first time in the history of gravimetry, practically simultaneously, ten absolute gravimeters made 18 independent absolute gravity determinations on six pillars, and observations of 43.000 drops were processed and the results generalized.

By using measurements of relative gravimeters, all these results were reduced to one point A (0.05) located at the height of 5 cm over the metallic disc mounted in the upper surface of pillar A (on the first floor in room 1 of the Laboratory Building of BIPM in Sèvres).

In the reduction of the measured absolute gravity values particular attention was focused on nonlinear dependence of the value of vertical gravity gradients on the height over the pillar. On the basis of comparison of the obtained results the following conclusions can be drawn :

1. The full mean square error of absolute gravity determination with one instrument by convergence of 19 independent measurements amounts to $\sigma = \pm 7.1$ mcgal.
2. Same by convergence of measurements on one and the same pillar with different instruments is $\sigma = \pm 6.2$ mcgal.

*"The BIPM absolute gravimeter operated during the period 13 to 21 November 1989, but it was subsequently found that the data contained anomalies that made it impossible to evaluate the uncertainty of the measurements. The BIPM result has, therefore, been withdrawn" T.J. Quinn, Director BIPM.

3. Same from estimation by the authors of measurements with allowance for all systematic errors known to them reaches $\sigma = \pm 3.9$ mcgal.
4. Same from convergence of measurements of differences of gravity values between pillars carried out by absolute and relative gravimeters is $\sigma = \pm 1.9$ mcgal.
5. The absence of systematic difference is established between the results of measurements made by the JILAG group of gravimeters (eleven measurements) and a group of gravimeters of other types (eight measurements). The difference amounted to 0.0 ± 3.8 mcgal.
6. By convergence of measurements, carried out by groups of three-four absolute gravimeters from observations at five pillars, the error in mean gravity determination is consistently ± 3.4 mcgal (± 0.4 mcgal).
7. The modern level of accuracy of absolute gravimeters allows us to set up a World Gravimetric Network of the First Order with measurements by one instrument at about ± 7 - ± 8 mcgal, and by a group of three-four gravimeters the accuracy can be increased to ± 3.4 mcgal.

A more detailed description of results of the comparison of absolute gravimeters shall be published by the BGI.

In conclusion I would wish to express deep gratitude to Pr. T. Quinn, the new Director of BIPM, for kindly inviting the 3rd International Comparison of Absolute Gravimeters to BIPM in Sèvres and to Pr. A. Sakuma for the excellent preparation and organization of the measurements.

Many cordial thanks are also extended to Dr. M. Louis, General Secretary of IAG, for his valuable assistance in the organization of this international enterprise.

July 1990, Moscow

Yu. D. Boulanger

Behaviour of Stabilized Lasers Used in Absolute Gravimeters

J.-M. Chartier
Bureau International des Poids et Mesures
Pavillon de Breteuil
92 312 Sèvres France.

Abstract

The behaviour of ten stabilized lasers used in absolute gravimeters has been studied at the BIPM. The absolute frequency of each laser has been calibrated by beat measurements against a BIPM reference laser: all the results are presented. They show relative frequency instabilities of some parts in 10^9 and provide a limit to the accuracy of the absolute determinations of gravity.

1. Introduction

During November and December 1989, the 3rd International Comparison of absolute gravimeters took place at the BIPM. Ten countries were represented, each by one absolute gravimeter.

In 1985, for the second comparison, the large spread of the results of the absolute determinations of gravity at the BIPM reference points was not completely explained by the estimation of the standard deviations of the measurements and doubts were expressed as to the accuracy of the laser frequency in certain gravimeters [1].

For this reason, in the third comparison, a systematic frequency calibration of the stabilized laser used in each gravimeter was decided. This task was carried out by the BIPM laser section which has acquired the necessary experience from international comparisons of stabilized lasers over a fifteen year period [2, 3, 4].

2. Stabilized lasers used as wavelength standards in absolute gravimeters and properties

With effect from October 1983, the 17th Conférence Générale des Poids et Mesures (CGPM) has adopted a new definition of the Metre based on a fixed value for the speed of light [5] and the Comité International des Poids et Mesures (CIPM) has adopted a recommendation as a "mise en pratique" of the definition [6].

Among the five recommended radiations contained in the mise en pratique, the best known and most used is the radiation of He-Ne at λ = 633 nm stabilized by saturated absorption of iodine. If all the characteristics for the realization of the laser described in the text are respected, the frequency of the radiation is realized with a relative estimated standard deviation of 3.4 parts in 10^{10} [6].

In the absolute gravimeters, a stabilized He-Ne à λ = 633 nm is used as the light source of an interferometer which is usually of Michelson type.

The use of an iodine stabilized He-Ne laser at λ = 633 nm is a delicate procedure and specialists in gravimetry often prefer to use, a simpler stabilized laser operating at the same wavelength.

The types of stabilized laser of possible use for this purpose are based on:

- Two orthogonally polarised modes (later called two modes lasers) [7]; (SP117 and SP117A from Spectra-Physics, RB1 from Newport Corporation);
- Lamb-dip [8]; (SP119 from Spectra-Physics);
- Zeeman effect [9]; (HP5500C from Hewlett Packard);
- Saturated absorption of iodine [10, 11, 12].

It is worth noting however that the three first types have a linear frequency drift due to leaks of the He-Ne gas mixture from the laser tubes. This relative frequency drift can reach one part in 10^8 per year for some lasers (SP119 Lamb dip stabilized laser), requiring frequency calibration two a three times a year.

A main limitation of the frequency reproducibility of the two modes laser is the quality of the optical isolation between its oscillating modes [7]. This quality is determined by the choice of the polarized beam splitter and by the adjustment which separates the two frequencies. On the RB1 lasers the two frequencies, called blue f and red f, are both available.

On the spectrum analyser where the beat frequencies were displayed, we always observed the presence of the two modes, sometimes with a ratio of only 40 dB. For the frequency measurement by beat, we are able only to measure the frequency of the selected mode, but in the gravimeter, the wavelength which is used is that of the total output light of the laser. A correction can be applied on the value of the wavelength if the ratio of the intensities of the two modes is known. But, this ratio can be changed, for example by a misalignment of the beam splitter as after a movement of the laser.

A study, made at the BIPM [13] showed that the value of the atmospheric pressure can influence the frequency of a laser. For example, with a two modes SP117 laser, the frequency variation can reach 2 or 3 parts in 10^8 for a 1500 m variation of altitude. We also have observed that the frequency of a SP117A laser can be changed of about 8 MHz (1.7 part of 10^8 in relative) as the laser is moved from a horizontal to a vertical position.

Some two modes lasers of such RB1 type showed a frequency difference of about 2 MHz between calibration in the laser laboratory and calibration in the gravimeter itself. This frequency shift is probably caused by the magnetic field around the gravimeter.

For the two modes stabilized lasers, some manufacturers give on indication of the expected frequency variation versus the temperature of the laboratory. As examples, the values 6 and 0.5 MHz/K respectively are given for the SP117 and SP117A lasers.

It is worth mentioning that these problems are not restricted to the iodine stabilized lasers.

In the tables 1 and 2, we have summarize all observations. We make the reservation, however, that our test depend on measurements made with just a few lasers and our results should not be generalized to describe a while type of laser.

Table 1 - **Stabilized laser properties**

		Two modes		Lamb dip	Zeeman	Iodine
	RB1	SP117	SP117A	SP119	HP	BIPM
Frequency drift (p_{He} and p_{Ne})	Yes	Yes	Yes	Yes (1×10^{-8}/y)	Yes	No
Noise due to modulation	No	No	No	Yes (10 MHzpp)	No	Yes (6 MHzpp)
Sensitivity to feedback light	Small	Small	Small	High	High	High
Sensitivity to atmospheric pressure		High 700 Hz/Pa	Medium 50 Hz/Pa	Medium		Very small 0.5 Hz/Pa
Frequency shift due to the change of laser position (vertical or horizontal)		Yes	Yes (some MHz measured)	No		No
Modes problems	Yes			No	No	No
Sensitivity to laboratory temperature		Yes (6 MHz/K)	Yes (0.5 MHz/K)	No		No
Sensitivity to magnetic field	Yes					
Power		1 mW	1 mW	100-200 µW	100 µW	100-200 µW

$$\Delta f = 4 \text{ MHz} \Rightarrow \frac{\Delta f}{f} = 1 \times 10^{-8}$$

Table 2 - **Relative frequency stability**

		1s	10s	100s	long term
Two modes	(SP117)	4×10^{-11}	3×10^{-10}	7×10^{-10}	$\pm 2 \times 10^{-8}$ in 3 months*
	(SP117A)	4×10^{-11}	4×10^{-11}	6×10^{-11}	$\pm 1 \times 10^{-8}$ in 3 months*
	RB1**	1.4×10^{-11}	1.4×10^{-11}	1.7×10^{-11}	
Lamb dip	(SP119)	6×10^{-10}	1.5×10^{-10}	2×10^{-10}	1×10^{-8} in 1 year
Zeeman	(HP)	2×10^{-11}	4×10^{-11}	2.5×10^{-10}	1×10^{-8} in 1 year
Iodine	(BIPM)	1×10^{-11}	2×10^{-12}	6×10^{-13}	$\pm 2 \times 10^{-11}$ for>15 years

* sometimes jumps of several 10^{-8}
** RB1 (n° 18, Finland)

3. Results of the frequency calibration of stabilized lasers used in the absolute gravimeters during the 3rd international comparison.

3.1 Participants and instruments concerned.

AUSTRIA

Institution: University of Vienna, Institute for Metrology and Geophysics, Hohe Warte 38, A-1190 Wien; telex: 13 18 37; fax: 222/369 12 33.

Instruments : absolute gravimeter, Jila-6; laser, RB1 N° 11.

CANADA

Institution: Geological Survey of Canada, 1 Observatory Crescent Ottawa Ontario, Canada K1A OY3; telex: 053 31 17 EMAR OTT.

Instruments : absolute gravimeter, Jila-2; laser, RB1 N° 14.

CHINA

Institution: National Institute of Metrology, Mechanical Division, Beijing, PRC.

Instruments : absolute gravimeter, constructed in PRC; laser, iodine stabilized laser built by the laboratory.

FINLAND

Institution: Finnish Geodetic Institute, Ilmalankatu 1A, SF-00240, Helsinki, fax: 358 0 414 946.

Instruments : absolute gravimeter, Jila; laser, RB1 N° 18.

GERMANY

Institution: Institute für Erdmessung, Universität Hannover, Nienburger Str. 6, D-3000, Hannover 1; telex: 92 38 68 UNIHN D, fax: (0511) 762 4006.

Instruments : absolute gravimeter, Jila; laser, RB1 N° 17.

ITALY

Institution: Istituto di Metrologia "G. Colonnetti", 10135 Torino, Strada Delle Casse 73; telex: 21 22 09 IMGC TO I, fax: (011) 34 67 61.

Instruments : absolute gravimeter constructed by Istituto "G. Colonnetti"; laser, iodine stabilized laser built by the laboratory.

JAPAN

Institution: National Astronomical Observatory, Mizusawa 2-12 Hosigaoka, Mizusawa, Iwate 023; telex 83 76 28; fax: 0197 23 51 56.

Instruments : absolute gravimeters, constructed in Japan; laser, SP117A N° 776.

USA

Institution: National Geodetic Survey, 11400 Rockville Pike, Rockville MD 20 852 fax: 301 468 57 14.

Instruments : absolute gravimeter, Jila; laser, RB1 N° 108.

USSR

Institution: Institute of Automatics and Electrometry, Siberian Branch of Academy of Sciences of the USSR, Novosibirsk 630090, USSR.

Instruments : Gabl USSR gravimeter, laser, iodine stabilized laser and a slave laser built by the laboratory.

BIPM

Institution: Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres CEDEX, telex: BIPM 201 067 F; fax: (33) 145 34 20 21.

Instruments : absolute gravimeter constructed by BIPM; laser, iodine stabilized laser built by the laboratory.

Among the ten laboratories from ten countries just two types of stabilized laser were used:

a) Two modes stabilized lasers; there were six such lasers, 5 lasers RB1 from Newport Corporation (Austria, Canada, Finland, Germany and USA) and 1 laser SP117A from Spectra-Physics (Japan).

b) Iodine stabilized lasers; there were four such lasers built by individual laboratories themselves (China, Italy, USSR and BIPM).

3.2 Results of the frequency calibration.

For the frequency calibration, a BIPM iodine stabilized laser was used as reference. This was brought alongside each absolute gravimeter in turn and the method of beat frequencies used to measure the frequency difference between the reference and the stabilized laser of each gravimeter.

Several times, some lasers have been removed from their gravimeter and their frequency have been determined in the laser laboratory against the frequency of the BIPM stationnary lasers. In table 1, we saw that some systematic frequency shifts of around 2 MHz were observed.

In table 3, are given all the results for the ten lasers; for the two modes lasers, the frequencies of both modes labelled blue f and red f are available: the corresponding values of the wavelength are also given. For the iodine stabilized lasers, we present only the frequency differences against the reference laser. The absolute values can be calculated using information given in [5].

The value of each calibration is expressed as the mean of 10 measurements on a 10 s sample time of the beat frequency, the reference laser being stabilized in turn on the four components d, e, f, g of the 11-5, R(127) line of $^{127}I_2$.

The estimated standard deviation for one measurement is in the range 5-100 kHz for the two modes lasers and the less than 5 kHz for the iodine lasers. Some lasers where also calibrated two or three times under the same experimental conditions during the four week period: among them the largest discrepancy was around 2 MHz.

Table 3 - **Results of the frequency calibration.**

Country	Laser Type	Date of measurements Localisation	red f/MHz	blue f/MHz	red λ/fm	blue λ/fm	Δf/kHz
Austria	2 modes RB1 n° 11	11-17-89 (lab.1) Pilar A2	473612291.1 473612291.1	473613077.3	632991296.1 632991296.1	632990245.3	
Canada	2 modes RB1 n° 14	11-24-89	473612295.6 473612295.6		632991290.1 632991290.1		
		11-27-89 (lasers lab.)		473613067.0 473613067.0		632990259.1 632990259.1	
		11-29-89 (lab.1) pilar A1	473612293.3	473613068.7	632991293.2	632990256.8	
China	Iodine	11-17-89 (lab.1) pilar A1				$f_{NIM} - f_{BIPM10}$	= -135
		12-04-89 (base) pilar A5				$f_{NIM} - f_{BIPM10}$	= -129

Table 3, continued

Finland	2 modes RB1 n° 18	11-15-89 (lasers lab.)	473611838.3	473612572.5	632991901.3	632990920.0
		11-17-89 (bas. lab.6) pilar A8	473611840.2	473612573.6	632991898.8	632990918.6
		12-04-89 (lab.1) pilar A1	473611840.5	473612570.7	632991898.4	632990922.4
Germany	2 modes RB1 n° 17	11-27-89	473611775.5	473612632.5	632991985.2	632990839.8
		11-28-89 (lasers lab.)	473611775.4	473612632.2	632991985.4	632990840.0
		11-30-89 (lab.6)	473611776.2	473612630.5	632991984.3	632990842.5
Italy	Iodine	11-15-89 (lasers lab.)				$f_{IMGC} - f_{BIPM2}$ = - 55 = - 21
Japan	2 modes SP117A n° 776	11-23-89 (lasers lab.)	473612516.3 473612515.1		632990995.1 632990996.7	
		11-29-89	473612507.7		632991006.6	
		11-30-89 (bas. lab.6) pilar A8	473612507.4		632991007.0	
		12-08-89 (lab. 1) pilar A2	473612505.8		632991009.1	
USA	2 modes RB1 n° 108	11-23-89	473612335.1		632991237.3	
		11-24-89	473612335.7		632991236.5	
		11-27-89 (lasers lab.)		473613038.4 473613038.4		632990297.3 632990297.3
		11-29-89 (lab. 1) pilar A2	473612337.2	473613035.5	632991234.5	632990301.2
USSR	Iodine + slave laser	12-01-89 (lab. 6) pilar A3	473612477.2		632991047.4	
BIPM	Iodine	09-15-89 (lasers lab.)				$f_{BIg} - f_{BIPM2}$ = 6.2
		12-08-89 (lab. 1) pilar A0				$f_{BIg} - f_{BIPM10}$ = 6.9
BIPM References	Iodine	11-14-89				$f_{BIPM4} - f_{BIPM10}$ = - 3.4

4. Conclusions and propositions.

One conclusion of this systematic frequency calibration of gravimeter lasers is that the method used to stabilize the frequency of some lasers cannot guarantee the accuracy to better than 1 or 2 parts in 10^8. This is not good enough if the full potential of the gravimeters is to be realized. We also showed that frequency calibration must be performed while a laser remains housed in its gravimeter.

Even, if the discrepancies of the absolute determinations of gravity in this 3rd international comparison, presented elsewhere in this issue, are smaller than those obtained in the 2nd, other sources of error must be found if the differences between these determinations that the frequency instabilities of the laser are to be explained.

To avoid doubts about the frequencies of the lasers involved it seems to us preferable to use iodine stabilized lasers. In this case, however, precautions must be taken in their utilisation, particularly against the return of light from the interferometer into the laser and against mechanical vibration.

To give weight to this proposition, a picture of a new small iodine stabilized laser prototype built at BIPM was presented during the conference. Its sizes have been chosen so that it was easily replace some of the two modes lasers actually in use.

The facilities offered by the BIPM in the performance of these frequency calibrations should be taken into account in arranging for future international comparisons of absolute gravimeters.

References.

[1] BOULANGER, Yu et al. Results of the second international comparison of absolute gravimeters, in Sèvres, 1975, Bulletin d'information du Bureau Gravimètrique International, 59, pp. 89-103, 1986 and IUGG Chronicle, 186, p 238, 1987.

[2] CHARTIER, J.-M., HELMCKE, J. and WALLARD, A.J. International intercomparison of the wavelength of iodine stabilized lasers, IEEE Trans. Instrum. Meas., IM-25, pp. 450-453, 1976.

[3] CHARTIER J.-M. Results of international comparisons using methane-stabilized He-Ne lasers at 3,39 µm and iodine-stabilized He-Ne at 633 nm, IEEE Trans. Instrum. Meas., IM-32, pp. 81-83, 1985.

[4] CHARTIER, J.-M., ROBERTSSON, L. and FREDIN-PICARD, S. Recent activities at BIPM in the field of stabilized lasers; Radiations recommended for the definition of the metre, Digest CPEM90, pp. 94-95, to be published in IEEE Trans. Instrum. Meas.

[5] Comptes Rendus 17ième CGPM, pp. 45-49, 1983.

[6] BIPM Proc. Verb. Com. Int. Poids et Mesures, 51, Recommandation 1 (CI-1983) 25-28; and Documents concerning the new definition of the metre. Metrologia 19, pp. 163-177, 1984.

[7] BALHORN, R., KUNZMANN, H. and LEBOWSKY, F. Frequency stabilisation of internal-mirror helium-neon Lasers, Appl. Opt., 11, p. 742, 1972.

[8] LAMB, W.E.JR. Theory of the Optical Maser, Phys. Rew., 134, pp. A1429-A1450, 1964.

[9] FERDINAND, P. LESNE, J.L., CAHEN, C. and BESSUS, B. Les avantages de l'emploi de lasers bifréquence en métrologie optique, published by the Direction des études et recherches EDF, Châtou, France.

[10] HANES, G.R., DAHLSTRON, C.E. Iodine hyperfine structure observed in saturated absorption at 633 nm, Appl. Phys. Lett., 14, pp. 362-364, 1969.

[11] WALLARD, A.J. Frequency stabilization of the helium-neon laser by saturated absorption in iodine vapour, J. Phys. E: Sci. Instrum., 5, pp. 927-930, 1972.

[12] CHARTIER, J.-M. Principes technologiques, PTB Bericht, Me 17, pp. 13-31, 1977.

[13] CHARTIER, J.-M. Etude de l'influence de la valeur de la pression atmosphérique sur la fréquence de lasers asservis. Rapport BIPM-87/2, 1987.

ABSOLUTE-GRAVITY MEASUREMENTS IN MADRID

J. Mäkinen

Geodetic Institute
Ilmalankatu 1A, SF-00240 Helsinki, Finland

R. Vieira, A.G. Camacho, M.J. Sevilla

Instituto de Astronomía y Geodesia (C.S.I.C.-U.C.M.)
Facultad de Ciencias Matemáticas, Universidad Complutense
28040 Madrid, Spain

Abstract. In May 1989, absolute gravity was measured at two sites in Madrid with the JILAG-5 gravimeter. We describe the measurements and discuss the effect of floor instability on gravimeter performance.

1. Introduction

The work described here is a cooperation between the Finnish Geodetic Institute and the Instituto de Astronomía y Geodesia (Consejo Superior de Investigaciones Científicas - Universidad Complutense de Madrid), I.A.G. for shortness. Absolute gravity was measured at two stations. The Madrid I.A.G. station was a typical good station with a stable floor and low microseismic noise. On the Valle de los Caídos station the seismic noise was low as well, but the unstable floor caused difficulties. However, this provided an opportunity to learn about the effects of floor instability on the observations.

2. Instruments and methods

The JILAG-5 gravimeter of the Finnish Geodetic Institute belongs to the series of 6 instruments built by J.E. Faller and his associates at the Joint Institute for Laboratory Astrophysics (JILA), National Institute of Standards and Technology and University of Colorado, Boulder (USA). A detailed description of the instrument is given by Faller et al. (1983), Niebauer et al. (1986), Zumberge et al. (1982) and Niebauer (1987).

The gravimeter measures the acceleration of an object which falls freely in vacuum over a distance of 0.2 m. The falling object is a corner cube retroreflector, which terminates one arm of a two-arm Michelson interferometer. The other arm is terminated by a reference retroreflector suspended by a long-period isolation device (the super spring). A frequency stabilized He-Ne laser serves as a light source and length standard, and a rubidium oscillator provides the standard for the timing of the interference fringes. A specialty of the instrument is the drag-free inner chamber, which falls (servo-driven) together with the falling object.

Acceleration is determined by fitting a second-degree polynomial to the (time, distance) pairs. We use 150 pairs taken at intervals of 4000 fringes (2000 wavelengths; 1.26 mm) and start sampling 15 ms after the triggering of the fall. The fitting is done online by the controlling microcomputer. On stable piers, root-mean-square residuals from the fit are in our instrument typically 2 nm, which corresponds to 15 µgal precision for the fitted acceleration. The drop-to-drop scatter then depends mainly on the level of microseismic noise and varies from 15 µgal (quiet conditions) to 100 µgal (very noisy sites). We use sets of 50 or 100 drops. The drops are taken at about 12 s intervals.

The local ties and the vertical gradients were measured with LaCoste & Romberg model G gravimeters using a feedback system (Van Ruymbeke 1985). In the gradient measurements the gravimeter was mounted on a special tripod constructed by J.L. Valbuena.

3. The stations

The Madrid station is situated in the basement of the multi-storey university building housing the I.A.G. (latitude = 40°26′52" N, longitude = 3°43′36" W, elevation = 646.2 m). The station is on a solid concrete floor, not on a pier. The observations were made during a weekend, when microseismic noise was low.

The Valle de los Caídos station is in the mountains near Madrid, close to the national monument of the same name (latitude = 40°38′57" N, longitude = 4°08′36" W, elevation = 1212 m). The station is on the ground floor of a villa standing on bedrock. At the time of the measurements there was no pier. At first sight the stone-tiled floor appeared very stable, but it turned out to be more or less "hanging" in the air. This is discussed later.

4. Corrections to the absolute observations

In post-processing, the tidal corrections made by the on-line microcomputer program were replaced by the Cartwright-Tayler-Edden expansion (505 constituents), where observed gravimetric factors and phaselags were inserted for the wave groups O1, P1, K1, N2, M2, S2 and M3. For details see Vieira et al. (1986) and Vieira and Camacho (1988). The Valle de los Caídos station is about 1 km away from a station of the Spanish tidal network and the Madrid station coincides with one. For other corrections, the recommendations for the IAGBN (Boedecker 1988) were followed, checking the ambiguity in sign for the polar motion correction given there.

The observations were independently processed by three authors. The differences in the results were less than half a microgal. Because the correction methods were fixed, the only real difference in the processing was the search for outliers. J. Mäkinen used routinely trimmed means (4 or 5 percent trimming) with no search for outliers, R. Vieira used the tau-test by Pope (1976) and M.J. Sevilla a simulated network concept (Sevilla et al., 1990). Space does not allow details here. No drops were flagged by

Table 1. Sample output from the post-processing of the absolute measurements at the Madrid I.A.G. station. Standard errors refer to statistical scatter only. The observations were made from Sunday night to Monday morning, note the increasing drop-to-drop scatter (column 9) when the city awakens. The laser of the gravimeter can be operated at two frequencies about 735 MHz apart; "red" and "blue" laser colour refer to the lower and higher frequency, respectively. For an explanation why the results differ, see Liard and Courtier (1990).

```
Station:  MADRID I.A.G.

Latitude = 40.4478  east longitude = -3.7267
Elevation =  646.2 m,  standard pressure =  938.0 hPa

Vertical gravity gradient = -292.0 uGal/m
Effective height =  819 mm

 100 drops per set
   5 drops are trimmed from each end of the ordered sample
     influence curve estimate for S.D.

Tidal recomputation using synthetized tide
MOSO =   7.9 uGal

Legend (units are microgal):

 1...6  mean time of set (UT)
 7      atmospheric pressure (hPa)
 8      laser colour, 1 = red, 0 = blue
 9      S.D. of single drop
10      mean tidal correction
11      mean g, contains (10)
12      correction for polar motion
13      correction for the gravity effect of the atmosphere,  -0.30 uGal/hPa
14      sum of columns 11 to 13

  1   2  3  4  5  6    7   8    9      10          11      12    13          14

1989  5  8  0 18 22  939.8 0   17.1  -51.9   979963889.1  -3.0   0.6   979963886.6
1989  5  8  0 44 20  939.6 1   15.9  -49.2   979963894.3  -3.0   0.5   979963891.8
1989  5  8  1 10 27  939.4 0   19.7  -47.8   979963892.1  -3.0   0.4   979963889.6
1989  5  8  1 40 23  939.2 1   16.8  -48.3   979963892.6  -3.0   0.3   979963890.0
1989  5  8  2  9 37  939.0 0   16.6  -50.7   979963889.7  -3.0   0.3   979963887.0
1989  5  8  2 39 40  939.0 1   16.0  -55.2   979963888.6  -3.0   0.3   979963885.9
1989  5  8  3 10 28  939.0 0   17.5  -61.4   979963889.6  -3.0   0.3   979963887.0
1989  5  8  3 39 53  939.0 1   18.3  -68.4   979963892.9  -3.0   0.3   979963890.2
1989  5  8  4  9 42  939.1 0   15.9  -75.8   979963886.7  -3.0   0.3   979963884.1
1989  5  8  4 39 56  939.3 1   15.6  -83.0   979963892.3  -3.0   0.4   979963889.7
1989  5  8  5  9 38  939.6 0   17.5  -88.9   979963886.0  -3.0   0.5   979963883.5
1989  5  8  5 40  3  939.8 1   18.0  -93.0   979963892.2  -3.0   0.6   979963889.8
1989  5  8  6 10 12  940.1 0   21.4  -94.3   979963888.6  -3.0   0.6   979963886.2
1989  5  8  6 39 58  940.3 1   24.5  -92.5   979963891.3  -3.0   0.7   979963889.0
1989  5  8  7 10  4  940.6 0   28.3  -87.0   979963883.6  -3.0   0.8   979963881.3

   7 red  sets, mean = 979963889.5 stdev =     1.8
   8 blue sets, mean = 979963885.7 stdev =     2.6

                 mean = 979963887.6 stdev =     2.2, stderr =     0.6  at eff. height  819 mm
                            239.1 reduction to standard level         at                0 mm
            final g = 979964126.7                                     at                0 mm
```

the tau-test on the 1 percent level (set-by-set).

5. Results and discussion

The results at the Madrid I.A.G. station are summarized in table 1, a sample of the processing by J. Mäkinen.

Starting observations on the Valle de los Caídos station, we found that the rms residuals in the (time,distance) fit for each drop were 15...20 nm or almost 10 times the usual size. The dominant frequency in the residuals was about 70 Hz (Figure 1,a). An audible sound from the floor accompanied the triggering of each drop. Obviously, floor reaction to the drop was the source of the problem.

This recoil reaction is discussed in detail by Niebauer (1987). The release of the object and of the drag-free inner chamber creates an unbalance force in the beginning of the drop. The movements due to this force affect the length measurement in two ways.

First, the dropping chamber starts vibrating vertically relative to the interferometer. Since the dropping chamber is evacuated and the rest of the optical path is not, the optical path length to the dropping object changes by about 0.3 nm when the chamber around it moves 1µm. We observed the vertical movement of the dropping chamber using a photodetector device. The amplitude was maximally 15 µm. Using the refraction index of air at 1200 m elevation (0.00023) this gives an optical path length variation of 3.5 nm (Figure 1: e,f), much too little to explain the up to 40 nm drop residuals. We also fitted a second degree polynomial to the observed vertical movement (using actual fringe times) and found that the correction to g was only +0.4 µgal.

From earlier experience we know that on stable piers, the vertical movements of the dropping chamber closely reproduce the systematic

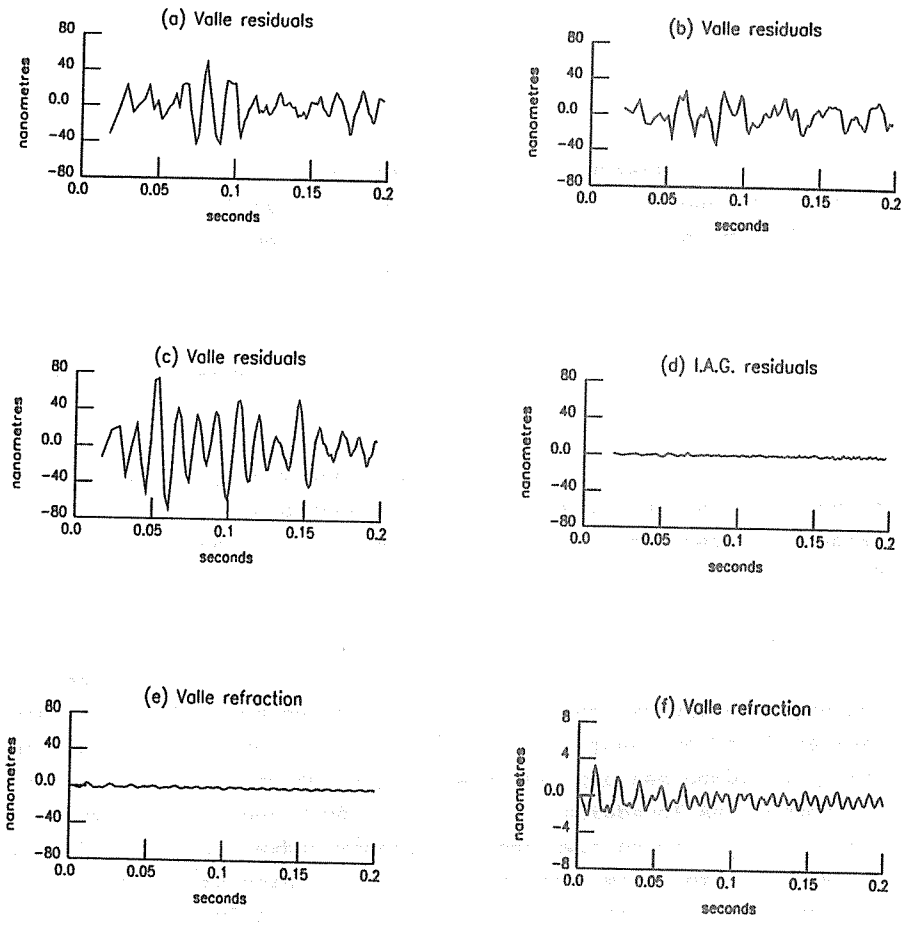


Figure 1. Typical residuals from the least squares fit to (time,distance) pairs in the 3 positions at the Valle de los Caídos station (a,b,c), with unstable floor, and, for comparison, at the Madrid I.A.G. station (d) with stable floor. To emphasize systematic features, residuals shown have been averaged over 50 drops. (a) is 0.6 m from the center of the room, (b) and (c) are in the center of the room with different orientations. Part (e) then shows the error in distance measurement to the falling object, due to the vertical movement of the dropping chamber relative to the interferometer, measured in position (a). The vertical movement observed has just been multiplied by the index of refraction (0.00023). Obviously, the movement does not explain the residuals in (a). Part (f) is the same as (e) but ten times enlarged.

features in the drop residuals. It appears then that the second mechanism described by Niebauer (1987) was the culprit: The recoil may tilt the floor, and the interferometer along with it. The two vertical arms of the interferometer are not on the same optical axis (in no present-day absolute gravimeter they are), but at a horizontal distance of 0.2 m. A tilt of ± 0.2 µrad in this direction would produce the observed 40 nm residuals. We did not have equipment to observe tilts this small at the 70 Hz frequency required. Using the spirit levels of the gravimeter we found that the first author (80 kg) standing close to the instrument tilted the floor by about 8 seconds of arc or 40 µrad. According to Niebauer (1987) the recoil force is about 5 N, which translates to 0.2 µrad, probably just a fortuitous agreement.

The initial position of the gravimeter in the 2.8 by 3.2 m room was (0.4 m, 0.5 m) off-center, the tilt sensitive direction of the interferometer longitudinally in the room. We then attempted to minimize the tilt effect by moving the gravimeter into the middle of the room. This reduced the residuals slightly (Figure 1,b). The next step was to rotate the gravimeter 90 degrees on-the-spot, which brought the biggest residuals of all (Figure 1,c).

The g results in the different positions are collected in Table 2.

Table 2. Results of absolute gravity measurements at the Valle de los Caídos station in 3 different positions. Labels (a),(b), and (c) correspond to Figure 1. (a) is at 0.6 m distance from positions (b) and (c), which only differ in orientation. Gravity has been reduced from (a) to (b),(c) using ties with feedback LCR gravimeters. Standard errors given include the statistical scatter only.

position	number of sets	number of drops	S.D. of single set mean	mean g reduced to (b,c)	S.E. of mean g
(a)	15	750	13.4	979884941	3.5
(b)	17	850	5.4	979884928	1.3
(c)	22	1100	10.2	979884869	2.2

Since the tilt effect is systematic in a given setup, the scatter within setups is small compared with the differences between them. The maximum difference is 72 µgal. Normally, measurements with residuals this big (Figure 1) would be discarded. But it appears that with ten times smaller residuals, considered acceptable, we still might find tilt effects of 7 µgal.

Klopping et al. (in press) have presented a method of mathematically filtering the observed (time, distance) data of a drop to remove any sinusoidal noise signals which might bias the result for g. Initial experiments with our data using their computer program were encouraging, the 72 µgal discrepancy was reduced to 34 µgal. The problem is that we stored too few complete (time, distance) data sets during the observations. We postpone more detailed reporting until we have gained more experience with the method.

The Valle de los Caídos station has recently undergone reconstruction: the floor has been replaced by a double pier standing on bedrock. Before the work gravity was referred by relative measurements to excenters outside the building. We now plan to repeat the absolute measurement.

6. Acknowledgements

The measurements were financed by the Consejo Superior de Investigaciones Científicas. The first author learned about the recoil effect during a stay at JILA in 1989. The computer program for the filtering of the (time,distance) sets was put to our disposal by G. Peter (U.S. National Geodetic Survey).

7. References

Boedecker, G., International Absolute Gravity Basestation Network (IAGBN). Absolute gravity observations data processing standards & station documentation. BGI Bull. Inf. 63, 51-57, 1988.

Faller, J.E., Y.G. Guo, J. Gschwind, T.M. Niebauer, R.L. Rinker, and J. Xue, The JILA portable absolute gravity apparatus. BGI Bull. Inf. 53, 87-97, 1983.

Klopping, F.J., G. Peter, D.S. Robinson, K.A. Berstis, R.E. Moose and W.E. Carter, Improvements in absolute gravity observations. J. Geophys. Res., in press.

Liard, J. and N. Courtier, Canada's contribution to the 1989 International Comparison of Absolute Gravimeters at the BIPM, this meeting, 1990.

Niebauer, T.M., New absolute gravity instruments for physics and geophysics. Ph.D. thesis, 155 pp. University of Colorado, Boulder, Colorado, 1987.

Niebauer, T.M., J.K. Hoskins, and J.E. Faller, Absolute gravity: a reconnaissance tool for studying vertical crustal motion. J. Geophys. Res.,91, 9145-9149, 1986.

Pope, A.J., The statistics of residuals and the rejection of outliers. NOAA Tech. Rep. NOS 65 NGS 1, 133 pp., 1976.

Sevilla, M.J., A.J. Gil, and P. Romero, Adjustment of the first order gravity net in the Iberian peninsula. BGI Bull. Inf. 66, 21-54, 1990.

Van Ruymbeke, M., Transformation of nine LaCoste-Romberg gravity meters in feedback systems. Bull. Inf. Marées terrestres 93, 6202-6228, 1985.

Vieira, R., J.M. Torroja and C. Toro, A general discussion about the normalization of gravimeters in the Iberian gravity tide profile. Proc. 10th Int. Symp. Earth Tides, 165-175, Madrid 1986.

Vieira, R. and A.G. Camacho, Corrección de las medidas gravimétricas por efecto de marea obtenida a partir de las observaciones efectuadas en la red Ibérica de mareas gravimétricas. Revista de Geofísica 44, 119-128, 1988.

Zumberge, M.A., R.L. Rinker, and J.E. Faller, A portable apparatus for absolute measurements of the Earth's gravity. Metrologia 18, 145-152, 1982.

ABSOLUTE GRAVIMETRY AND GRAVITY GRADIENTS

by A.V.Kopaev*, M.B.Shteyman+, I.A.Leontyev+,
V.K.Milukov* and V.D.Yushkin*

* Sternberg State Astronomical Institute
of Moscow State University,
Division of Gravitational Measurements
13 Universitetsky prosp.
V-234 Moscow 119899 USSR

+ All-Union Research Institute of Natural Gases

Abstract

The strict mathematical approach to the space reduction problem in gravimetry permits to solve it completely, that is confirmed by our experimental data. Repeated measurements of gravity gradients inside fundamental gravimetric laboratories, especially with help of automatized gradiometers, may contribute to the solving of geodynamical problems.

Introduction

The problem of the space reduction of precise gravity measurements results is now very actual in connection with increasing accuracy of absolute gravimeters and occuring possibility to investigate geodynamical phenomena. Existed methods of solving this problem have considerably disadvantages - 1)it divide reduction process in vertical transfer of gravity value and its horizontal reduction and 2) don't take into account for the harmonic properties of the local gravitational field. Both facts may lead to considerable difficulties and errors.

1. About the possible approach to the space reductions problem

From strict mathematical point of view the space reduction means the interpolation of harmonic function - of gravity. Hence for proper solution of reduction problem inside of certain space volume above the pillar, where ballistic and relative gravimeters may be placed, it is necessary to have some kind of model of local gravity field inside of this space volume. Then we will have the possibility to calculate gravity difference between any given points in choosen space volume and also to calculate gravity gradients. It is naturally to use some set of harmonic functions for approximation. From comparative analysis of observed gravity distributions above different pillars and theoretical distributions like shown on fig. 1, calculated for model of pillar in Ledovo gravimetric laboratory we have made a conclusion that main non-uniformities of local gravity field in laboratories are caused by pillars, walls and other nearest objects that have the simple geometrical parallelepipedal form. Residual fields, obtained after subtraction of theoretical fields from observed ones, reflect the attraction of relief and underground density anomalies and are quite uniform. That is why we decided to use for approximation of most non-uniform part of gravity field the functions describing the gravitational effect from single parallelepipedals (see for example fig. 2) representing pillars and walls with roughly known densities. For approximation of uniform 'regional' residual it is naturally to use harmonic polynomials, which are the analogues of spherical harmonic functions in Cartesian coordinate system. Thus the unknowns vector consists of single parallelepipedal densities and polynomial coefficients.

The regressional approach to this problem permits to minimize the amount of observation points with help of methods of optimal planning. This minimal amount (as a rule from 20 to 50 points, depending on the situation) must be located as far as possible uniformly inside of choosen space volume.

We have carried out a number of space gravimetric surveys in main fundamental gravimetric laboratories of USSR. As an example we consider here the results of investigations in Ledovo gravimetric laboratory of the Institute of Physics of the Earth of USSR where the basestation N 5035 of IGSN-71 is located. The sketch of pillars and observation points location inside the laboratory room is shown on the fig. 3. The main pillar is fully deepened into the ground.

We have observed the gravity differences between the mark located at the center of pillar and specially choosen points located along the vertical lines going through the mark and four additional point around mark (see fig. 3) with height interval 40 cm. (The heights of observation points above pillar surface were 10 cm, 50 cm, 90 cm, 130 cm). Thus we had the space structure from 20 observation points. The observations were carried out with well-investigated termostatized Sodin-gravimeters of GT-model. Each difference was

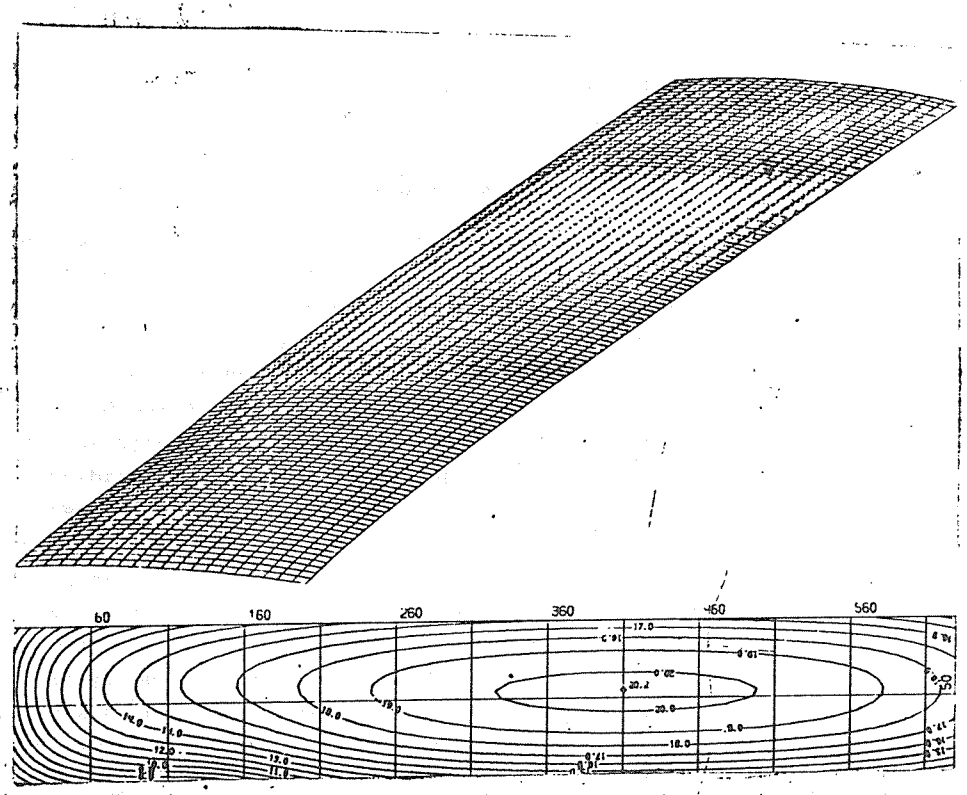


Fig. 1. Theoretically calculated distribution of gravity at the height 10 cm above the model of the main pillar of Ledovo gravimetric laboratory. The surrounding pillars and walls are also taken into acccount. Contour interval 1 mcGal.

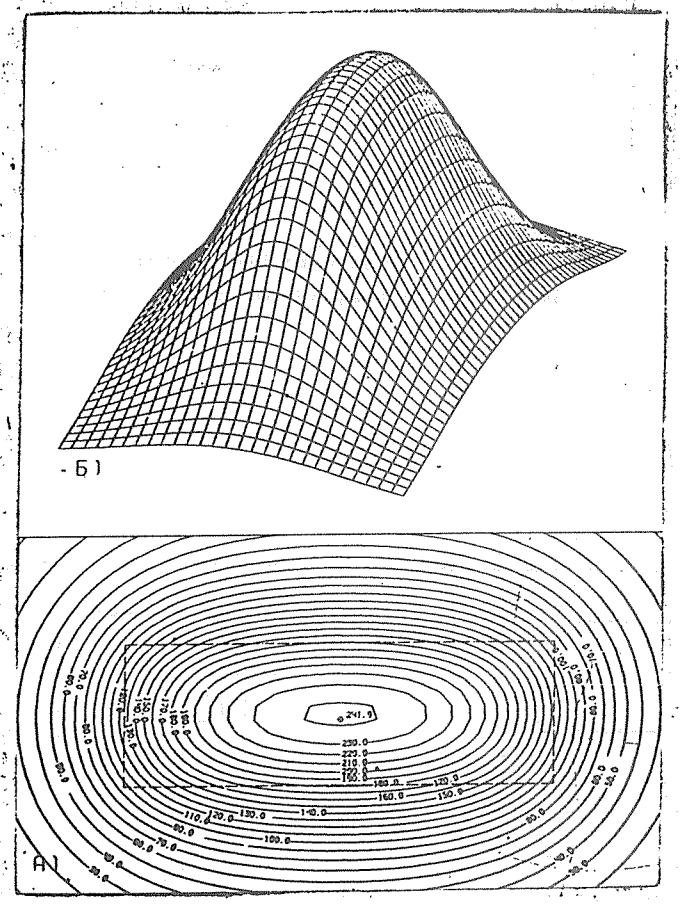


Fig. 2. Theoretically calculated distribution of vertical gravity gradient at the height 100 cm above the single isolated pillar like A_3 pillar in Sevres. Contour interval 10 E.U.

measured independently 20-25 times so that resulting accuracy of gravity differences was smaller than 2 mcGal. For approximation of data we have developed special program package for personal computer. The algorithms are based on the least-squares method. The choosen functional basis corresponds very well the physical nature of problem. As a result the system of normal eqations is quite correct. Our programs permit to make various maps of distribution of gravity and its vertical gradient in vertical (see fig. 4) and horizontal (see fig. 5) sections. This maps show that the gravity field even above fully deepened pillars may be very non-uniform and don't become more quiet with increasing of height above the pillar's surface. With help of special program it is very easy to determine the value of gravity difference between two given points and to evaluate the standard deviation according the least-squares statistics. For case under consideration the precision of gravity difference determination is about 2 mcGal.

It is obvious that such an approach gives a complete and optimal solution of reducing problem and permits to combine gravimetric data with gradiometric ones. It is worthwhile to have such model of local field at least for the main fundamental gravity basestations. We have made such models, for example, for all fundamental gravity basestations of USSR. It is of interest to note that we use for description of local gravity field of laboratories mathematical considerations similar that being employed for the representation of the gravity field of the planets. We believe also that such models may be used for preliminary rough calibration of the gradiometers. The horizontal gravity gradient for example changes along the Ledovo's pillar from -30 to 50 E.U. (see fig. 6) and may be calculated with an precision better than 1 E.U. if we add in the experimental data set the readings of our torsion-balance gradiometer (see below).

2. Investigation of vertical gravity gradient and its time variations

The isolated gravity surveys along the vertical lines may be used for the detailed investigation of the vertical gravity gradient and its time variations /1/.

We consider here the results of measurements of the small vertical gravity differences according the techniques described above (the independent repeated measurements relatively to single basepoint located on the pillar's surface) made at the three points in Ledovo laboratory

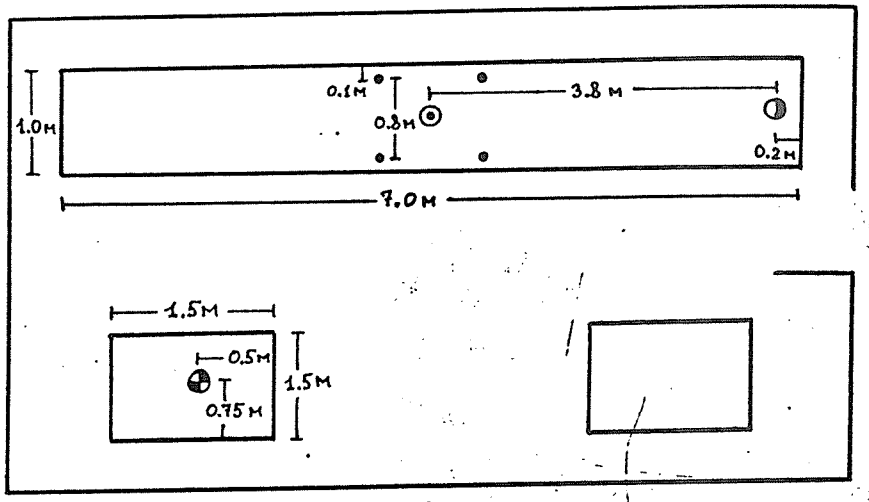


Fig. 3. Sketch of location of pillars and observation points inside of the Ledovo laboratory.

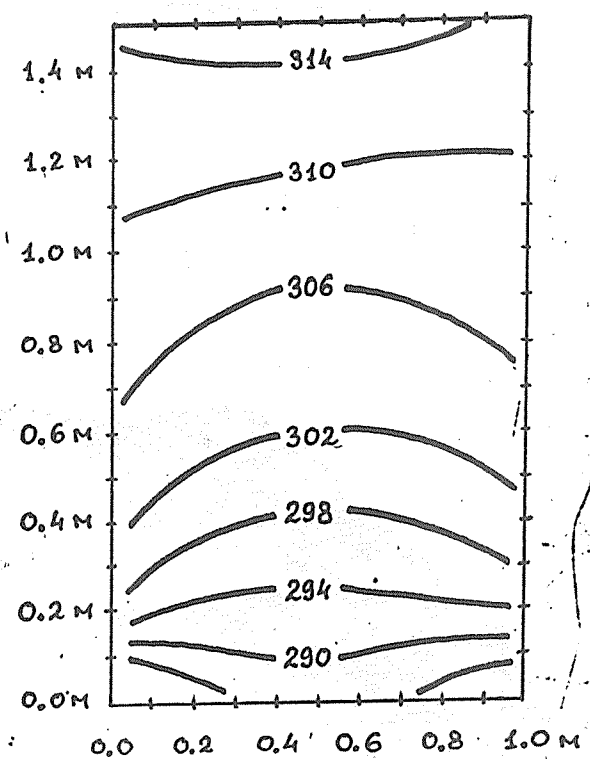


Fig. 4. Vertical section of the vertical gravity gradient field above the main Ledovo pillar perpendicularly to the pillar's axes (see fig. 3) obtained on the base of transformation of the set of relative gravity measurements.

Contour interval 4 mcGal/m.

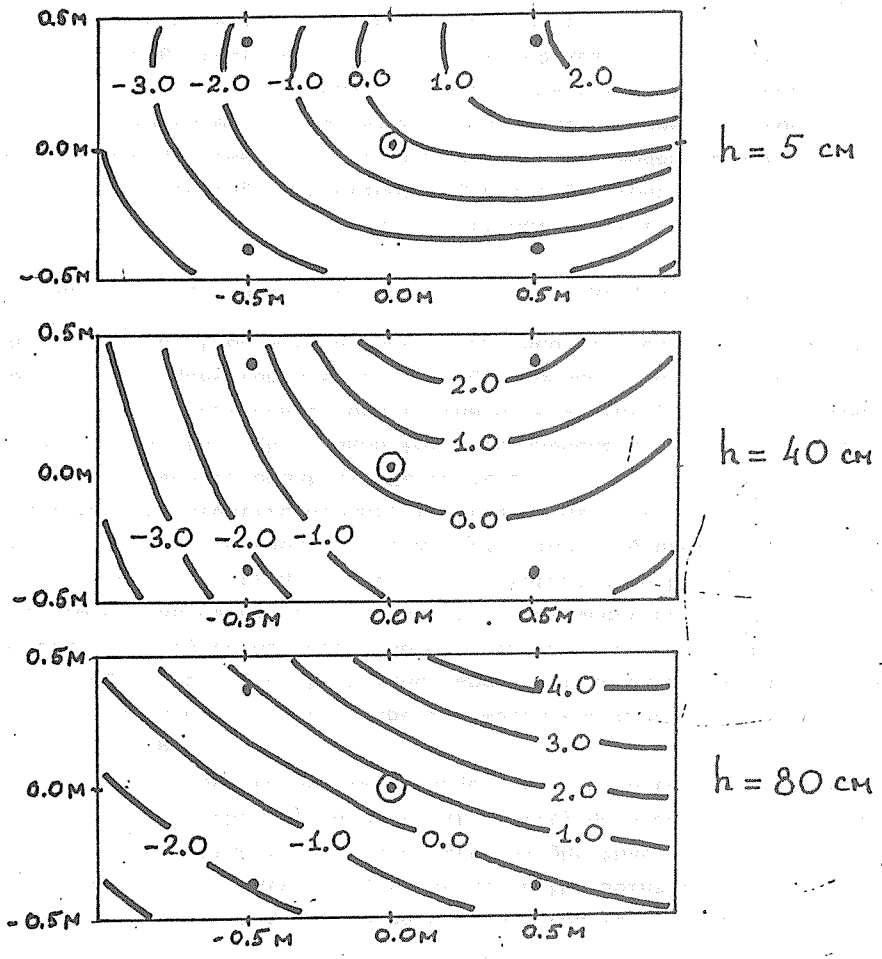


Fig. 5. Set of horizontal sections of the gravity field at different height levels above the main Ledovo pillar obtained on the base of approximation and interpolation of the set of relative gravity measurements.

Contour interval 1 mcGal.

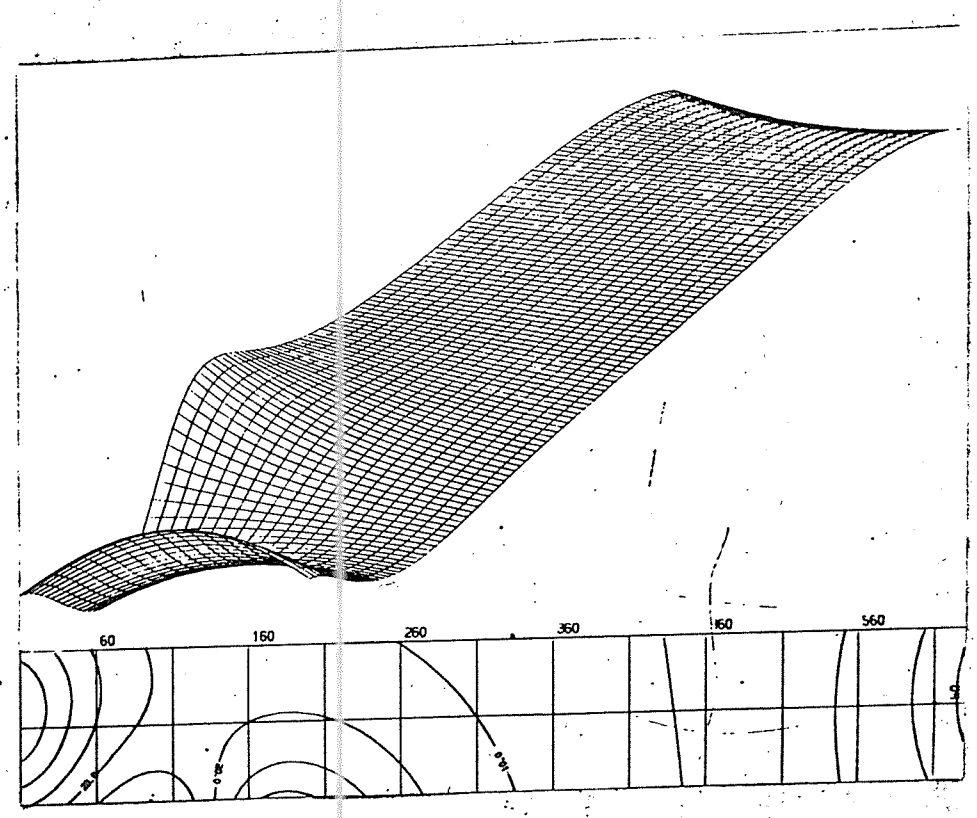


Fig. 6. Theoretically calculated distribution of the horizontal gravity gradient above the model of the main Ledovo pillar. Contour interval 10 E.U.

(see fig. 3). One point is located at the centre of the considered space volume on the main pillar's surface, the second one - at the edge of this pillar and the third one - at the centre of the other nearly located pillar. The observed gravity differences were approximated with the second degree polynomial, resulted dependences are shown on fig. 7.

The most interesting results are the following: 1) above the point located at the centre of the main pillar the vertical gravity gradient increases with height but above the point located at the edge of this pillar it decreases with height that is more naturally, 2) the value of the second vertical gravity gradient above the second pillar is at least three times larger that above the point at the edge of the main pillar.

We have carried out also special measurements of gravity gradients according to described techniques above all three points during the daytime and nighttime (with the time interval about 12 h). This experiment was repeated 1 month later. The short-period variations of the vertical gravity gradient were registrated in both cases at all points and are about 2 - 3 mcGal/m. The long period variation is statistically significant only for the point at the center of the main pillar and is about 4 mcGal/m (see fig. 8).

We believe that the reason for this phenomena may be in variations of hidrogeological conditions in the near vicinity of observation points. This question must be very good understood in order to make the space reduction with an precision about 1 mcGal really possible.

3. About the possibility to observe horizontal gradients variations

To our opinion, in this context it may be of interest to make the permanent recording of horizontal gravity gradients variations inside of absolute gravimetric laboratories. We have modernized for this aim early manufactured in USSR simple field quickly operated torsion balance gradiometer. We have developed the original 4-channel optical system of registration on the base of CCD-scales and Spectrum-computer. We have achieved in stationary conditions the accuracy about 0.1 E.U. in 10 min. of observations and have carried out calibration and detailed investigations of sensitive systems dynamical properties. After the complete analysis of data we plan to begin the next step of our work - the construction of new multi-aimed device with the help of our chinese friends. It will be used both for stationary observations with 0.1 E.U. precision and for field

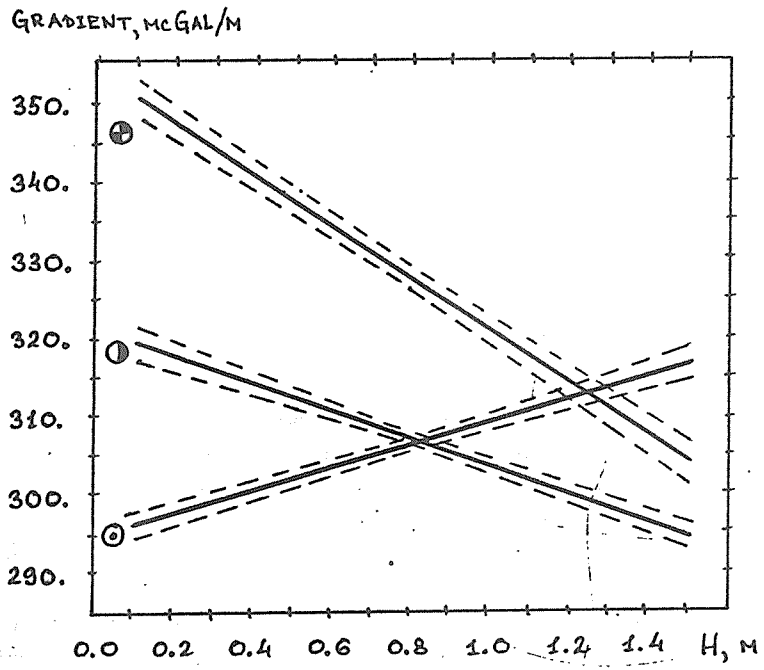


Fig. 7. Smoothed simplificated linear dependence of the vertical gravity gradient on the height above three points inside of the Ledovo laboratory (see fig. 3). Dashed lines show the accuracy for the 95 % confidence level according to the least-squares statistics.

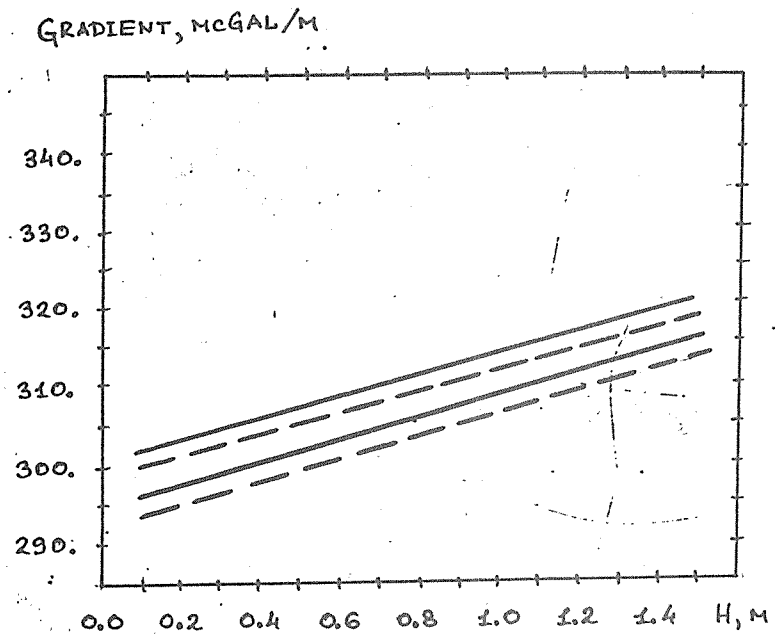


Fig. 8. Short- and long-period variations of the vertical gravity gradient above the mark 5035 of the IGSN71 located on the center of the main Ledovo pillar. Dashed lines represent night values, solid ones - day values, lower pair of graphs was obtained one month later than upper one.

measurements with accuracy about 1 E.U. that may be valuable for engineering geophisics and archeology. It may be used also for investigation of the local gravity field of the gravimetric laboratories (see above). It may be also of interest to make correlational analysis of gravity gradient variations records and variations of gravity observed with help of absolute gravimeters. Such gradiometers may be relatively cheap and simple in construction and operation.

Conclusion

The described model approach may contribute to the solution of the problem of the space reduction and make it more clear.

The observations of various gravity gradients may be useful for more exact interpretation of repeated absolute gravity measurements.

References:

1. Shteyman M.B., Kopayev A.V.,Leontyev I.A. On the determination of the height correction in the measured absolute gravity value.//BGI, Bull.d'Inform.-Juin 1987.-No. 60.-P. 97-106.

FLOOR-GRAVIMETER SYSTEM RESPONSE WITH JILAG-4

F. J. Klopping and G. Peter
National Geodetic Survey, Charting and Geodetic Services,
NOS, NOAA, Rockville, MD 20852

Abstract: Floor-gravimeter system response affecting free-fall absolute gravimeters, such as the types developed at the Joint Institute for Laboratory Astrophysics (JILA), reduces the ability of these devices for making high-precision measurements. Quantification and removal of the floor-gravimeter system response components from each individual drop accurately corrects for this effect. Based on over seventy site occupations, it was found that at sites, which are characterized by thick floors or floors connected to bedrock, the majority of the floor-gravimeter system response errors were under 5 μGal. However, it was also seen in one case, that observed gravity from two consecutive setups at a given site can differ by close to 40 μGals due to this effect. The magnitude of the errors and their successful reduction using the corrections developed by *Klopping et al.* (1990) is discussed and demonstrated on JILAG-4 results.

Floor rebound or floor recoil has been described as one of the potentially troublesome systematic errors affecting the JILA-type absolute gravimeters (*Niebauer,* 1987). It causes systematic variations of the optical path length in one of the arms of the interferometer due to vibrations of the interferometer and the dropping chamber. In addition to the floor rebound characteristics, the instrument setup (such as dropping chamber tripod rigidity, tripod-floor coupling, and vibration dampening techniques employed) can also significantly influence the amplitude and frequency of these vibrations and the resulting systematic error. Because of this additional role of the instrument, the use of the term "floor-gravimeter system response" is preferred in discussing this phenomenon.

The position errors of the falling corner cube retroreflector due to systematic vibrations caused by floor-gravimeter system response appear as the sum of decaying sinusoids in the least squares residuals (Figure 1). An introduction dealing with the potential magnitude of this problem, and with a method that allows for its correction was given in *Peter et al.* (1990); detailed explanation of the mathematical filtering method, which quantifies and removes these sinusoids (including tests of the method), was given in *Klopping et al.* (1990).

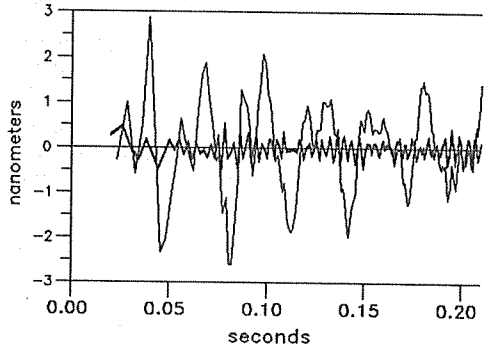


Figure 1. Systematic floor-gravimeter response signal in the cumulative least squares residuals of 250 drops before (thin line) and after (thick line) removal of the dominant sinusoids.

The potential problem that floor-gravimeter system response may cause and the effectiveness of the filtering method was highlighted in a recent data set obtained at an absolute gravity station in Bergen Park, Co, U.S.A.. Shortly after the beginning of the measurements it was noted that the observed absolute gravity values were close to 30 μGals higher than the previous value obtained at this site. Because this difference was larger than that expected due to environmental effects, and because another site nearby was occupied just a few days earlier with close agreement with the previous gravity value, the performance of the instrument became suspect. The measurements were stopped after the 12th 250-drop set, and following a series of checks, realignments, and tripod adjustments, the measurements were restarted. At this time the drop set mean gravity values were about 10 μGal lower than the expected value, which was within acceptable limits, considering the size of the usual environmental corrections that were to be added.

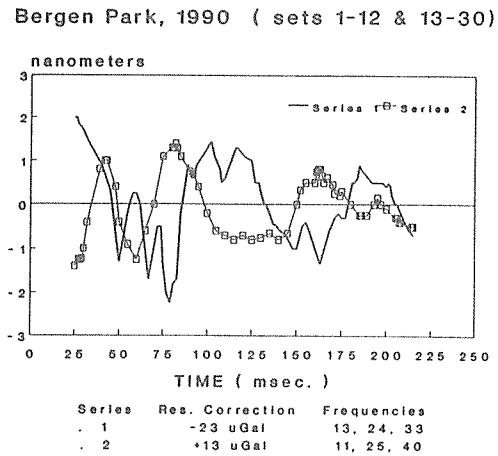


Figure 2. Systematic floor-gravimeter system response signals in the least squares residuals before and after instrument adjustment.

Figure 2 shows the floor-gravimeter system response signals in the least squares residuals before and after the adjustments. These responses are considerably different from those obtained customarily before 1990 (Figure 1), because beginning this year vibration dampening pads are used under the feet of the tripod and the interferometer. "Series 1" in Figure 2 refers to the averaged floor-gravimeter system response for the first 12 drop sets; "Series 2" is the same for drop sets 13 to 30. The mean dominant frequencies and mean corrections for the two setups are indicated.

Figure 3 shows the distribution of the drop set means for the two halves of the measurements without and with the correction of these data for floor-gravimeter system response. As shown, the 36 μGal offset in the original distribution has been eliminated by application of the filtering process (*Klopping et al.,* 1990).

These results imply that gravity values obtained with two absolute gravity instruments with different floor-gravimeter system response characteristics could disagree significantly when occupying the same site. While large amplitude and low frequency oscillations in the least squares residuals could alert one to a serious potential problem, the magnitude and sign of the error cannot be obtained without the detailed analysis and removal of the disturbing signals. The problem in Bergen Park was noted by the observers only because the previous absolute gravity value was known at the site, and because the observed gravity difference between this and the previous occupations was larger than what could be expected due to the changes in the environmental conditions at this site.

Without the ability to quantify the gravity error due to floor-gravimeter system response, disagreements with previous gravity values are often blamed on instrument biases and changed environmental conditions. This is particularly common when station reoccupations are years or decades apart. The results above suggest the need to reexamine these disagreements and, where possible, to add corrections for floor-gravimeter system response.
Computations using synthetic gravity data indicate that 1 nm (nanometer) amplitude sine waves simulating floor-gravimeter system response could cause a maximum error between 40 μGal and

50 μGal between 5 Hz and 10 Hz (*Klopping et al.*, 1990; *Peter et al.*, 1990). In real data thus far only a few occupations showed dominant system response frequencies in the vicinity of 10 Hz. The amplitude and phase relationships were such in these cases that the errors (or corrections) were between 8 μGal and 23 μGal, much lower than the potential maximum. At the majority of the sites occupied thus far the lowest dominant frequency was above 20 Hz, and even with a common amplitude of 3 nm, the corrections rarely reached 10 μGal.

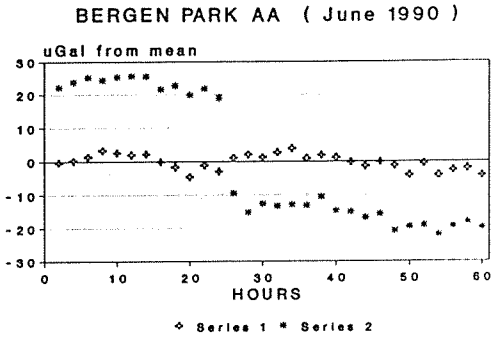


Figure 3. Distribution of drop set mean gravity values without (Series 2) and with (Series 1) the corrections for floor-gravimeter system response.

An analysis of about seventy site occupations revealed that at 5% to 10% of the sites, the combination of non-rigid floors and/or slight imperfections in the tripod to floor coupling have caused up to ±20 μGal floor-gravimeter system response errors in observed gravity. At approximately 50% of the sites, which were on solid bedrock, the floor-gravimeter system response errors were under ±2 μGal. For all site occupations thus far, about 85% of the errors were under ±5 μGal. Differences among gravity values obtained during different reoccupations of gravity stations have been substantially reduced, when corrections for floor-gravimeter response errors were applied.

The mean gravity value (transferred to the floor mark) based on three occupations at Bergen Park is 979 469 128.3 μGal, with a scatter (standard deviation from this mean) of ±2.4 μGal. The June 1990 occupation, with the -23 μGal and +13 μGal floor-gravimeter system response corrections applied to the appropriate drop sets, gave a gravity value of 979 469 130.7 μGal. Corrections for system response for the 1987 and 1988 Bergen Park occupations were determined from 100-drop time-distance data sets collected at the beginning and at the end of station occupations. These corrections were -2.8 μGal and -2.2 μGal for 1987 and 1988, respectively. The uncertainty estimates of the individual gravity values were ±4.7 μGal, ±4.3 μGal, and 4.6 μGal for 1987, 1988, and 1990, respectively.

Another gravity value was obtained in Bergen Park in 1988, with the instrument raised by 2 cm. This value was rejected, however, because of 1) excessive temperature fluctuations during the station occupation, and 2) the character of the floor-gravimeter system response signals varied throughout the measurements, and were different from that seen in the two available (initial and last) 100-drop time-distance data sets. Therefore, while the need for floor-gravimeter system response corrections was indicated, these could not be computed. The gravity value obtained by this (rejected) measurement was 979 469 135.3 μGal, ±6.6 μGal.

Based on the JILAG-4 station occupations, it is recommended that the floor-gravimeter system response be determined and corrected for all instruments measuring at the International Absolute Gravity Basestation Network (IAGBN) sites, and at sites used for high-precision monitoring of temporal gravity variations.

Acknowledgement We gratefully acknowledge the contributions of D. S. Robertson, and R. E. Moose to the development and testing of the floor-gravimeter system response correction, and K.A. Berstis to the development of the new gravimeter controller. These results would not have been possible without J. S. Griffin, B. Bernard, J. Fried, and D. Winester, operators of the absolute gravimeter, and J. E. Faller of the Joint Institute for Laboratory Astrophysics (JILA), who provided continued support for NGS in assuring that the JILAG-4 instrument remained in excellent working condition.

REFERENCES

Klopping, F.J., G. Peter, D.S. Robertson, K.A. Berstis, R.E. Moose, and W.E. Carter, Improvements in absolute gravity observations, *J. Geophys. Res.*, 1990, (submitted).

Niebauer, T.M., New absolute gravity instruments for physics and geophysics, *Ph.D. Dissertation, Univ. of Colorado, Boulder,* 155 pp., 1987.

Peter, G., F.J. Klopping, K.A. Berstis, and B. Bernard, Reduction of the systematic errors caused by floor-gravimeter system response, using JILAG-4, *Bur. Grav. Int., Bull. d'Inf.*, 66, 55-59, 1990.

STATUS OF IAGBN

G. Boedecker

Text already published in issue n° 66 of Bulletin d'Information

A TOWER GRAVITY EXPERIMENT: PAST, PRESENT, AND FUTURE

by

Anestis J. Romaides
Air Force Geophysics Laboratory, Hanscom AFB, MA, 01731

Paul Kasameyer
Lawrence Livermore National Laboratory, Livermore, CA, 94550

ABSTRACT

Previously reported results from the AFGL tower gravity experiment conducted on a 600 m television tower in Clayton, NC, indicated a departure from Newton's inverse-square law of gravity. The departure was of the form of an attractive non-Newtonian component to gravity modeled as the derivative of a Yukawa potential, and asymptotically approached -540 μGal at the top of the tower. Refined analyses including the addition of high frequency terrain information and additional gravity data in the upward continuation algorithms led to the disappearance of the supposed non-Newtonian effect. AFGL now finds no conclusive evidence for a non-Newtonian force with a scale length, λ, on the order of several hundred meters. The results, when combined with those of the LLNL experiment performed on the BREN tower, put tight constraints on the possible Yukawa coupling coefficient and scale length parameters of α and λ. AFGL is planning a follow-up tower experiment, near Greenville, MS, that should provide even tighter constraints.

INTRODUCTION

It has been known for some time using satellite and planetary orbit determinations that the inverse-square law accurately describes gravity over very large distances. Also from laboratory experiments it is known that the inverse-square law holds over very short distances. But for the range 10 m to 10 km there was a dearth of data, comparatively speaking, and over this range it was conceivable that the Newtonian gravitational constant, G, could differ from the laboratory value by as much as 1%. In recent years many experiments have been performed to determine if in fact the inverse-square law holds over the intermediate range between the laboratory and satellite ranges known as the "geophysical window." Most of these early experiments known as Airy-type experiments involve measuring gravity in mines and boreholes as a function of depth, and comparing the measurements with predictions of gravity based on Newton's law. Frank Stacey at the University of Queensland in Australia had been performing these type of measurements for some time. He made several measurements of gravity down a 1 km mine shaft and compared the measurements with the predictions based on a layered-earth model. The measurements consistently disagreed with the predictions (by 0.7%) suggesting that perhaps gravity is not as simple as Newton envisioned it. Stacey's results could be explained if the gravitational potential equation were modified to include the effects of an intermediate-range force which operates to counteract gravity over short distances (Stacey *et al.*, 1981). The modified potential would be of the form

$$\Phi(r) = -\frac{GM}{r}(1 + \alpha e^{-r/\lambda})$$

where the first term is the Newtonian gravitational potential of infinite range and the second is a limited-range Yukawa potential with parameters α, the coupling coefficient, and λ, the range. Just such a force had been postulated by Fuji (1971) who set the force parameters as $\alpha = 0.33$ and $\lambda =$ 10 - 1000 m. Clearly if these results were correct they would rock the very foundations of Newtonian physics. Consequently, they were not taken too seriously until 1986 when Ephraim Fischbach published the results of a reanalysis of the Eötvös torsion balance experiment. What Fischbach found in the analysis was a correlation between gravity and baryon number (which is equal to the number of protons and neutrons in objects). This composition dependence to gravity was consistent with a short-range repulsive force (the "fifth force") with $\alpha = -0.007$ and $\lambda = 200$ m (Fischbach *et al.*, 1986). The results implied objects of different composition would fall at different rates contrary to the fable about Galileo dropping two different sized cannon balls off the tower of Pisa. A flurry of experiments ensued in an attempt to investigate the possible existence of a fifth force in nature (also referred to as non-Newtonian gravity). The experiments fell along two lines: One set of experiments was searching for a compositional dependence to gravity (e.g., Boynton *et al.*,1987; Thieberger, 1987; Stubbs *et al.*,1987, Adelberger *et al.*,1987). The other set comprised the geophysical experiments which merely sought to examine a possible breakdown of the inverse-square law (e.g., Stacey and Tuck, 1984; Holding *et al.*,1986; Hsui, 1987). In measuring gravity down a mine or borehole one must accurately know the density of the surrounding rock; any unmodeled inhomogeneities could easily mimic non-Newtonian gravity.

We at the Air Force Geophysics Laboratory (AFGL) and Lawrence Livermore National Laboratory (LLNL) reasoned it was far better to measure gravity up a tall tower where the density of the surrounding air was much easier to model. Also since air is much less dense than rock, any modeling errors would be minor in nature.

THE EARLY RESULTS

In 1987 AFGL performed an experiment in Clayton, NC, where gravity was measured at various elevations on a 610 m television transmitting tower. The tower was the WTVD-TV station in Durham, NC. Also an extensive array of gravity measurements were made on the ground in the vicinity of the tower (< 5km). The ground data were then merged with existing surface data in that area, provided by the Defense Mapping Agency (DMA), creating a data base of gravity values that extended to about 200 km from the tower. The surface data were upward continued using two independent techniques (Romaides *et al.*, 1989). After eliminating all possible sources of error in December 1987 AFGL announced the results which indicated a significant departure from the inverse-square law asymptotically approaching -500 μGal at the top of the tower. After several months of open discussions at conferences with physicists and geophysicists it was felt best to publish the results (Eckhardt *et al.*, 1988) and allow the debate to continue in the scientific literature. In the subsequent year as more data both on the ground and on the tower were collected, and the upward continuation calculations refined, the effect grew to about -540 μGal. Using the Yukawa potential we obtain a model of the observed discrepancy given by

$$g_o(z) - g_m(z) = 2\pi G\rho\alpha\lambda(e^{-z/\lambda} - 1)$$

where $g_o(z)$ = observed gravity and $g_m(z)$ = measured gravity. Performing a least-squares fit to the WTVD results using $\rho = 2.67$ g/cm^3 and z = elevation above tower base, obtains the force parameters $\alpha = 0.023$ and $\lambda = 283$ m. Note the α in the results is positive thus yielding an attractive force versus a repulsive interaction posited by Stacey and Fischbach. Although this supposedly was the final AFGL result, we continued to be our own worst critic by searching for possible unsuspected errors. We also shared our data with all other individuals or agencies who were interested in examining our results.

In late 1988 David Bartlett of the University of Colorado at Boulder analyzed the terrain in the vicinity of the WTVD tower and claimed that the surface data did not do an adequate job of modeling the local topography. Bartlett's claim was that the terrain within 1 km of the tower forms a local hill which if not properly modeled neatly explains the non-Newtonian effect (Bartlett and Tew, 1988). Examination of this claim eventually led to the discovery that the surface data (mostly beyond 2 km) used in the upward continuation did not accurately represent the topographic features in the area. Most of the AFGL data, as well as the data in the DMA data base, were taken near roads which are easily accessible but higher in elevation than the surrounding local terrain. In other words the surface data were biased towards the higher elevations. In an effort to remove the bias the tower site was revisited, and some additional surface data at several selected low-lying areas was collected. After including the new surface data in the upward continuation, the discrepancy between observed and predicted was reduced to about -340 μGal. Even this addition of data did not totally correct the problem, however, as there we still biases in the data (Figure 1). One could easily see how these remaining biases could reduce the effect down to the noise level of the data thus yielding a null result. The only way to remove all the terrain biases was to terrain correct the surface data prior to upward continuation then add the terrain back at altitude.

THE TERRAIN CORRECTION

Obtaining quality digital terrain data and performing the terrain correction to the data turned out to be the most tedious and time consuming portion of this experiment. There are two aspects to the terrain correction procedure. The first is the removal of the high frequency terrain information from all the gravity measurements. Once this is done, the remaining gravity field should only possess long wavelength components and thus be adequately modeled by the existing survey. The second involves upward continuing the effect of the terrain and adding it to the upward continued gravity at altitude yielding consistent gravity predictions which can then be compared with the observations.

Ideally what one would like to have when performing an upward continuation is gravity information at every point on the Earth's surface. Obtaining gravity everywhere is clearly impossible but detailed terrain information is readily available from large scale topographic maps, and provides an excellent substitute for high frequency gravity information. The terrain in a 10 km radius about the WTVD tower was digitized using 7.5 arc-minute US Geological Survey (USGS) topographic maps. The accuracy of the elevations on the maps were quoted at half a contour interval or 1.5 m. Prior to implementing the digitization we provided USGS with the survey data whose elevations were known to 2 cm. Vince Caruso of the USGS compared the elevations with those of the topographic maps and found that 71% of the map elevations were within half a contour interval of the data points. There were some outliers, however, with some differences as high as 3.4 m. Using the computed differences between the data points and map, the digitized elevations were adjusted to agree with the surface data, after which three nested grids were constructed. The innermost grid was of 5 m spacing and extended ±165 m from the tower. In constructing this grid a two step procedure was employed: First the adjusted digitized terrain was gridded and the values of the grid intersections were printed out to determine how well they compared with the survey data (within 165 m of the WTVD tower there were a total of 40 survey points). Due to the imperfect nature of the gridding, the adjustment was not good enough given the fine structure of the grid that was being used. So the grid was manually modified to fit the data better, and then using both the modified grid and the elevations of the survey points a new and final grid of terrain elevations was constructed. The middle grid was of 33 m spacing and extended ±2574 m from the tower. This grid was first digitized by AFGL but later Marc Zumberge the University of California at San Diego provided us with a similar grid which he had obtained with the aid of an electronic digitizer. (Zumberge used the grid in a paper he and Robert Parker were writing on ideal bodies.) Although this grid only differed from the other grid by an rms of 2 m, it was deemed to be the more accurate and was the one finally used. The outermost grid was of 99 m spacing and extended ±9999 m from the tower. In all the digitizations that were done the WTVD tower which was shown on the USGS map was used as the origin of the coordinate system. Unfortunately this was not the actual tower but an older tower 23 m to the east which had been taken down prior to the

construction of the new tower in 1979. Because of this, all of the grids had to be shifted for the elevations to be consistent with the positions.

Using the three nested grids the terrain was modeled as a series of right rectangular prisms. Formulae for computing the gravitational effect of such prisms exist (Forsberg and Tscherning, 1979) and were used to remove and add terrain information mathematically. The mean of the digitized elevations (89.455 m above mean sea level) served as the datum plane for all the calculations. Each survey point out to 10 km was Bouguer corrected as follows:

$$\Delta g_b = \Delta g_f - 2\pi G\rho(h_p - \bar{h})$$

where Δg_b = Bouguer anomaly, Δg_f = free-air anomaly, G = Newtonian gravitational constant, the density $\rho = 2.67$ g/cm^3, and the thickness of the Bouguer slab is the difference between the elevation of the survey point, h_p, and the mean elevation of $\bar{h}$ = 89.455 m. For points inside 5 km a terrain correction was applied resulting in terrain-corrected Bouguer anomalies given by

$$\Delta g_b = \Delta g_f - 2\pi G\rho(h_p - \bar{h}) + \Delta g_t$$

where Δg_t is the terrain correction. In this scheme all the hills above the mean elevation were mathematically removed and the valleys below this elevation were mathematically filled. Because of the mathematical removal of mass, it is possible for the terrain correction to be negative instead of always positive as in the classical sense. The end result was a very smooth gravity field of long-wavelength content suitable for upward continuation. Employing the same formulae used in the terrain correction, the gravitational attraction of the terrain at the various tower elevations was computed.

THE FINAL RESULT

The data set used in the final upward continuation consisted of terrain-corrected Bouguer anomalies out to 5 km, simple Bouguer anomalies 5 to 10 km, and free-air anomalies out to 200 km. The Bouguer anomalies were upward continued, and the gravitational attraction of the terrain that was removed (< 10 km) was subsequently added back at the various tower elevations. Since terrain corrections were only performed within 10 km of the tower, some estimate had to be made for the effect of the terrain out to 200 km. Given the fact that the near-tower gravity measurements were biased towards higher elevations, it was logical to assume all of the data were biased since they are all in the same area, namely the North Carolina coastal region. Despite only terrain correcting out to 10 km, some rudimentary terrain calculations out to 18.6 km were performed. What was found is that indeed the bias does continue out to 18.6 km at an average of about 6 m. Taking into account the computed biases from 10 to 18.6 km and assuming the bias is a constant 6 m from 18.6 to 200 km, a small additional correction to the upward continued anomalies is obtained. When all the corrections were taken into account, and the final predictions differenced with the measurements, almost the entire non-Newtonian effect disappears (Table 1). There still appears to be some residual curvature left (Figure 2) but it is hardly suggestive of non-Newtonian gravity. Thus we find no conclusive evidence for non-Newtonian gravity for a scale length of several hundred meters.

The final result is in good agreement with that of the LLNL experiment which was performed on the BREN tower and got a null result (Thomas *et al.*, 1989). Although neither experiment can totally rule out the existence of non-Newtonian gravity the results can be used to put tight constraints on its possible range and magnitude. In constraining the Yukawa potential parameters of α and λ, it was discovered that one must include correlation effects which if neglected make the constraints seem stronger than they actually are (Kammeraad *et al.*, 1990). This arises from the fact that there are correlated errors that have a significant effect on the final constraints. In general, measurements of gravity on the tower made at different times are independent. There is some correlation between gravity measurements made in the same loop, but generally readings taken in different loops are uncorrelated. In the prediction of gravity, however, the same surface gravity data were used for each prediction and hence the predicted values are highly correlated. The total variance of the observed minus predicted values on the tower is given by the matrix

$$\Sigma_{DIFF} = \Sigma_{UC} + \Sigma_{TOW}$$

where Σ_{UC} is the variance matrix of the upward continued gravity anomalies, and Σ_{TOW} is the variance matrix of the gravity measurements on the tower. Because the tower measurements are uncorrelated Σ_{TOW} is diagonal, but Σ_{UC} is not, and does contain off-diagonal elements which significantly affect the results. We merged the results of the WTVD and BREN towers taking into account the effects of correlated errors, and obtained constraints on α and λ. Figures 3 and 4 show the allowed regions for any possible non-Newtonian forces for the WTVD and BREN towers respectively. After merger of the two data sets the constraints on α and λ become slightly tighter (Figure 5). Note the $\chi^2 = 5\%$ line is slightly smaller after the merger. It is difficult to see how further improvement can be achieved without either reducing the errors or collecting additional data. LLNL continues to work on the upward continuation by using isostatic anomalies which have a small truncation error but are much smoother than the free-air anomalies used here; however, these data represent the final AFGL results for the WTVD tower.

THE FUTURE

At this point one could make an argument for concluding the experiments on non-Newtonian gravity. After all, a null result has been obtained which is what most physicist have looked for all along. Furthermore, improvements in the current experiments will be difficult to achieve especially given the meticulous care taken. But physics does not end when an expected result is achieved or improvements in experimental methodologies prove difficult. Examination of Figure 5 shows that there are still zones of allowance for non-Newtonian gravity. (Further constraining possible non-Newtonian gravity in these zones is of more significance to physicists than geodesists and geophysicists.) We plan to investigate these regions to determine if there could still be some additional undetected force albeit much weaker than previously expected. We still

believe tower experiments are the best way to investigate possible non-Newtonian forces with scale lengths of several hundred meters. Another tower experiment in a more advantageous area should resolve any lingering problems. Ideally we would obtain more accurate results which could be used to further constrain non-Newtonian force parameters.

The two major problems in North Carolina were the inaccessibility of certain areas and the lack of good terrain information. These are two problems AFGL hopes to avoid in the next tower. After a comprehensive search of all tall towers in the U.S., we narrowed the field down to three: A 610 m tower in Greenville, MS, a 628 m tower in Fargo, ND, and a 610 m tower in Tallahassee, FL. We decided on the tower in Greenville, MS, as the best possible site for the next experiment with the other two towers serving as backups. This tower is the WABG-TV television transmitter constructed by Stainless Inc. and has several advantages: 1) The area surrounding the tower consists mainly of plowed fields and is therefore very accessible with the exception of a few trees and streams. 2) The local topography is free of major hills and valleys (Figure 6) mostly due to the fact that the tower is only about 40 km east of the Mississippi river. 3) There is an abundance of existing gravity on the surface surrounding the tower with the data being very uniformly distributed throughout the area; and the gravity field being rather featureless. 4) There exist high quality digital terrain data which can be used in the necessary terrain computations of the entire data set. 5) Finally this tower does not contain a great degree of communication equipment and should be very stable.

Why should this tower be any different than WTVD or BREN, and what more do we hope to gain from another experiment? When the ground survey for the new tower region is done, GPS will be used to position the points. This should provide extremely accurate vertical and horizontal positioning superior to the data in North Carolina. The availability of quality digital terrain data and the benign nature of the local terrain should provide much more accurate terrain-corrected Bouguer anomalies. As a test of smooth gravity field in this area, we attempted to perform an upward continuation just using the data that were available. We selected a data set circularly symmetric about the tower and extending to 200 km (Figure 7), then rotated our data selection template 4.5 degrees and selected another data set from the existing data. We upward continued both data sets which consisting of free-air anomalies using the Fourier-Bessel/Numerical Integration method. The results (Table 2) show that at the top of the tower the two sets give identical results which lends confidence to the future results where much more accurate data close to the tower will be available. Naturally the error estimates are high due to the fact that the only existing data are of 1 and 2 mGal accuracy, and sparsely distributed near the tower. Once a detailed regional survey is completed, the proposed error budget for the Greenville tower is

Error Source	Error [μGal]
Upward Continuation Error	25
Measurement Error	14
Scale Factor Error	9
Drift Correction Error	5
Tide Correction Error	3
Position Error	6

which results in a total rss error of 31 μGal at the top of the tower. If achieved, this represents a 25% improvement in the error estimate from the WTVD tower. More importantly, the flat terrain will insure a lessening of the systematic effects such as biases in the terrain. Finally, in the latter days of the tower experiment we constructed a temporary platform that we used to clamp to the tower and place the gravimeter to take a measurement, the reason being there were elevations that we wished to collect data where there were no platform gratings upon which to measure gravity. As it turned out, this platform was much more stable than the existing platform gratings that we previously used, and our aim is to use this platform for all the measurements in the second tower. All these factors combined with greatly improved upward continuation algorithms (Jekeli *et al.*, 1990; Romaides *et al.*, 1991) should enable us to achieve results with smaller error estimates than those of the WTVD tower. The final step will be to take all of the tower results and merge them with some other geophysical experiment, such as a reservoir experiment (Stacey and Tuck, 1984), which is only sensitive to shorter ranges (10 - 50 m). In doing so we should be able to further constrain any possible non-Newtonian force parameters within the geophysical window, and perhaps close the chapter on this very interesting period in gravitational physics.

ACKNOWLEDGEMENT

We thank Charles Taylor of the Air Force Geophysics Laboratory for his computational support in the upward continuation of the Mississippi data.

REFERENCES

Adelberger, E.G., C.W. Stubbs, W.F. Rodgers, F.J. Raab, B.R. Heckel, J.H. Gundlach, H.E. Swanson, and R. Watanebe, "New Constraints on Composition-Dependent Interactions Weaker than Gravity," *Physical Review Letters*, vol.59, no.8, pp.849-852, 1987.

Bartlett, D.F. and W.L. Tew, "Possible Effect of the Local Terrain on the North Carolina Tower Gravity Experiment," *Physical Review Letters*, vol.63, no.14, p.1531, 1989.

Boynton, P.W., D. Crosby, P. Ekstorm, and A. Szumilo, "Search for an Intermediate-Range Composition-Dependent Force," *Physical Review Letters*, vol.59, no.13, pp.1385-1389, 1987.

Eckhardt, D.H., C. Jekeli, A.R. Lazarewicz, A.J. Romaides, and R.W. Sands, "A Tower Gravity Experiment: Evidence for non-Newtonian gravity," *Physical Review Letters*, vol.60, no.25, pp.2567-2570, 1988.

Fischbach, E., D. Sudarsky, A. Szafer, C. Talmadge, and S.H. Aronson, "Reanalysis of the Eötvös Experiment," *Physical Review Letters*, vol.56, no.1, pp.3-6, 1986.

Forsberg, R. and C.C. Tscherning, "The Use of Height Data in Gravity Field Approximation by Collocation," *Journal of Geophysical Research*, vol.86, no.B9, pp.7843-7584, 1981.

Fujii, Y., *Nature*, vol.234, no.5, 1971.

Holding, S.C., F.D. Stacey, and G.J. Tuck, "Gravity in Mines - an Investigation of Newton's Law," *Physical Review D*, vol.33, no.12, p.3487, 1986.

Hsui, A., "Geophysical Determination of the Newtonian Gravitational Constant Based on a Borehole Gravity Measurement," *Science*, vol.237, pp.881-883, 1987.

Jekeli, C., D.H. Eckhardt, and A.J. Romaides, "Tower Gravity Experiment: No Evidence for Non-Newtonian Gravity," *Physical Review Letters*, vol.64, no.11, pp.1204-1206, 1990.

Kammeraad, J., P. Kasameyer, O. Fackler, D. Felske, R. Harris, M. Millet, M. Mugge, J. Thomas, "New Results from Nevada: A Test of Newton's Law Using the BREN Tower and a High Density Ground Gravity Survey," in New and Exotic Phonomena '90, edited by O. Fackler and J. Tran Thahn Van, pp.245-254, Editions Frontieres, Gif-sur-Yvette, France, 1990.

Romaides, A.J., C. Jekeli, A.R. Lazarewicz, D.H. Eckhardt, and R.W. Sands, "A Detection of Non-Newtonian Gravity," *Journal Of Geophysical Research*, vol.94, no.B2, pp.1563-1572, 1989.

Romaides, A.J., C. Jekeli, D.H. Eckhardt, and C.L. Taylor, "The Rise and Fall of a Non-Newtonian Gravity Experiment," submitted to *Journal of Geophysical Research*, 1990.

Stacey, F.D., G.J. Tuck, S.C. Holding, A.R. Maher, and D. Morris, "Constraint on the Planetary Scale Value of the Newtonian Gravitational Constant from the Gravity Profile within a Mine," *Physical Review D*, vol.23, no.8, pp.1683-1692, 1981.

Stacey, F.D. and G.J. Tuck, "Non-Newtonian Gravity: Geophysical Evidence," in *Precision Measurement and Fundamental Constants II*, B.N. Taylor and W.D. Phillips, eds., National Bureau of Standards, Special Publication no.617, pp.597-600, 1984.

Stubbs, C.W., E.G. Adelberger, F.J. Raab, J.H. Gundlach, B.R. Heckel, K.D. McMurry, H.E. Swanson, and R. Watanabe, "Search for an Intermediate-Range Interaction," *Physical Review Letters*, vol.58, no.11, pp.1070-1073, 1987.

Thieberger, P., "Search for a Substance-Dependent Force with a New Differential Accelerometer," *Physical Review Letters*, vol.58, no.11, pp.1066-1069, 1987.

Thomas, J., P. Kasameyer, O. Fackler, D. Felske, R. Harris, J. Kammeraad, M. Millet, and M. Mugge, "Testing the Inverse-Square Law of Gravity on a 465-m Tower," *Physical Review Letters*, vol.63, no.18, pp.1902-1905, 1989.

FIGURE CAPTIONS

Figure 1. The bias in elevations out to 18.6 km from the WTVD tower. The solid line consists of azimuthally averaged elevations digitized off 7.5 minute USGS topographic maps after the map elevations had been adjusted to our control points. The boxes connected by a dashed line are mean elevations of our survey data out to 5 km. Beyond 5 km the numbers are the mean of existing DMA data.

Figure 2. The final observed minus predicted values with their associated errors. The error bars contain all known errors including the effect of terrain bias beyond 18.6 km. The diamonds are the Least-squares collocation method and the boxes are the Fourier-Bessel/Numerical Integration method.

Figure 3. Allowed regions for α and λ for the WTVD tower (12 degrees of freedom) with correlated errors of the surface data taken into account. Any particular set of χ^2 contour lines represents the probability of exceeding the observed χ^2 statistic as a function of different model parameters α and λ. The one-sided 95% confidence interval for these parameters is represented by the 5%. The $\chi^2 = 30\%$ contour line represents the one standard deviation.

Figure 4. Allowed regions for α and λ for the BREN tower (11 degrees of freedom) with correlated errors of the surface data taken into account. The $\chi^2 = 30\%$ contour line again represents the one standard deviation.

Figure 5. The constraints on α and λ for the combined WTVD and BREN tower data (23 degrees of freedom). Note how the one standard deviation line is brought in after the merger yielding a slightly smaller allowed region.

Figure 6. The topography within 40 km of the Greenville, MS, tower as obtained from elevations of gravity stations in the existing DMA data base. The data used to construct the contour map are fairly uniformly distributed throughout the area with no preponderance of data in any given direction.

Figure 7. The surface data that were used in the upward continuation. The figure depicts 2189 points (selected from 50292 available) contained in 40 spokes separated by 9°. The rotated data set (not shown) contains 2166 points and also consists of 40 spokes but rotated 4.5° from the first set creating a set of spokes that fall exactly between the first data set.

Table 1. Observed Minus Model Differences and Associated Errors

Elevation Above Tower Base [m]	Fourier-Bessel/ Numerical Integration [μGal]	Estimated Error [μGal]	Least-squares Collocation [μGal]	Estimated Error [μGal]
0.69	-14	23	-3	20
7.58	24	23	14	21
9.38	28	23	19	21
23.07	21	25	15	23
45.93	1	26	0	23
68.76	-19	28	-17	24
93.92	-6	29	-2	25
192.17	8	35	15	30
283.58	-22	38	-13	34
379.54	-28	38	-17	35
473.24	-18	42	-5	40
562.27	17	43	32	43

Table 2. Greenville Tower Upward Continued Anomalies

Elevation [m]	Angle = 0° [mGal]	Angle = 4.5° [mGal]	Error Estimate [mGal]
50	10.157	10.099	1.750
100	10.159	10.111	1.487
150	10.154	10.113	1.354
200	10.137	10.102	1.266
250	10.114	10.086	1.199
300	10.087	10.065	1.146
350	10.057	10.039	1.102
400	10.025	10.011	1.065
450	9.990	9.979	1.032
500	9.952	9.945	1.002
550	9.915	9.911	0.975
600	9.877	9.877	0.950

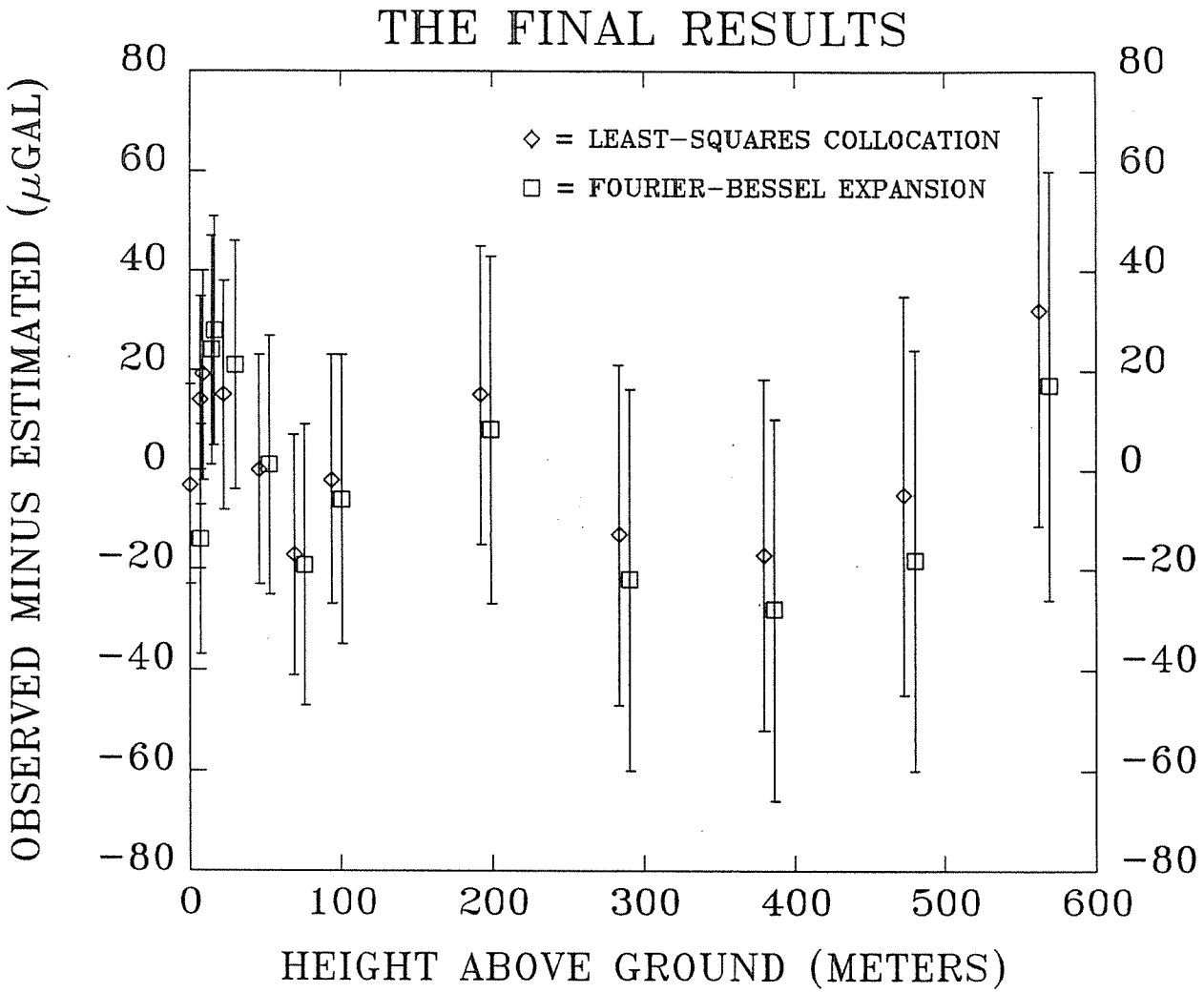


Figure 2

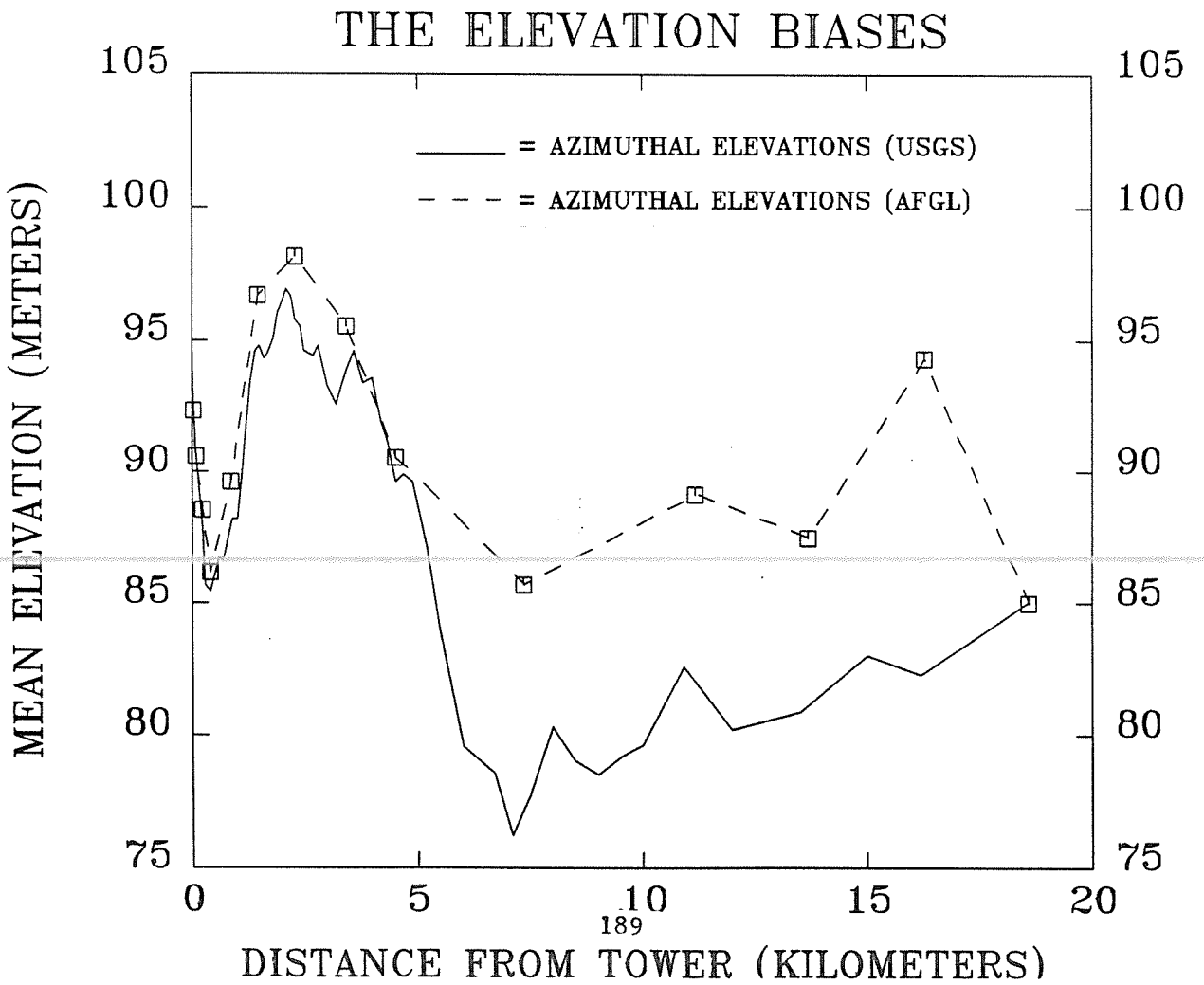


Figure 1

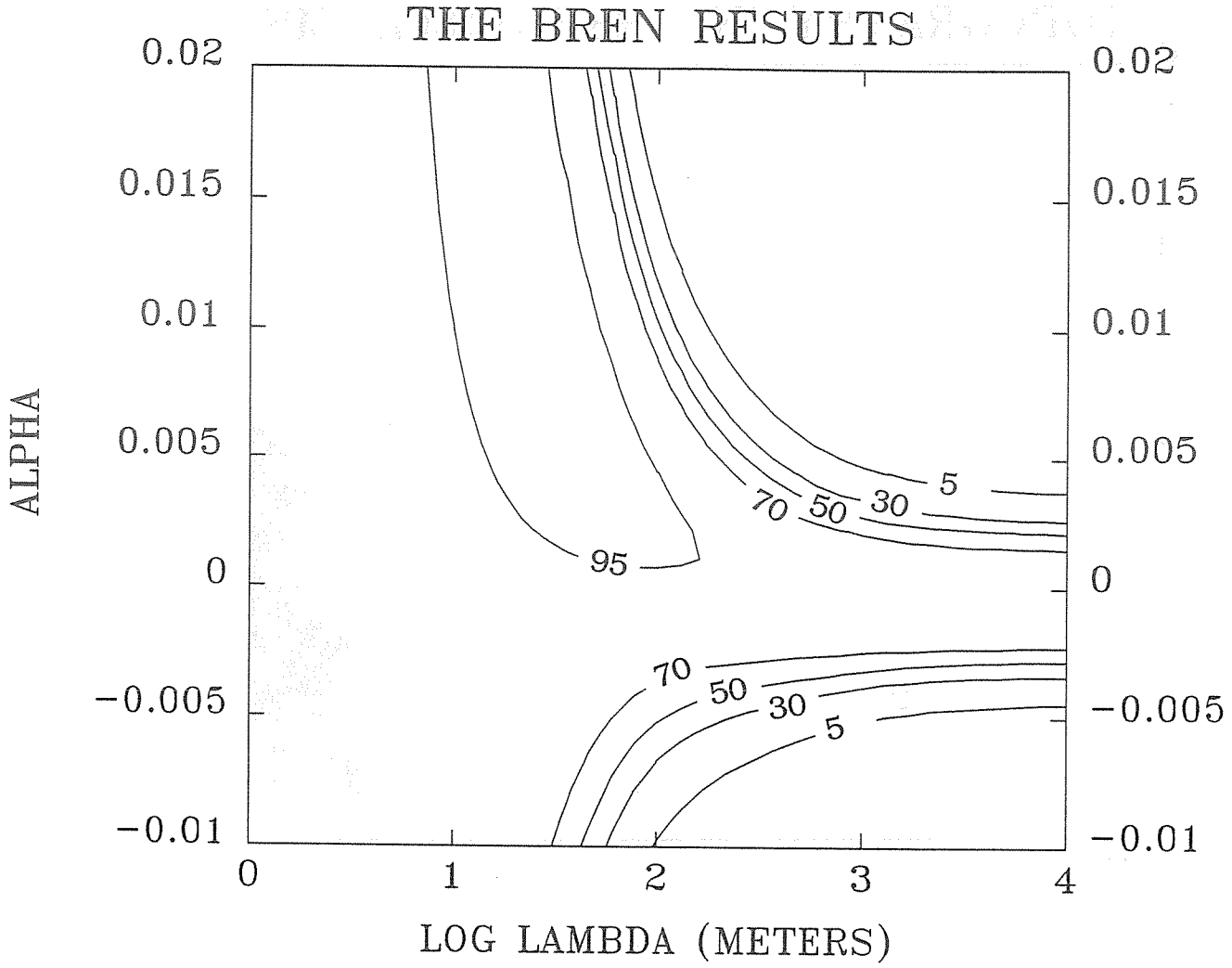


Figure 4

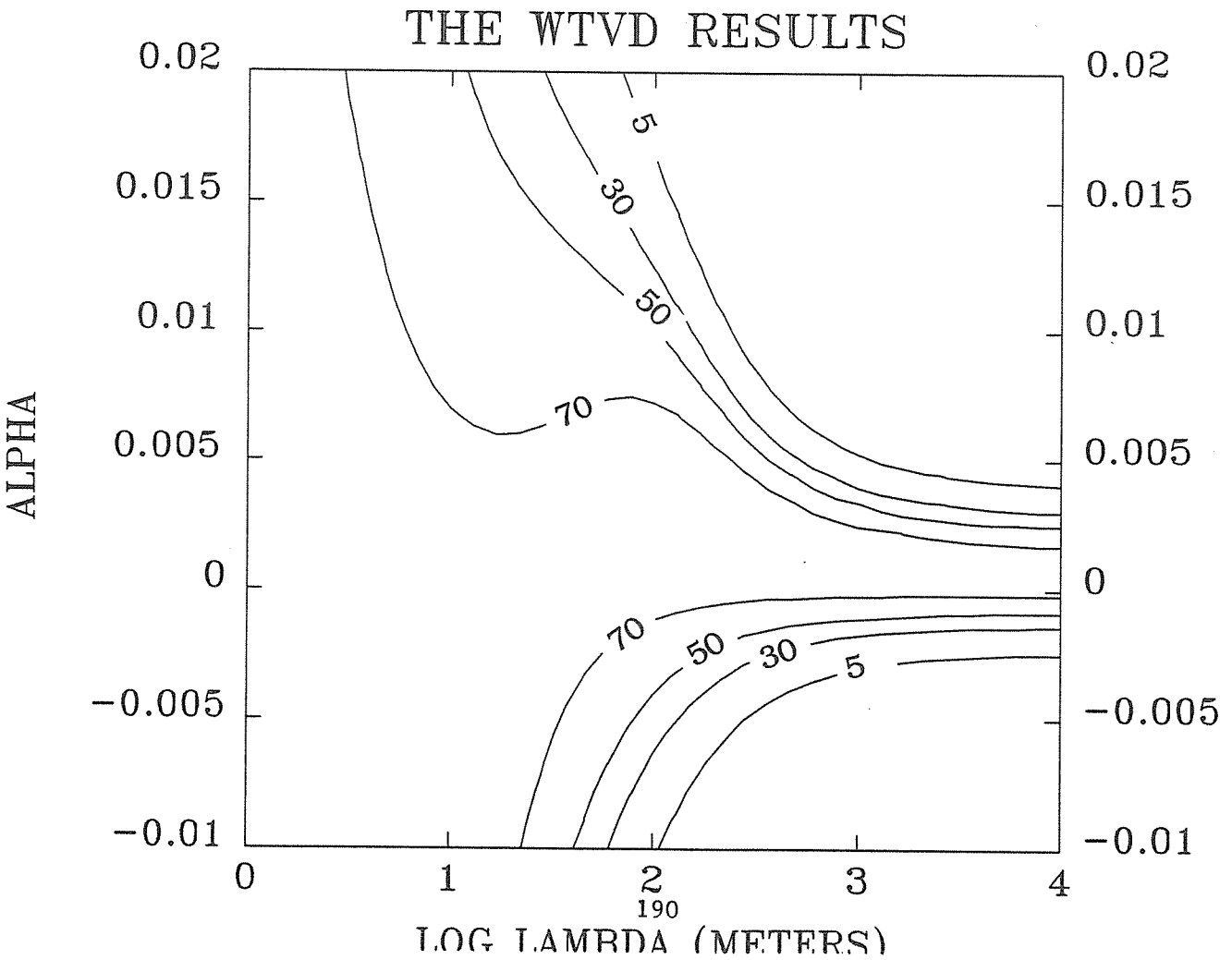


Figure 3

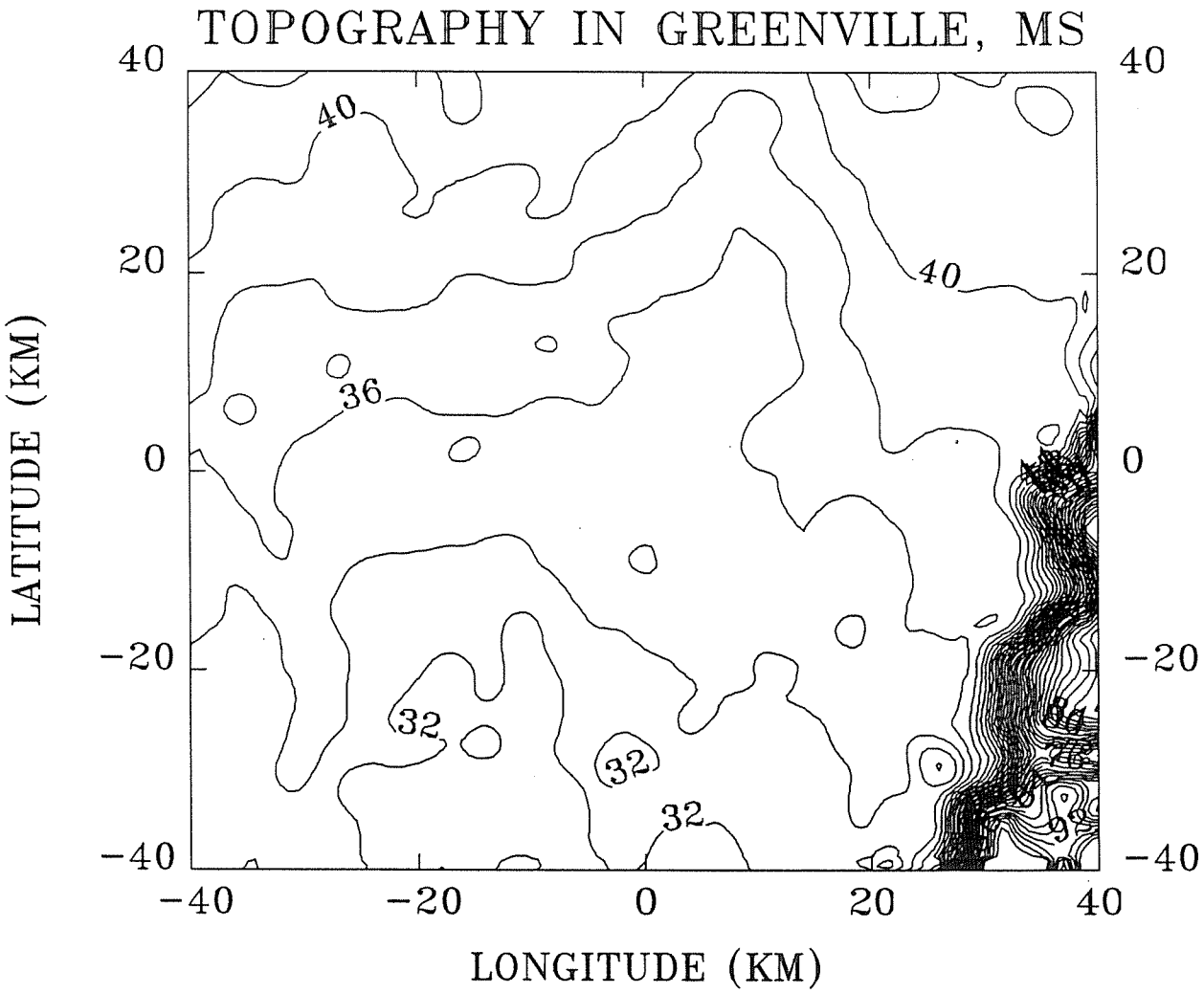


Figure 6

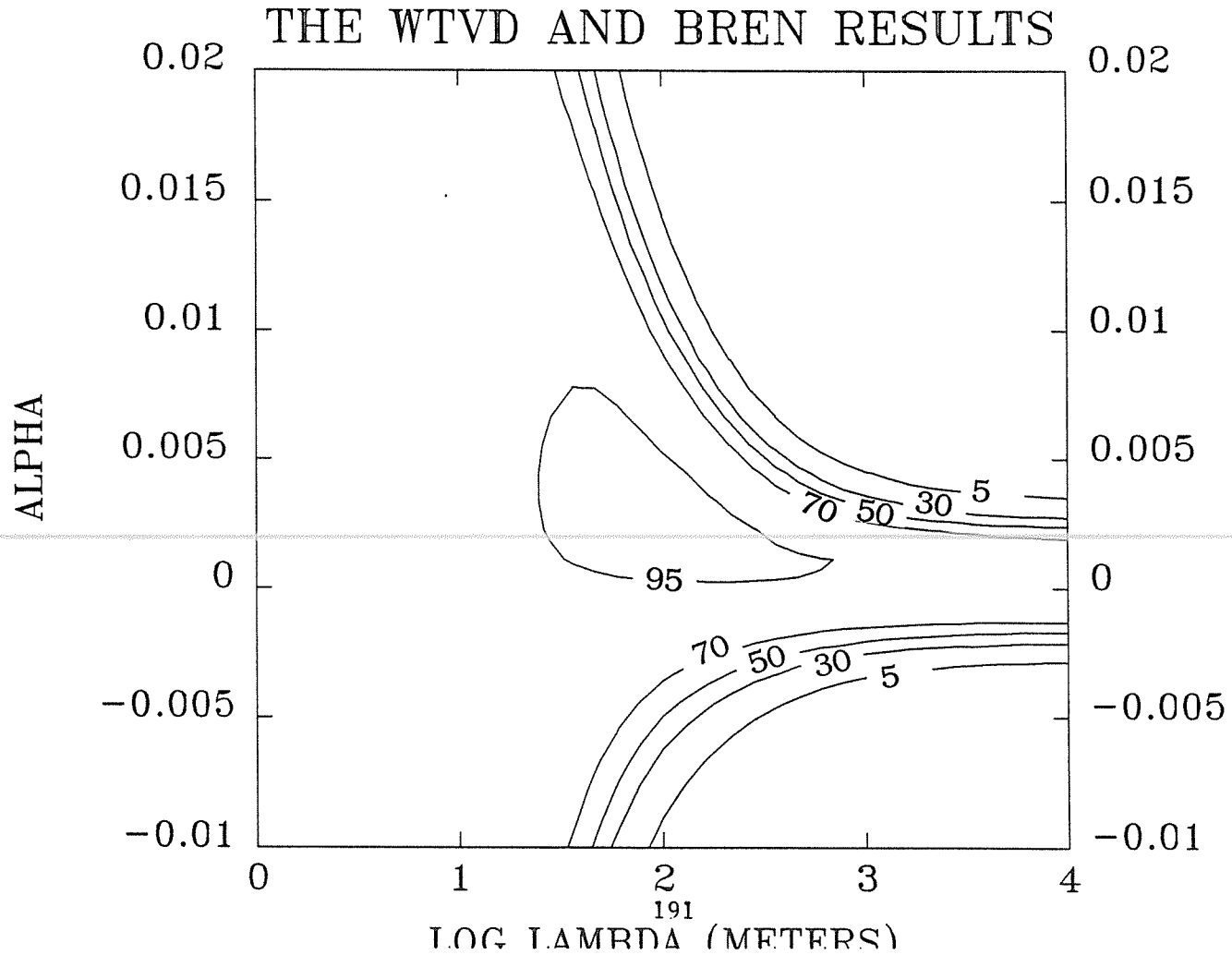


Figure 5

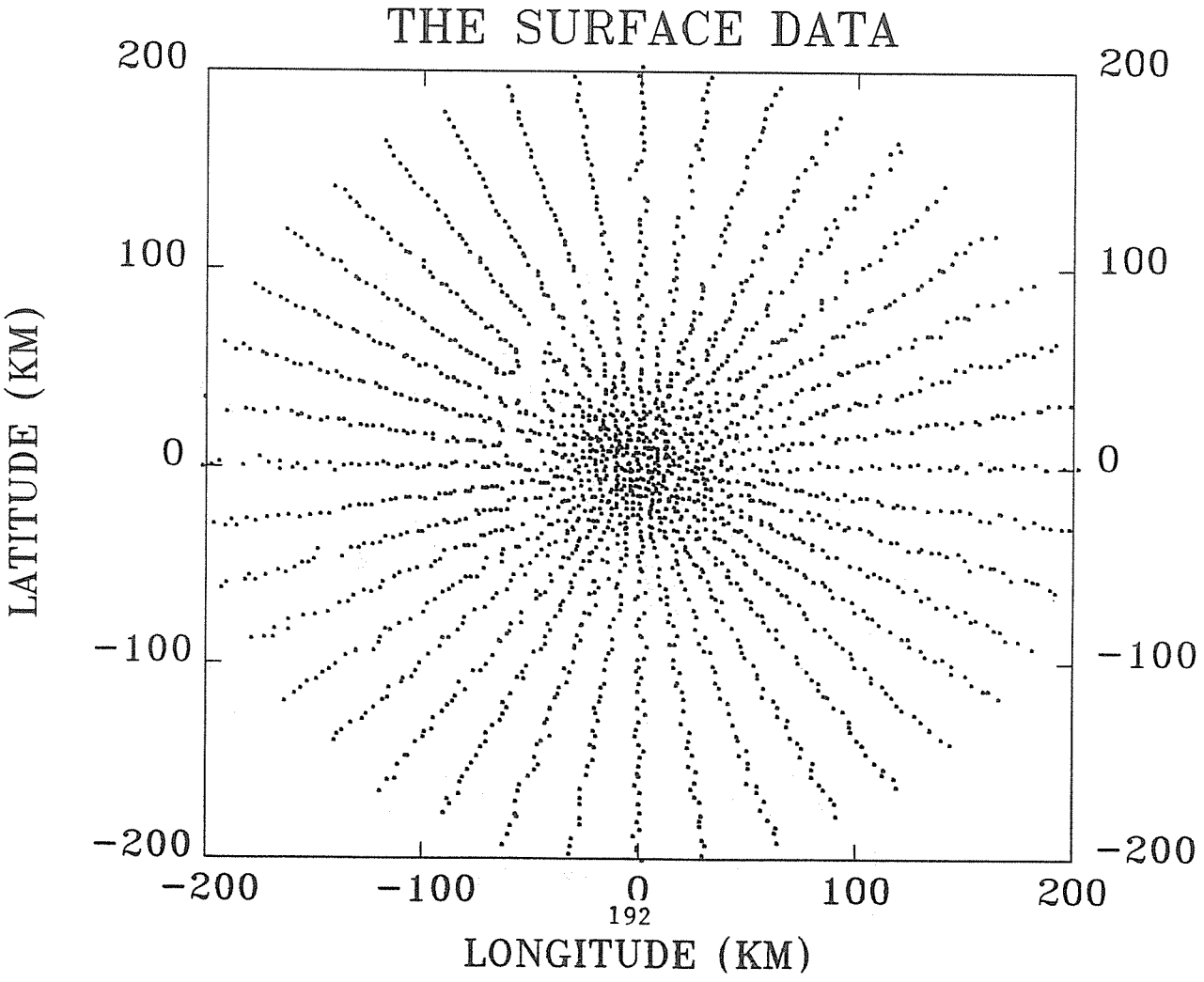

THE SURFACE DATA
200
100
0
−100
−200
LATITUDE (KM)
−200
−100
0
100
200
LONGITUDE (KM)

Figure 7

THIRD GENERATION GYRO -- NO EVIDENCE FOR ANOMALOUS WEIGHT REDUCTION

by

Gerald L. Shaw and Anestis J. Romaides
Air Force Geophysics Laboratory, Hanscom AFB, MA, 01731

The Third Generation Gyro (TGG) is a single degree of freedom floated rate integrating gyroscope (Figure1). The wheel is suspended in the float by two hemispherical hydrodynamic gas bearings and is driven by a two phase, dual hysteresis spin motor. The cylindrical float (Figure 2) is fully floated in a concentric housing. The viscous flotation fluid provides rotational damping and buoyant support and a bellows assembly maintains flotation fluid volume over temperature changes.

It is of some importance that the float be neutrally buoyant and centered within the housing cavity. A flotation error will result in radial motion of the float; and, in the event of radial accelerations and orientation changes, these float motions cause fluid torques which directly perturb the gyro. For this reason the TGG should be sensitive to the anomalous weight reductions reported by Hayasaka and Takeuchi.

Hayasaka and Takeuchi reported a weight reduction, only in the spin vector pointing down orientation, that is linearly proportional to the rotor mass, radius of gyration and angular frequency. For a rotor 2.26 cm in radius, weighing 175 g, and spinning at 12000 rpm they observed an apparent weight reduction of about 11 mg. The predicted magnitude of such a weight shift (which would appear as a buoyancy shift in the TGG) can be determined from the gyro's operating parameters. Using an equivalent wheel radius of 1.6 cm, a spin rate of 32000 rpm and a wheel mass of 56 g gives an expected weight reduction of about 6 mg. The capability of the TGG to sense buoyancy shifts is nearly two orders of magnitude better than this. During testing and calibration the TGG is operated in several orientations (including spin up and spin down). The fact that no such anomalous shifts have been reported refutes the claim that weight changes will be experienced depending on the rotational sense about the vertical axis.

ACKNOWLEDGEMENTS

We thank Col. Richard Evans of the Ballistic Missile Office and Warren Fitzgerald of the Charles Stark Draper Laboratory for the detailed information on the Third Generation Gyro.

REFERENCES

Hayasaka, H. and S. Takeuchi, "Anomalous Weight Reduction on a Gyroscope's Right Rotation around the Vertical Axis on the Earth," *Physical Review Letters*, vol.63, no.25, pp.2701-2704, 1989.

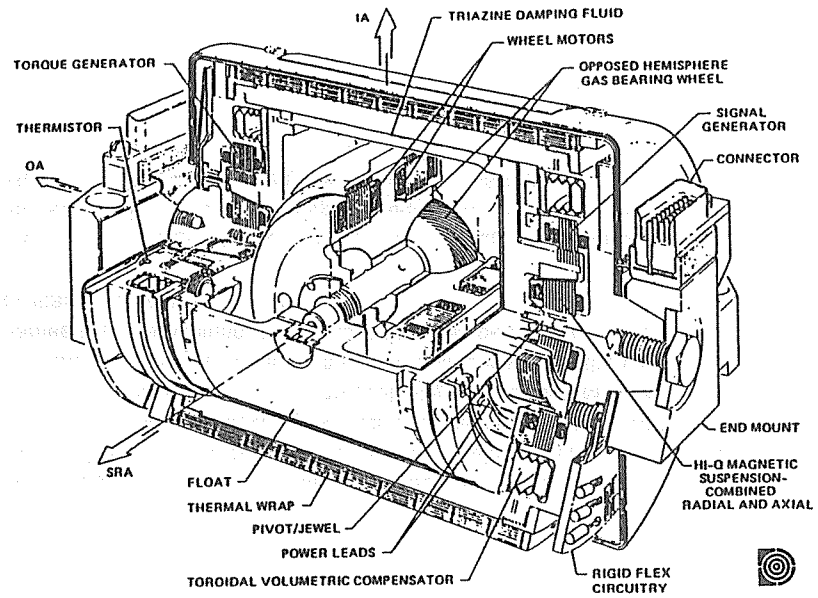


Figure 1 Third Generation Gyro (TGG) Assembly

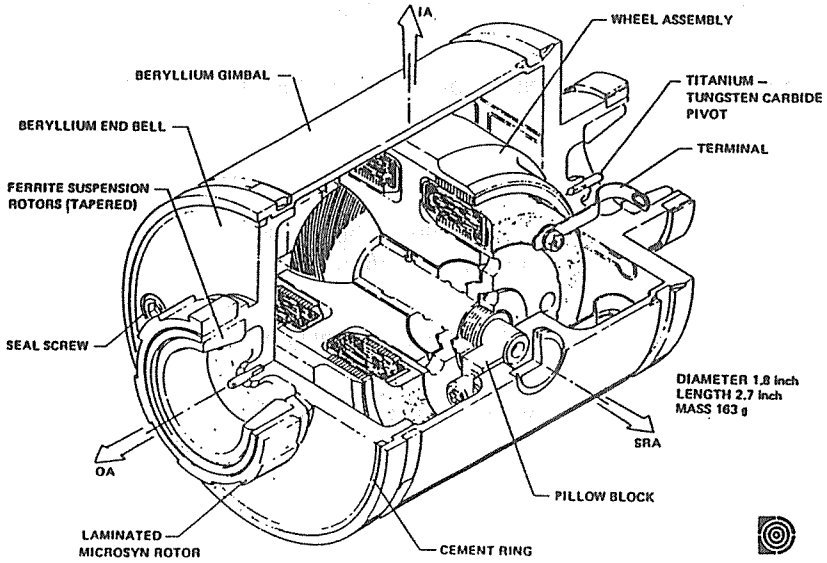


Figure 2 TGG Float Assembly

MAJORANA SHIELDING

Donald H. Eckhardt
Air Force Geophysics Laboratory
Hanscom AFB, MA 01730
USA

1. Majorana's Proposed Modification of Newton's Inverse-Square Law[1]

$$F = G M_1 M_2 r^{-2} \exp\left(-\int h \rho \, dr\right) \qquad (1)$$

h is Majorana constant.
ρ is density along integral path.

2. Effect on Ratio of Gravitational Mass to Inertial Mass for Spherical Body[2]

$$\delta \frac{M_G}{M_I} \sim -h \rho a$$

ρ is density of body.
a is radius of body.

[1]Q. Majorana, "On Gravitation. Theoretical and Experimental Results", *Philos. Mag.* **39**, 488-504 (1920). Quirino Majorana (1871-1957), born in Catania, Sicily, was an Italian physicist and engineer. He is not to be confused with the renowned Italian theoretical physicist Ettore Majorana (1906-1938) who was also born in Catania. It is, perhaps, because of the identity of their surnames that the (Quirino) Majorana theory has been accorded far more legitimacy than it warrants.

[2]Henry Norris Russell showed that, with a factor close to 3/4 on the RHS of this expression, it is the appropriate equation. H. N. Russell, "On Majorana's Theory of Gravitation", *Astrophys. J.* **54**, 334-346 (1921).

3. The Heliocentric Viewpoint

Newtonian Physics: The Earth and Moon travel around the Sun at the same mean distance, $R_\odot$, the same mean angular rate, n, and consequently, in the same mean orbit with the same mean acceleration toward the Sun, $n^2 R_\odot$. Although they perturb each other, both instantaneous orbits are always concave toward the Sun.

Majorana Shielding: The Weak Equivalence Principle is violated, so the centripetal acceleration of the Earth is slightly less than that of the Moon. Because the mean rates are locked to each other, $\delta(n^2 R_\odot) = n^2 \delta R_\odot$.

4. The Geocentric Viewpoint

Newtonian Physics: Because of solar perturbations (not to mention other sources), the orbit of the Moon around the Earth is complex. Nevertheless, the orbit can be modeled and measured precisely.

Majorana Shielding: The constant heliocentric offset, $\delta R_\odot$, manifests itself as $\delta r_{☾} = \delta R_\odot$, the amplitude of a (synodic) monthly perturbation in the Earth-Moon distance.

5. Order of Magnitude Estimation of Effect on Earth-Moon Orbit

$$[\rho\, a]_\oplus \gg [\rho\, a]_☾$$

$$\left|\frac{\delta r_☾}{R_\odot}\right| \sim \left[\frac{M_G}{M_I}\right]_☾ - \left[\frac{M_G}{M_I}\right]_\oplus \approx h \rho_\oplus a_\oplus$$

$\delta r_☾$ is amplitude of monthly perturbation of orbit.
$R_\odot$ is distance to Sun (about which both the Earth and Moon orbit).

6. Order of Magnitude Calculation

$$\rho_\oplus = 5.5\ \mathrm{g/cm^3}$$
$$a_\oplus = 6.4 \times 10^8\ \mathrm{cm}$$
$$R_\odot = 1.5 \times 10^{13}\ \mathrm{cm}$$
$$\delta r_☾ < 4\ \mathrm{cm}\ ^{(3}$$

$$\therefore\ h < 10^{-22}\ \mathrm{cm^2/g}$$

<u>Detailed Analysis</u>[4]

$$h \leq 1.0 \times 10^{-21}\ \mathrm{cm^2/g}$$

[3]J. G. Williams, R. H. Dicke, P. L. Bender, C. O. Alley, W. E. Carter, D. G. Currie, D. H. Eckhardt, J. E. Faller, W. M. Kaula, J. D. Mulholland, H. H. Plotkin, S. K. Poultney, P. J. Shelus, E. C. Silverberg, W. S. Sinclair, M. A. Slade, and D. T. Wilkinson, "New Test of the Equivalence Principle from Lunar Laser Ranging", *Phys. Rev. Lett.* **36**, 551-554 (1976).

[4]D. H. Eckhardt, "Gravitational Shielding", *Phys. Rev. D.* **42**, 2144-2145 (1990). This calculation uses $\delta r_☾ = 0 \pm 4$ cm from Reference 3, so it is at the 68% confidence level. This is a conservative estimate because the lunar laser ranging experiment has since narrowed the uncertainty to about ±1 cm.

7. Geophysical Estimates Based on Earth Tides

Harrison[5]: $h < 10^{-15}\ \mathrm{cm^2/g}$

Slichter *et al.*[6]: $h < 8.3 \times 10^{-16}\ \mathrm{cm^2/g}$ (50% confidence)
$h < 2.6 \times 10^{-15}\ \mathrm{cm^2/g}$ (95% confidence)

8. Conclusions

For detecting Majorana shielding, analysis of lunar laser ranging data is approximately one million times more sensitive than analysis of earth tide data.

To a very high precision, there is no Majorana shielding.

Moreover, Majorana's theory is physically untenable without major modification. The reason for this difficulty and an approach to overcome it are given in the Appendix. Then the altered theory conforms, more or less, with the precepts of classical field theory even though it is ungainly, intrinsically barely plausible, and observationally unsubstantiated.

[5]J. C. Harrison, "A Note on the Paper 'Earth-Tide Observations Made during the International Geophysical Year'", *J. Geophys. Res.* **68**, 1517-1518 (1963).

[6]L. B. Slichter, M. Caputo, and C. L. Jager, "An Experiment Concerning Gravitational Shielding", *J. Geophys. Res.* **70**, 1541-1551 (1965).

9. Appendix: Majorana Shielding in the Procrustean Bed of Classical Field Theory

Geometrized units are adapted ($G = c = 1$). By Majorana's theory, if the acceleration of gravity $\vec{g}$ due to a remote source is tangent to the boundary of a body of shielding matter, then the attenuation of $\vec{g}$ is different on either side of the boundary, and so its curl at the boundary cannot remain zero; more generally, if $\vec{g} \times \vec{\nabla}\rho \neq 0$ then $\vec{\nabla} \times \vec{g} \neq 0$ almost everywhere. Such a non-conservative field is physically untenable, but Majorana's theory can still be salvaged if it is understood to be an approximation to a conservative theory. In Equation (1), let $M_1 \Rightarrow M$ and $M_2 \Rightarrow 1$ so that F represents a specific attractive force (acceleration) at a distance r from a source of mass M. According to Majorana's theory, F is the magnitude $|\vec{F}|$ of a radial vector $\vec{F} = -(\vec{r}/r)F$ whose divergence is

$$\vec{\nabla} \cdot \vec{F} = \frac{1}{r^2}\frac{d}{dr}(r^2 F) = h\rho F. \qquad (2)$$

Because Equation (2) represents a non-conservative field, if $\vec{F}$ is forced to be the gradient of a potential on the LHS, then the RHS must also be modified for the equation to be mathematically consistent. A way of doing this is to make the replacements

$$\vec{F} \Rightarrow -\vec{\nabla}\phi$$

and

$$F \Rightarrow \phi^2/M \approx M/r^2 \approx |\vec{\nabla}\phi| = F$$

Thus (2) becomes $\nabla^2\phi = -h\rho\phi^2/M$ which can be made marginally plausible by setting $h = \alpha M$ and proffering α rather than h as a universal constant. With the addition of a source term,

$$\nabla^2\phi = 4\pi\rho - \alpha\rho\phi^2$$

is now suitable over all space. The Lagrangian density of the field is

$$\mathcal{L} = \tfrac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - 4\pi\rho\phi + \alpha\rho\,\phi^3/3\,.$$

MICHEL DENIS
DOMAINE DE LA BATAILLE
7, RUE GUSTAVE-CHARPENTIER
78370 PLAISIR
TÉL. 30.54.23.43

EXPERIMENTS ON GRAVITY ANOMALIES DURING THE TOTAL SOLAR ECLIPSE IN FINLAND ON 22 JULY 1990

ABSTRACT

Author has recorded significant gravity anomalies by use of a short response time relativ gravimeter. This apparatus is derivated of an industrial dynamometer, it uses high gain optical amplification.

Gravity bursts have been highlighted from 16 minutes after the begining of the eclipse until 8 minutes after the maximum.

Video recording can be shown on SECAM television set.

EXPERIMENT WITH THE PARACONIC PENDULUM DURING THE TOTAL SOLAR ECLIPSE JULY 22, 1990 IN REGION OF BIELOMORSK

L.A. Savrov, R.A. Kashcheev, F. Pedrielli

State Sternberg Astronomical Institute, Moscow USSR
Kazan University, Kazan USSR
Ferrara University, Ferrara Italy

Abstract. The behaviour of the paraconic pendulum before and after eclipse is characterized by the permanent change of the azimuth of the plan of oscillation of pendulum as the analog of Foucault effect. The computer control and the photorecording are shown that the behaviour of pendulum during the eclipse distinguishes qualitatively from usual. The results have to be analyze carefully.

The idea of experiment is to study the motion of the paraconic pendulum during the solar eclipse like it was in experiments of prof. M. Allais /1/. Our group took part in the international scientific expedition organized by State Sternberg Astronomical Institute in the region of Bielomorsk-city in North Karelia.

The construction of the pendulum made by L. Savrov (fig. 1) was this time different from previous /2/ : the niobium cylinder body instead of bronze lens body, the rod and stirrup were made of titnium to avoid the electromagnetic influence. The mass of pendulum is 376 gramm, and the length is 20.5 cm, it was suspended by steel ball 3 mm in diameter, the support was made from high-carbon polished steel (fig. 2). The laboratory of Pr. F. Pedrielli provide us by special photoelectric sensor linked directly to PC-286 to control the start of pendulum (Fig. 2,3).

Automatic starting mechanism was placed under pendulum (Fig.3). The construction has been put in the steel vacuum camera (Fig. 4), the pendulum was started by remote control.

The beam from a source of light reflected by the small mirror placed on the top of pendulum forms a spot on the surface of sensor. The oscillations of pendulum give the vertical lightline on the surface of sensor and the change of azimuth of the plan of oscillation has to be shown on the surface of sensor as an analog of periodic curve.

Each start of pendulum was imaged immediately on display of PC, we could see the curve with its essential characteristics (form, period, harmonics and s.o.). After some time the spot was gone from the surface of sensor, and the recording continued on photofilm. In Fig. 5 one can see the pictures of photofilms before during and after eclipse. Even these rather bad images give the possibility to state that the picture during eclipse distinguishes from pictures before and after. The lightsource worked in permanent regime, so we received the films without traces of curves but with different kind of blackness of their surfaces. The degree of blackness corresponds the velocity of the change of oscillation plan of pendulum, less slowly the azimuth changes, more black is the film.

Conclusion. It takes a time to analyze and interpret all datas especially that in memory of PC. We consider our installation as a first model and experiment as a first step. Now we have the possibility to construct a new instrument and hope that the future experiment will advance us to the solution of this problem.

References

/1/ M.F.S. Allais, Should the laws of gravitation be reconsidered ? AERO/SPACE Engineering September, October, November 1959, Vol. 18, n° 9, 10, 11.

/2/ L.A. Savrov, Paraconic pendulum : proposal to detect the gravity screening effect during the full solar eclipse. Il Nuovo Cimento, Settembre-Ottobre, 1989, Vol. 12C, N° 5.

Fig. 1

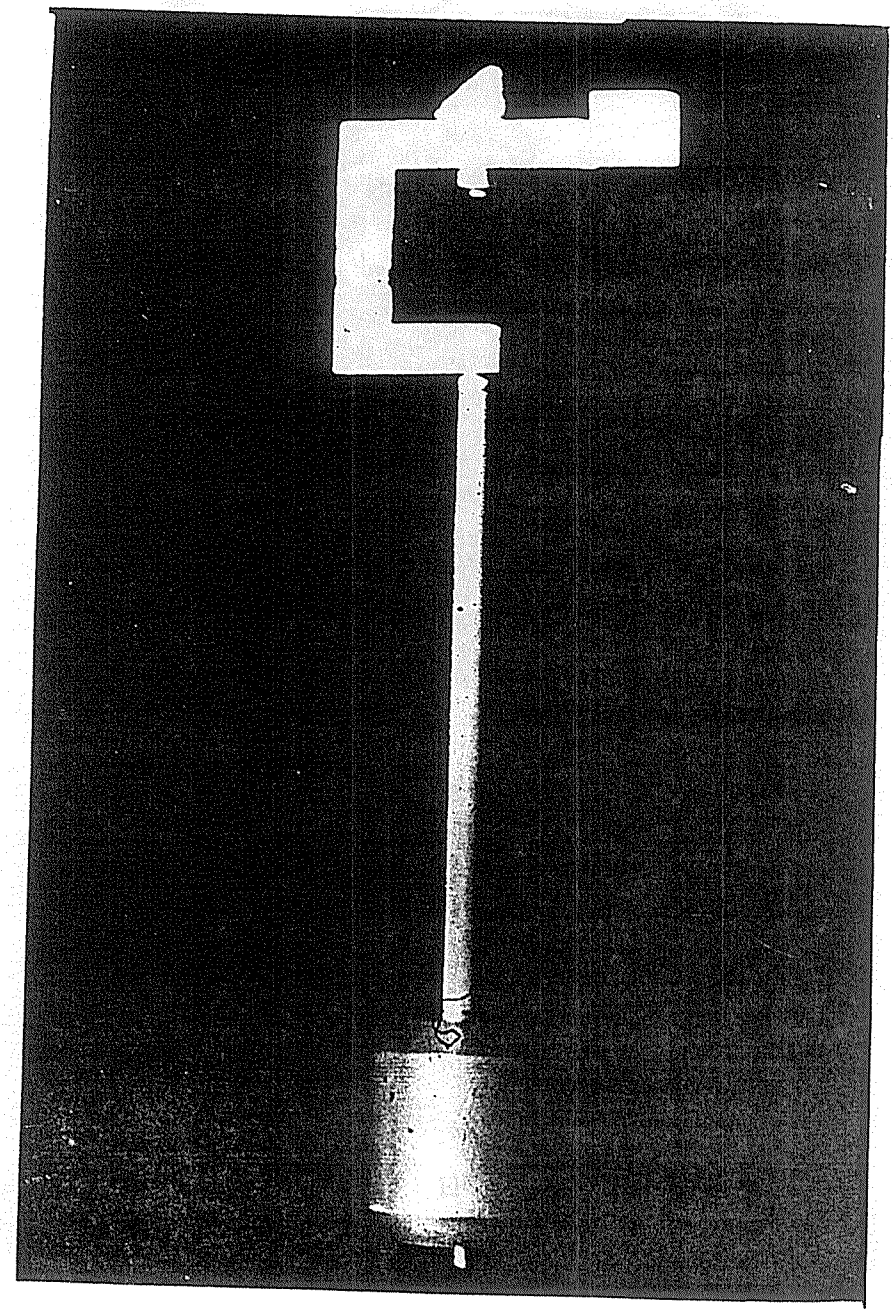


Fig. 2

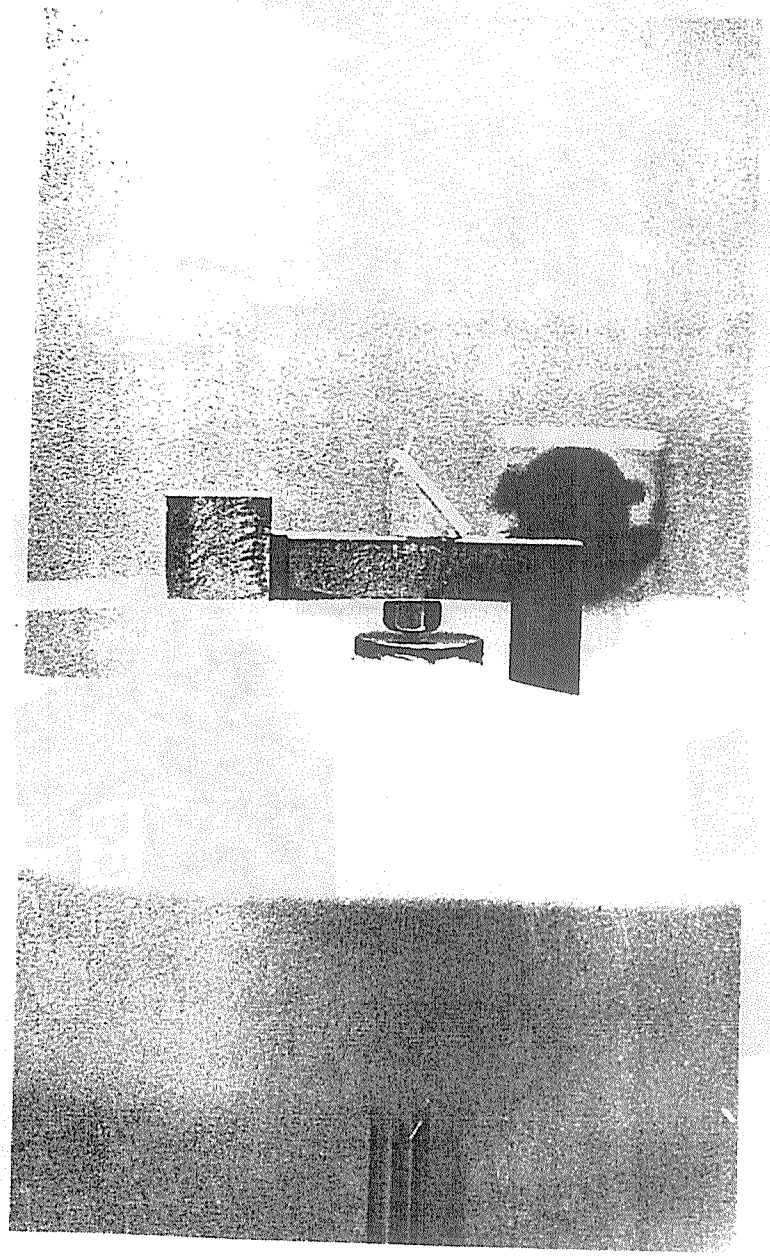


Fig. 3

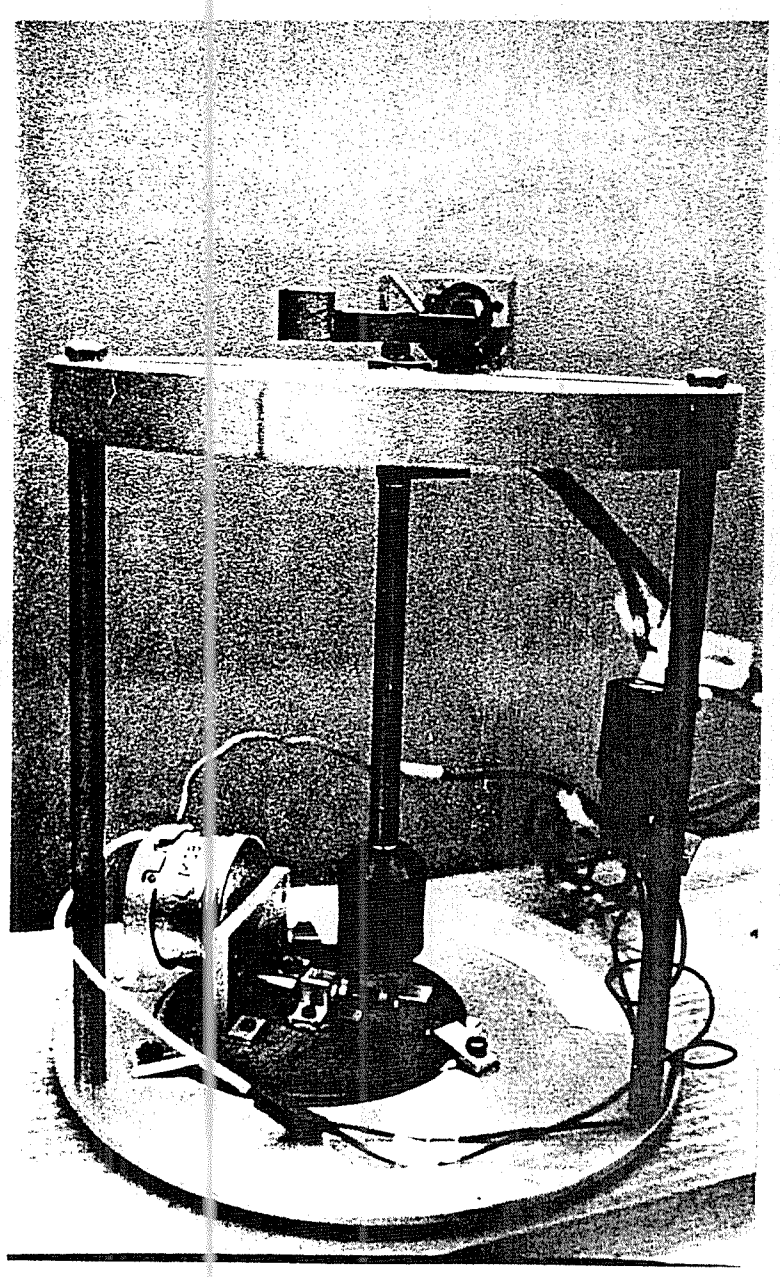


Fig. 4

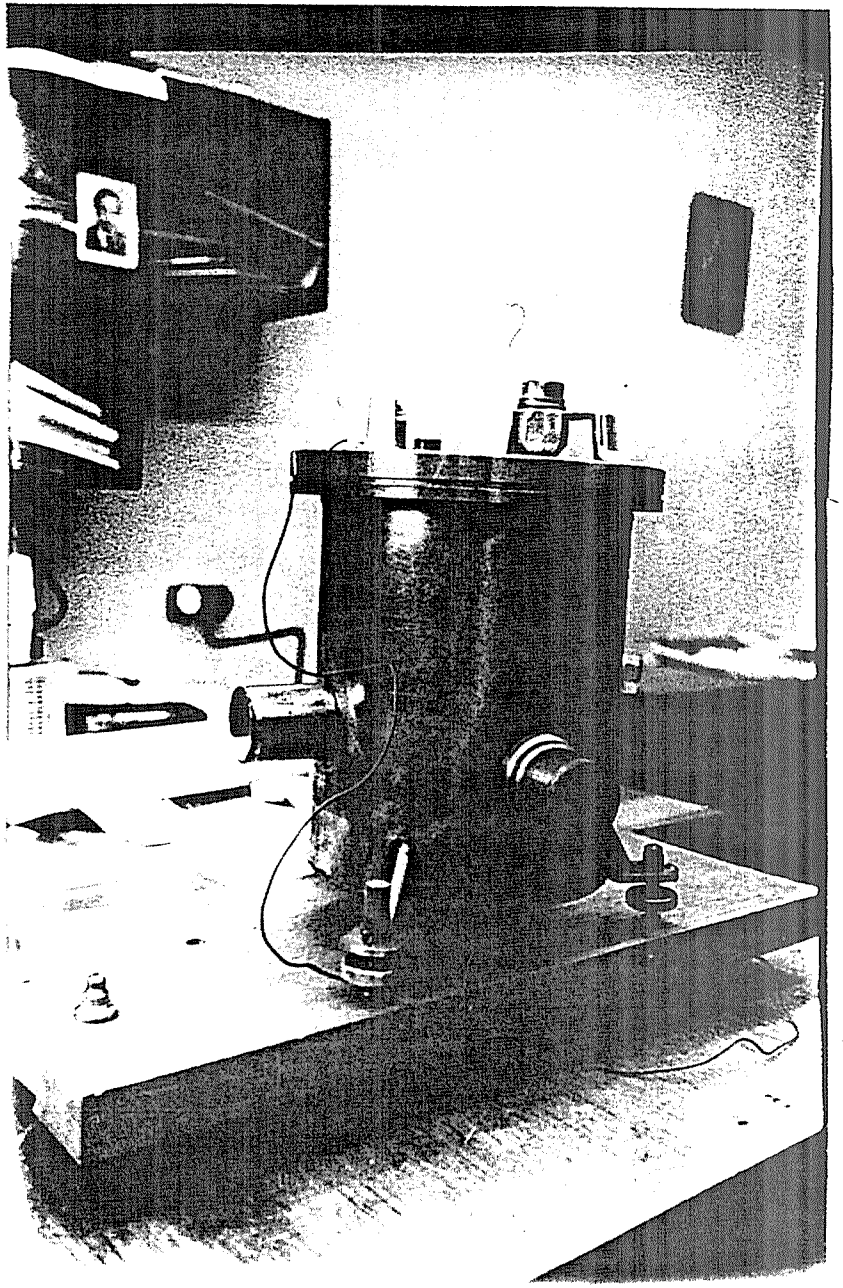
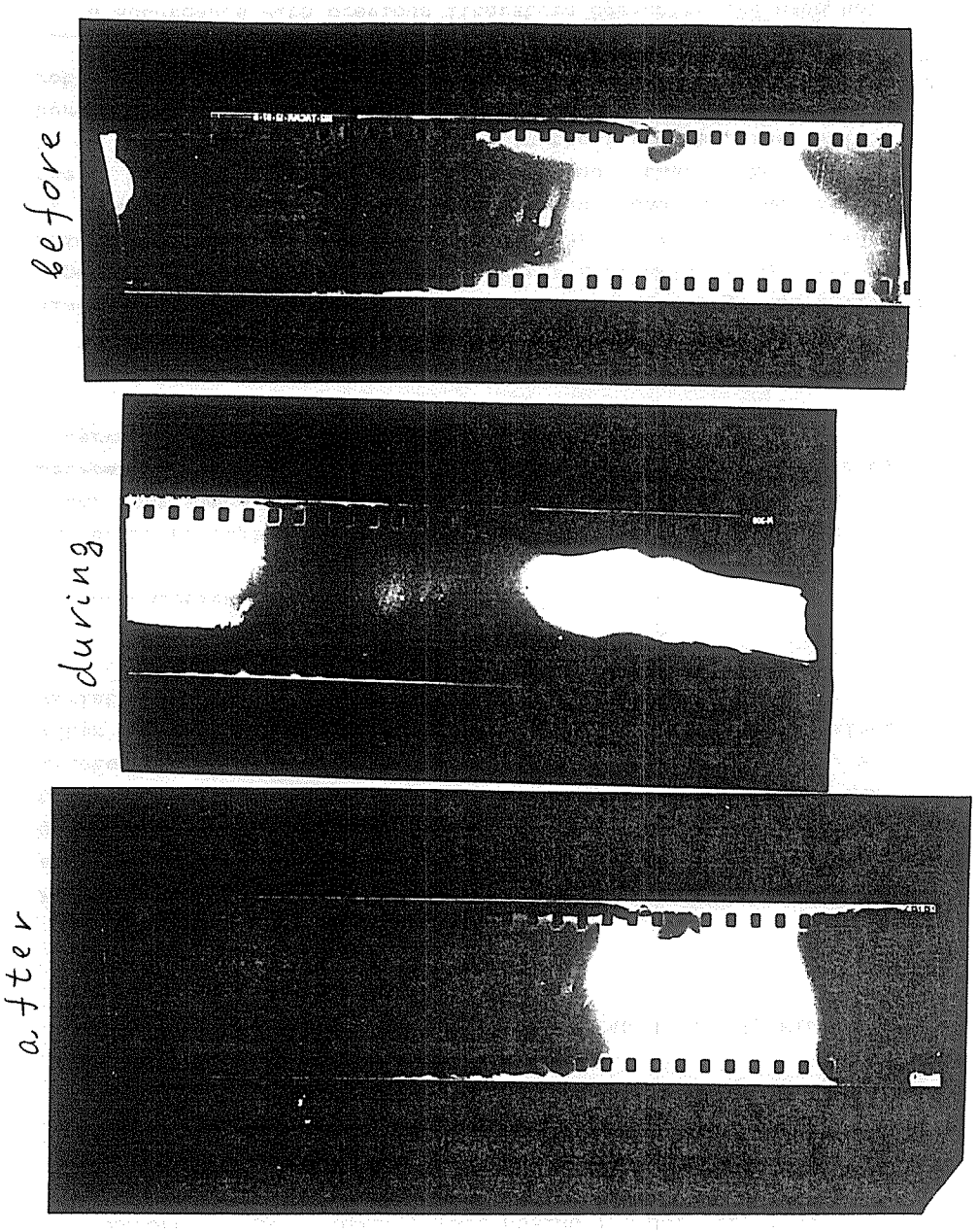


Fig. 5



ABSOLUTE GRAVITY MEASUREMENTS DURING THE JULY 22, 1990 TOTAL SOLAR ECLIPSE IN FINLAND

Jaakko Mäkinen

Geodetic Institute, Ilmalankatu 1A, SF-00240 Helsinki, Finland

Abstract. A 52-hour series of measurements with the JILAG-5 absolute gravimeter was made in order to look for variation in gravity, due to hypothetical shielding of the Sun's attraction by the Moon during the eclipse. The standard deviation of 507 six-minute averages, each consisting of 50 drops, was 3.7 µgal, and after long-period phenomena was removed, 2.5 µgal. No anomalous variation was detected.

1. Introduction.

In order to explain apparent irregularities in the motion of the Moon, Bottlinger in 1912 proposed that gravitational attraction between two point masses might be weakened by absorption by intervening matter according to the law

$$F = F_o \exp(- \int \lambda \rho \, dr)$$

also called Majorana gravitational shielding (see e.g. the review paper by Caputo, 1977). Here F_o is the attractive force with no shielding, ρ is the density of the matter, λ is the "coefficient of absorption" and the integral is taken along the line joining the two points. Bottlinger found that the value[1] $\lambda = 3 \times 10^{-15}$ $g^{-1}cm^2$ would explain the irregularities, which, however, were just errors in the time standard based on Earth rotation (Caputo, 1977).

1. In accordance with previous literature cgs-units are used here throughout.

Since then, most empirical investigations of gravity absorption have brought null results, i.e., no detectable absorption. The outcome is then a bound on the absorption coefficient λ, based on the estimated accuracy of the experiment. Three main types of observations have been used: laboratory experiments, variation in apparent gravity (magnitude and direction) during solar eclipses, and the motion of celestial bodies. Gillies (1987) gives an extensive bibliography.

In laboratory experiments, Majorana (1920) found a positive effect, $\lambda = 2...7 \times 10^{-12}$ $g^{-1}cm^2$, depending on the material of the shield. The latest laboratory-scale measurement is apparently that of Braginsky and Martynov (1968), yielding a null result $\lambda < 1 \times 10^{-12}$ $g^{-1}cm^2$.

If the absorption law is valid, the moon acts as a shield during an eclipse and the attraction of the Sun decreases in the zone where the Sun is at least partially obscured. Were the whole Earth uniformly subjected to the same decreased attraction, the earth-bound observer would only see the effect in the solar tide. It would be modified in the same proportion as the solar attraction, i.e. extremely little in absolute terms. However, since the decrease hits a relatively small slice of the Earth, to first order the plain decrease itself should be observed (excluding e.g. secondary atmospheric attraction effects due to temperature changes). This should work independently whether the Sun is below or above the horizon of the observation site. So far all experimental work seems to have been done with "visible" eclipses. Then gravimeters should show a increase in gravity. The plumb line (down) should be pushed away from the sun, whether below or above the horizon.

To give an idea of the magnitudes involved: One µgal is about 1.7×10^{-6} of the total solar attraction. For the February 15, 1961 eclipse Slichter et al. (1965) calculated that the decrease δa (in µgal) in attraction towards the Sun at totality and the absorption coefficient lambda (in $g^{-1}cm^2$) were related by

$$\lambda = 1.42 \times 10^{-15} \, \delta a$$

So in order to constrain λ below 1×10^{-15} $g^{-1}cm^2$ it suffices to constrain gravity change below 0.7 µgal for a zenithal (or nadiral) eclipse, or to constrain the change in plumb line below 0.14 milliseconds of arc for an eclipse close to the horizon.

Tidal gravimeters were first used by Brein (1957) and Tomaschek (1955) during the June 30, 1954 eclipse. Results from the February 15, 1961 eclipse were reported by Caputo (1962, 1977), who found $\lambda < 0.6 \times 10^{-15}$ $g^{-1}cm^2$, by Sigl and Eberhard (1961) who only state that λ is certainly below Bottlinger's value 3×10^{-15} $g^{-1}cm^2$, and by Tomaschek and Groten (1963) who give $\lambda < 0.7 \times 10^{-15}$ $g^{-1}cm^2$. They all used horizontal pendula. Dobrokhotov et al. (1961), Slichter et al. (1965), and Venedikov (1961) used tidal gravimeters. The most detailed analysis seems to be that by Slichter et al. (1965), who found for the vertical component $\delta a_g < 0.471$ µgal on the 95% level. The elevation of the Sun was 15° which put only 26% of the attraction on the vertical, so $\lambda < 2.6 \times 10^{-15}$ $g^{-1}cm^2$ on the 95% confidence level.

Arnautov et al. (1983) show a plot of absolute gravity measurements during the July 31, 1981 total eclipse in Novosibirsk, but do not comment it. The standard error is about 2 µgal, and no special effect can be seen.

In a different vein (no eclipses), Harrison (1963) noted that shielding of the Sun's attraction by the Earth itself should show up in the tidal amplitude at the period of the solar day, and be discernible in observations made close to the equator, where the tide at this period is very small. His null result was that the amplitude is less than 2 µgal, or $\lambda < 1 \times 10^{-15}$ $g^{-1}cm^2$. With the wealth of tidal observationss accumulated since it should now be possible to improve considerably on that.

The tightest bounds for λ come from observations on the movements of celestial bodies. Russell (1921) pointed out that because of self-shielding the ratio of gravitational to inertial mass would not be the same for the Earth and the Moon. This should show up as an influence of the Sun on the Earth-Moon system. Eckhardt (1990) used the results of lunar laser ranging to show that $\lambda = 0.0 \pm 1.0 \times 10^{-21}$ $g^{-1}cm^2$.

I report here briefly on absolute gravity measurements made in Finland during the July 22, 1990 total solar eclipse. The eclipse was not favorable for gravimetric observations: it took place at sunrise. The altitude of the Sun at totality was only 4.7° at the observation site. That was about the highest one could get in Finland. On the other hand, two permanent tidal stations with clinometers were in the zone of totality. Their results will be published elsewhere.

2. The experiment and results

The absolute gravimeter JILAG-5 of the Finnish Geodetic Institute belongs to the series of six instruments built by J.E. Faller and his associates at the Joint Institute of Laboratory Astrophysics (JILA), National Institute of Standards and Technology and University of Colorado, Boulder (USA). For a description see Faller et al. (1983), Niebauer et al. (1986), Niebauer (1987), Zumberge et al. (1982).

The approximate eclipse statistics are shown below:

Observation site lat = 62°40′ N, long = 30°56′ E, h = 160 m
First contact at 01:02:04 UT
Totality from 01:52:45 to 01:54:11 UT
Maximum at 01:53:28 UT
Altitude of the Sun at maximum 4.7°
Fourth contact at 02:46:50 UT; duration 1 h 44 min 46 s

At totality only 8% of the Sun's attraction is on the vertical. I have not calculated the shielding effect for the present eclipse. Using the value of Slichter et al. (1965) for the February 21, 1961 eclipse as an estimate, the absorption coefficient λ (in $g^{-1}cm^2$) and apparent gravity increase δa_g (in µgal) at totality

are related by

$$\lambda = 17 \times 10^{-15}\ \delta a_g$$

We would need to fix δa_g below 0.15 µgal in order to equal the bound of Slichter et al. (1965) for λ, obviously an impossible task. The experiment, however, was a useful exercise in taking a massive amount of absolute gravity data over a short period. Those aspects will be commented in more detail elsewhere.

The gravimeter was set up in the basement of a school on concrete floor (no pier). Drops were made in sets of 50. Each lasted 302 seconds including the reading of meteorological equipment and computing and displaying the results. The measurements were started 25 hours before the eclipse and continued for another 25 hours after it. Before the start the gravimeter had been running on the site for a day and a half. Room temperature variation during the series was 0.5° and atmospheric pressure variation 8 hPa (Figure 1,a). Drop-to-drop scatter in the sets was mostly 12 to 20 µgal, in a few sets up to 27 µgal when people were running around upstairs. The quadratic mean for 507 sets was 17.4 µgal. The raw set means are shown in Figure 1,(b). Altogether 507 sets, 25350 individual drop were made. The on-line computer program had rejected 4 drops. These seemed to be associated with banging doors and the like.

The results were corrected for atmospheric pressure variations using the locally observed pressure and the coefficient 0.3 µgal/hPa. A provisional tidal correction was made using the program by Heikkinen (1978), gravimetric factor 1.164 and zero phase lag. This left a considerable diurnal signal in the observations (Figure 1,c). The standard deviation of one set mean is 3.7 µgal.

There is a 6-minute gap in the observations at 19:00 UT, June 21, when the controlling microcomputer stopped because of a disc write error, and a 30-minute gap at 15:09 UT, June 22, when the isolation device (the super spring) had to be rezeroed because of drift and needed time to ring down. This latter event seems to have caused a jump in the results (Figure 1,c). Possibly the spring had already drifted outside its proper working range before adjustment.

After the variations at the diurnal and at the semidiurnal period and the jump are eliminated, the residual standard error of one set mean is 2.5 µgal (Figure 1, d). Neither Figure 1,(d) nor the enlarged section (± 12 hours around the eclipse) in Figure 2 show any anomalous gravity variation during the eclipse.

3. References

Arnautov, G.P., Yu.D. Boulanger, E.N. Kalish, V.P. Koronkevitch, Yu.F. Stus, and V.G. Tarasyuk., 1983: "Gabl", an absolute free fall laser gravimeter. Metrologia 19, 49-55.

Braginsky, V.B. and V.K. Martynov, 1968: Investigation of the effect of intermediate bodies on gravitational interaction (translation from Russian). Moscow Univ. Phys. Bull. 21, 35-40.

Brein, R., 1957: Die Schwerkraftregistrierungen. Beitrag zur Frage einer Absorption der Schwere. In: Beobachtungen zur Sonnenfinsternis 1954 in Südnorwegen. Deutsche Geod. Kommission B 34, Mitt. Inst. angew. Geod. 16, 30-45, 52.

Caputo, M., 1962: Un nuovo limite superiore per il coefficiente si assorbimiento della gravitazione. Atti della Reale Accademia di Lincei 32, 509-515.

Caputo, M., 1977: Experiments concerning gravitational shielding. In: Gravitazione Sperimentale, ed. B. Bertotti, Atti dei Convegni Lincei 34, 193-211.

Dobrokhotov, Yu.S., N.N. Pariisky, and V.I. Lysenko, 1961: Observations on tidal variations of gravity during the solar eclipse on February 15, 1961. Quatrième Symp. Int. Marées Terrestres, Commun. Obs. Royal Belgique, 188, Série Géophys. 58, 66-69.

Eckhardt, D.H., 1990: Gravitational shielding. Phys. Rev. D 42, 2144-2143.

Faller, J.E., Y.G. Guo, J. Gschwind, T.M. Niebauer, R.L. Rinker, and J. Xue, 1983: The JILA portable absolute gravity apparatus. BGI Bull. Inf. 53, 87-97.

Gillies, G.T., 1987: The Newtonian gravitational constant. An index of measurements. Metrologia 24 (Suppl.), 1-57.

Harrison, J.C.,1963: A note on the paper 'Earth-tide observations made during the International Geophysical Year'. J. Geophys. Res. 68, 1517-1518.

Heikkinen, M., 1978: On the tide-generating forces. Publ. Finn. Geod. Inst. 85, 150 pp.

Majorana, Q., 1920: On gravitation. Theoretical and experimental results. Philos. Mag. 39, 488-504.

Niebauer, T.M., 1987: New absolute gravity instruments for physics and geophysics. Ph.D. thesis, 155 pp. University of Colorado, Boulder, Colorado, 155 pp.

Niebauer, T.M., J.K. Hoskins, and J.E. Faller, 1986: Absolute gravity: a reconnaissance tool for studying vertical crustal motion. J. Geophys. Res. 91, 9145-9149.

Russell, H.N., 1921: On Majorana's theory of gravitation. Astrophys. J. 54, 334-346.

Sigl, R. and O. Eberhard, 1961: Horizontalpendelbeobachtungen in Berchtesgaden während der Sonnenfinsternis vom 15.2.1961. Quatrième Symp. Int. Marées Terrestres, Commun. Obs. Royal Belgique, 188, Série Géophys. 58, 70-75.

Slichter, L.B., M. Caputo, and C.L. Hager, 1965: An experiment concerning gravitational shielding. J. Geophys. Res. 70, 1541-1551.

Tomaschek, R., 1955: Tidal gravity measurements in the Shetlands. Effect of the total eclipse of June 30, 1954. Nature 175, 937-939.

Tomaschek, R. and E. Groten, 1963: Untersuchung von Gravitationswirkungen während der totalen Sonnenfinsternis am 15. Februar 1961. Nachrichten aus dem Karten- und Vermessungswesen, Inst. angew. Geod., Reihe 1, 25, 17-26.

Venedikov, A., 1961: Premiers enregistrements des marées terrestres a Sofia. Quatrième Symp. Int. Marées Terrestres, Commun. Obs. Royal Belgique 188, Série Géophys. 58, 144-148.

Zumberge, M.A., R.L. Rinker, and J.E. Faller, A portable apparatus for absolute measurements of the Earth's gravity. Metrologia 18, 145-152, 1982.

Figure 1. Results.

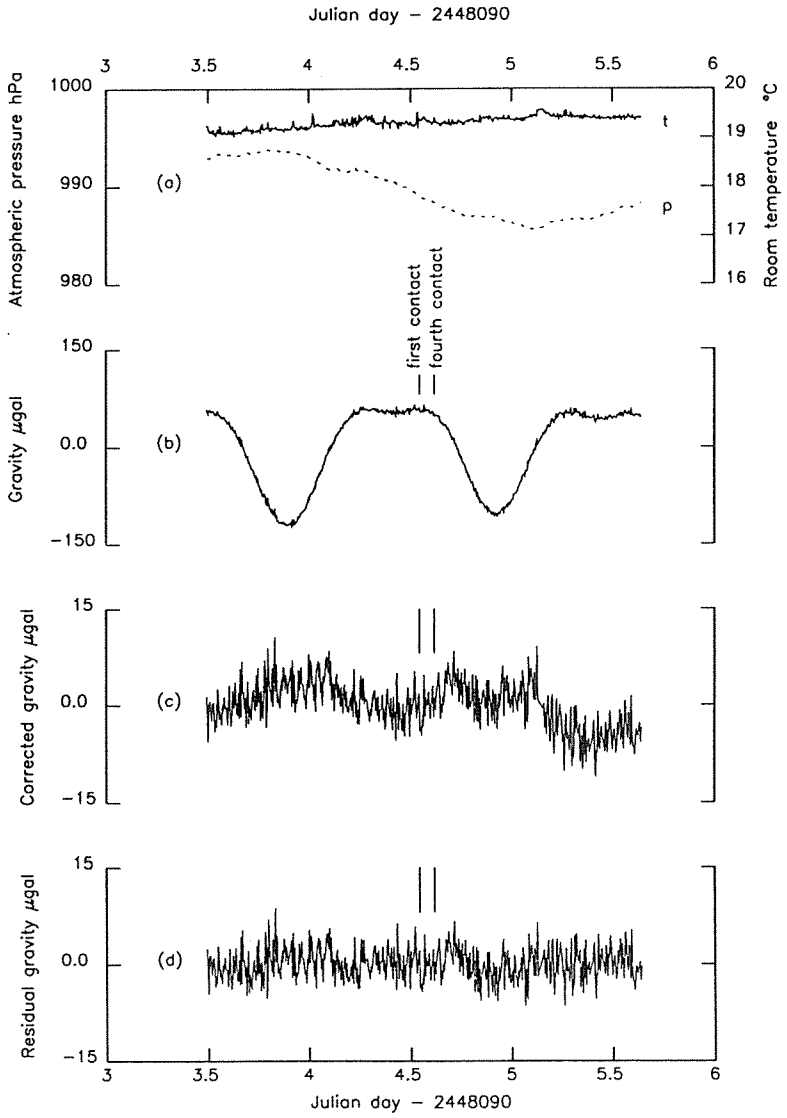
(a) Room temperature variations (solid line) and atmospheric pressure variations (dashed line) during the experiment.

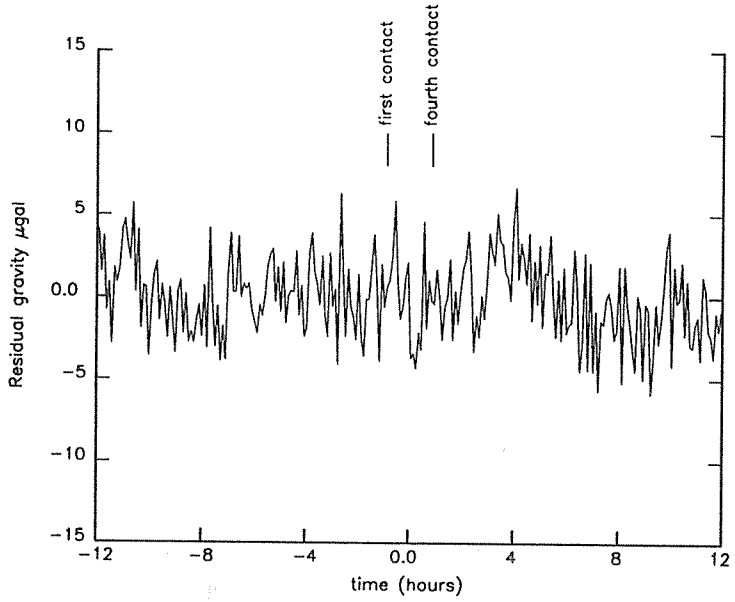
(b) The absolute gravity record. Each data point represents the mean of 50 drops.

(c) Record (b) corrected for tides and variations in atmospheric pressure. There is still considerable variation at the tidal periods. The jump at abscissa 5.1 is commented in the text.

(d) Residuals of (c) after removing the jump and the tidal periods. The two vertical bars point at the beginning and the end of the eclipse. No anomalous variation in gravity can be seen.

Figure 2. Absolute gravity residuals after removing the tidal periods. This is the same as the central part of Figure 1,(d). Time is centered at eclipse maximum. No anomalous variation in gravity is visible.




first contact
fourth contact
Residual gravity μgal
15
10
5
0.0
−5
−10
−15
−12
−8
−4
0.0
4
8
12
time (hours)

ARISTOTELES: Surface Gravity from Space Geometry.

Reiner Rummel,
faculty of geodesy,
Delft University of Technology.

1. Principle of Gradiometry.

Everybody likes the pictures of astronauts floating on board of the space shuttle "in the absence of gravity". We are also aware that important experiments in material science, chemistry, biology, or life sciences on board of space vehicles rely on the "zero-g"-environment. Strictly speaking, however, gravity is not felt in only one point inside the spacecraft, its center of mass. A proof mass placed at any other point experiences a small acceleration, relative to the center of mass and when viewed over several revolutions, carries out rather complicated motions relative to it, compare FIGURE 1. Of course, these

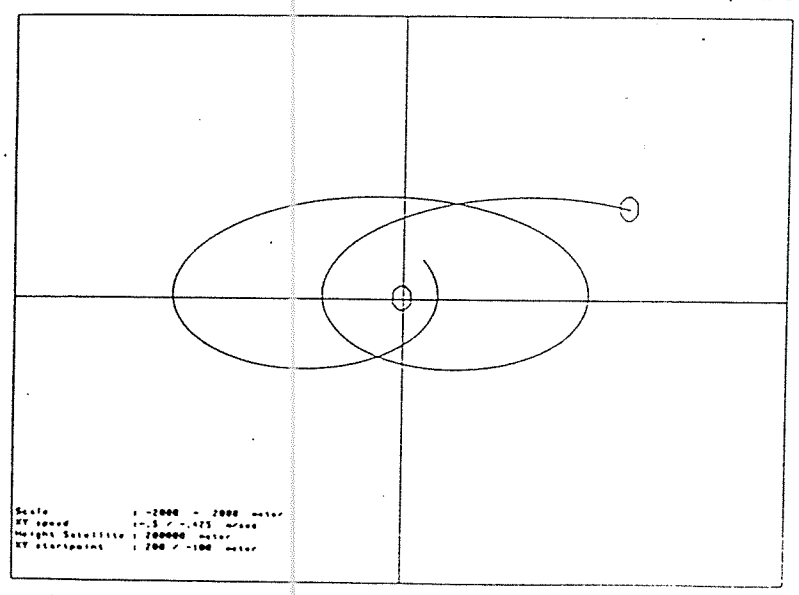


FIGURE 1: Motion of proof masses relative to center of mass of one central free falling body.

relative accelerations are small, much smaller than the 9.81 $\frac{m}{s^2}$ we experience on our spaceship - the Earth - relative to its center of mass. The accelerations are smaller by 10^{-7} to 10^{-6} at 1 m from the center of mass. They have their cause in the fact, that each point in space senses the gravitational attraction of the Earth in a slightly different manner, the main effect coming from the Earth's almost spherical mass. But also its flattening and all mass inhomogeneities inside the Earth and on its surface contribute to the relative accelerations. It is therefore only logical that one reverses this reasoning and tries to determine the structure of the Earth's gravitational field from the precise measurement of the relative motion of two or more adjacent proof masses in free fall. This is the principle of satellite gradiometry.

2. Gradiometry and Geometry.

Let us view this situation from a slightly different angle. Newton, when working on his law of gravitation, was inspired by a falling apple. Referring to the theory of gravitation as the tale of the falling apple, it would be appropriate to view gradiometry as the story of two falling apples. In their famous book on gravitation Misner, Thorne and Wheeler (1973) made this point clear. In one of their examples it is shown, that measuring the relative distance between the shortest paths taken by two ants walking on the skin of an apple, from two adjacent begin to two adjacent end points, the geometry of its curved surface can be derived. Translated to our case, shortest path means geodesic or free fall of two test particles (apples), from the relative motion of which the geometry of the curved space can be inferred; curved by the gravitational field of the Earth. It was Einstein, who interpreted gravity in terms of geometry, but one could as well call it a truly Italian view on gradiometry, because Marussi (1985), inspired by the famous Italian school of geometry, showed, that when measuring in a point all nine observable gradient components, the complete local geometry of the gravitational field is obtained (see also (Rummel, 1987)):

$$V_{ij} = \begin{pmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{yx} & V_{yy} & V_{yz} \\ V_{zx} & V_{zy} & V_{zz} \end{pmatrix} = -g \begin{pmatrix} k_1 & t_1 & f_1 \\ t_1 & k_2 & f_2 \\ f_1 & f_2 & -H \end{pmatrix}$$

where V_{ij}, gravitational tensor, $V_{xx} = \frac{\partial^2 V}{\partial x^2}$, a.s.o., the tensor components, which are the second derivatives of the Earth's gravitational potential, g, gravity, k_1 and k_2 the N-S and E-W curvature of the equipotential surface V = const., t_1, torsion, H, mean curvature, and f_1 and f_2, N-S and E-W curvature of the plumb line, when expressed in a local Cartesian (N, E, Up)-triad. The geometric view blends nicely with the physical one taken e.g. in (Bertotti, 1978). Out of the nine tensor components only five are independent in empty space, from the remaining four attitude information can be deduced. Two functions of the five independent components are even invariant with respect to the orientation of the measurement frame in space, compare (Sacerdote & Sanso, 1988).

One could probably directly observe the relative motion of adjacent proof masses in free fall, but it is more practical to constrain their relative motion by highly sensitive springs and measure instead the tension and compression of the springs, see e.g. (Falk & Ruppel, 1973, § 46). This is equivalent to saying that a gradiometer can be realized by a coupled system of highly sensitive micro-accelerometers. A gradiometer of this kind is envisaged for ARISTOTELES, see (Bernard, 1988).

3. ARISTOTELES - Difficulties or Challenges.

Naturally to put for the first time ever a gradiometer into space poses a variety of rather difficult problems. A few examples may make this clear:

- Because of the envisaged low altitude of only 200 km the satellite is heavily affected by air drag in the along track direction. The linear acceleration due to drag exceeds the gravitational differential acceleration by a factor of ten. As a consequence, the acceptable dynamic range of the accelerometers is exceeded and no accelerometer components shall be measured in this direction. The gradiometer shall be restricted to the normal plane (= (y-z)-plane). Instead of all nine only four components shall be delivered.
- Because all individual accelerometers, of which the gradiometer is composed, will never be exactly identical, the common mode rejection principle shall be violated. (Common mode rejection = skin forces, acting on the satellite, cancel out during the process of differencing because they affect all parallel accelerometers in the same way.) As a result, drag fluctuations (Barlier, 1988), compare FIGURE 2, may disturb the cross track components as a second order effect.

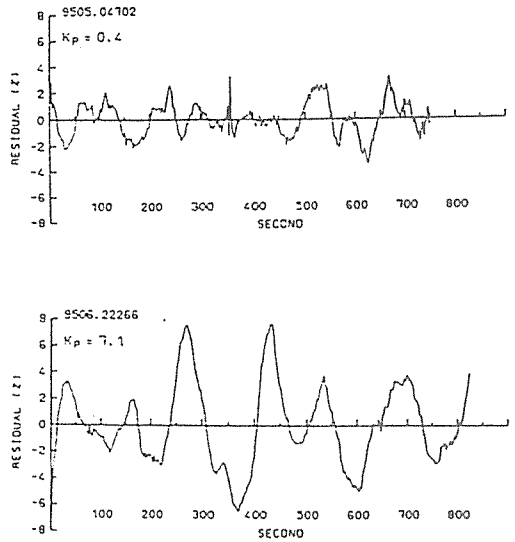


FIGURE 2: Percentage of Density Variations with respect to the Mean at altitudes between 270 km and 320 km (by Barlier, F. & C. Berger).

- Since the gradiometer cannot be sufficiently calibrated on Earth and might somewhat change its characteristics during the mission, biases and drift cannot be completely avoided. As a consequence the very long wavelengths part of the measurement spectrum cannot be observed reliably ($< 5 \cdot 10^{-3}$ Hz or $\lambda > 1500$ km).

- In order to keep the spacecraft in its low orbit corrections have to be applied periodically. Due to the fuel consumption during these correction manouevres, the gravitational field of the spacecraft itself changes. This effect can hardly be distinguished from the terrestrial gravitational signal.

Each of these difficulties poses a challenge in itself. Special design of the fuel tanks, so as the avoid sloshing, proper symmetrical arrangement and careful modelling of the gravity effect of fuel consumption should suffice to solve the problem of changing self-gravitation. The long wavelength part of the gravitational field must become available, in order not to jeopardize the oceanographic mission goals seriously. A GPS-receiver on board of ARISTOTELES would solve this problem, as shown e.g. by Colombo (1988). The consequences of non-linearities of the differential accelerometers are still open. Some claim movable flaps on the spacecraft would take care of the cross-track drag effect. However it is still uncertain whether drag fluctuations reach critical levels and whether they cannot be measured and corrected for. Finally, the restriction of the gradiometer to the cross-track plane is no major obstacle, as long as sufficiently accurate spacecraft attitude determination can be achieved. It diminishes, however, somewhat the beauty of the mission, in terms of delivering the complete local geometry, and asks for some modification in the gravity recovery procedures.

4. Science and Application.

For a pure theoretician ARISTOTELES shall deliver SPACE geometry of curved space with high precision and resolution. A second mission, planned by NASA for around 2000 and equipped with the super-conducting gradiometer by Paik & Richard (1986) shall provide improved SPACE geometry and allow to detect variations in TIME, when compared with the results of ARISTOTELES. Finally, if one would succeed to improve gradiometer technology even further, so as to detect relativistic effects (see (Soffel, Gill, Ruder & Schneider, 1987)), SPACE-TIME geometry could be measured for the first time. (Appropriate names of these three missions could be ARISTOTELES, GALILEI, and EINSTEIN. Unfortunately the latter two were given already to other experiments.)

These three experiments would form a highly attractive mission program.

To measure the global space-geometry may be a convincingly enough argument for theoreticians, but there are various science-application arguments as well. Before we give them, let us look into the question in what ways gravity manifests itself. Naturally gravity makes us stick to the Earth, obviously without flattening us all too much. Gravity also tells us what is up and down. Hence it results in a natural definition of heights, which permits to build e.g. buildings, streets, and canals in a sensible way. Gravity also fully determines the space trajectory of any object in free fall, whether it is the proof mass of a free fall gravity apparatus, a missile or a satellite, see FIGURE 3. All mass anomalies, inside the Earth or on its surface,

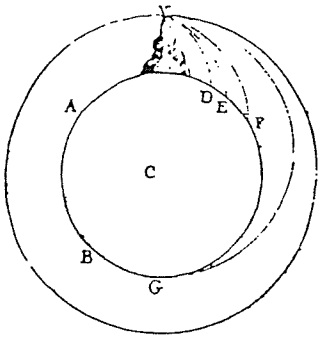


FIGURE 3: Free Falling Bodies (from Newtons "De mundi systemate" (1715)).

like mountains, result in gravity anomalies, where we define gravity anomaly as the difference of observable gravity and the gravitational attraction of some idealized body. Anomaly is synonymous to imbalance and imbalance to dynamics. Everything that gets imbalanced as a result of dynamic processes inside the Earth, in particular heat transfer, is tried to be smoothed out by gravity, compare (Kaula, 1977) or (Rummel, 1984). Finally in the complete absence of winds, storms, and surges etc. the ocean surface would be completely level, a level or equipotential surface called the geoid. When comparing the geoid with

e.g. a rotating, inhomogeneous fluid of the same mass and angular velocity as the Earth one would observe that the two surfaces deviate by up to 100 meters, compare FIGURE 4. The deviation of the geoid from such an idealized surface or simply from an ellipsoid is denoted geoid height. Again the existence of geoid heights reflects the presence of various dynamic processes inside the Earth. The deviation of the actual surface of the Earth from a level surface are the land

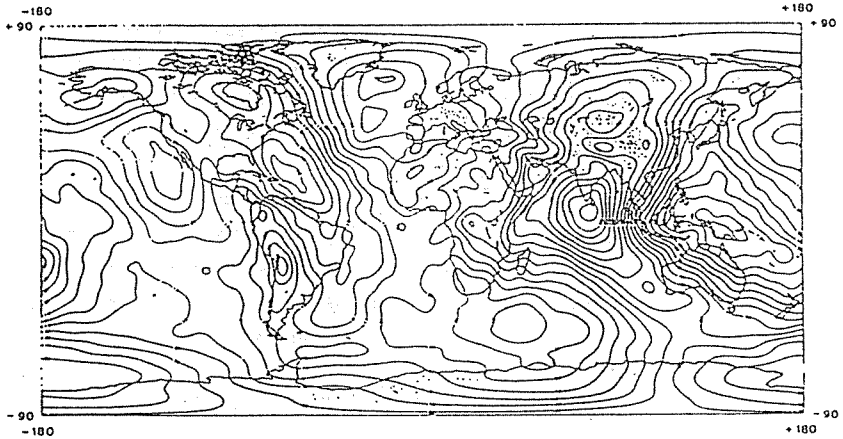


FIGURE 4: Worldwide Geoid as derived from the GRIM-L1 potential coefficients.

topography of up to 8000 m and the dynamic ocean topography of 1 to 2 meters. Their presence results on the one hand in ocean circulation and on the other hand, in continental areas, in everything that might be circumscribed in the widest sense as erosion.

Of course, we have already knowledge of the Earth's gravitational field, from terrestrial gravity measurements and indirectly from the analysis of satellite orbits (= proof masses in free fall) and satel lite altimetry, but not with sufficient accuracy and spatial resolu tion, see e.g. (Rummel, SESAME) or (Lambeck, 1989). As far as gravity is concerned satisfactory information is only available in North America, Europe and most of Australia, see FIGURE 5. Since the geoid heights are computed from gravity anomalies by Stokes integral formula

$$\Delta N = \frac{R}{4\pi g} \int_{\sigma} St(\psi)\Delta g \, d\sigma$$

errors in areas outside those mentioned above are propagated into geoid errors all over the globe of between 0.5 to 5 meters.

In conclusion: Gravity is known in some parts of the Earth satisfactory, the geoid nowhere.

Above it was explained in which ways gravity manifests itself. Let us now, along the same line, give five examples, that should demonstrate very desirable applications of the gravitational information as obtained from ARISTOTELES.

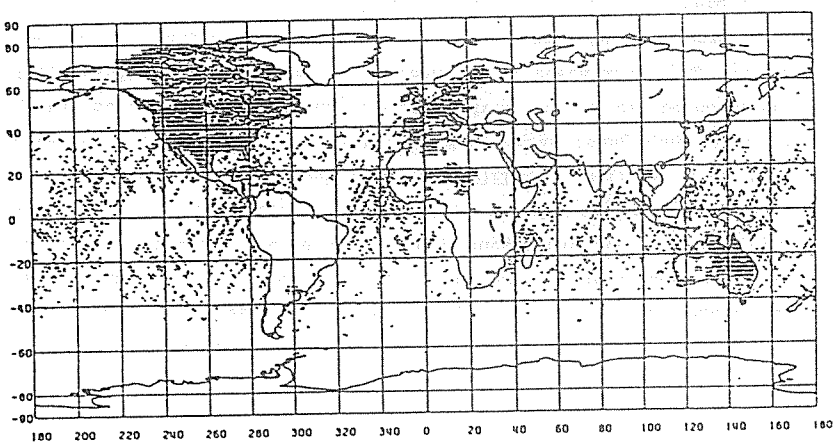


FIGURE 5: $1^{o} \times 1^{o}$ Gravity Anomalies with a Precision of better than 5 mgal (from (Rapp, 1980)).

Example 1: Geodesy.

Accurate heights are needed for civil constructions, mapping and exploration. They are obtained by geodetic levelling, a very time consuming and expensive procedure. Ourdays geometric heights can be obtained fast and efficiently from space positioning, e.g. GPS. The geometric heights can be converted to levelled heights by subtracting the geoid, see FIGURE 6. Hence from a combination of GPS and a precise

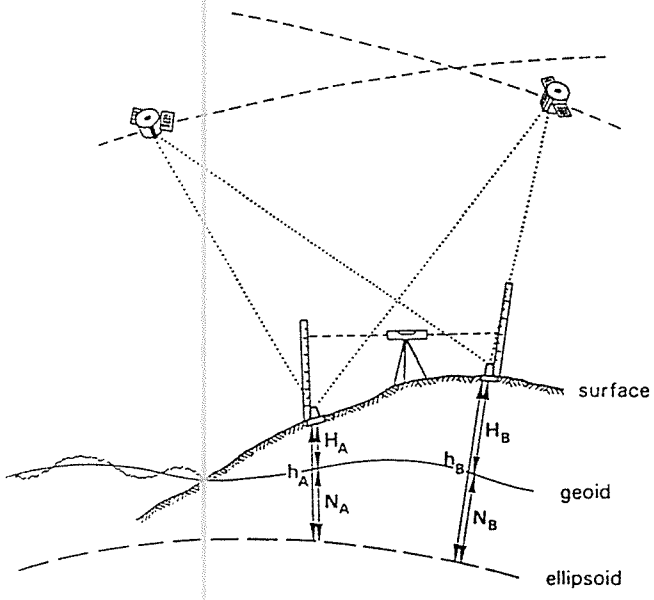


FIGURE 6: GPS based on geometric heigths h, geoid heights N, and leveled (orthometric) heights H.

geoid levelling can either be controlled independently or replaced. In those areas where good gravity information is available already, ARISTOTELES will eliminate all medium and longwavelength distortions, in unsurveyed areas, GPS together with ARISTOTELES will provide high quality height information at the 10 cm level.

Example 2: Satellite Orbits.

For any positioning from space, in particular for satellite altimetry, the uncertainty in the orbit of the spacecraft is the limiting factor. ARISTOTELES will eliminate basically all gravitational uncertainties in satellite orbits and bring the radial error of future altimeter satellites to below the 20 cm envisaged for TOPEX/POSEIDON or ERS-1. See also (Reigber, same issue).

Example 3: Solid Earth Physics.

An excellent account of all possible contributions of ARISTOTELES to solid earth physics is given in (GRAVITY WORKSHOP, 1987) and (Lambeck, 1989) and needs not to be repeated here. Let me mention only two aspects. For the first time in history we shall get full coverage of the gravity field in the polar regions. Second, the gravity anomaly field coming from the ARISTOTELES gradiometer has its origin mainly in mass inhomogeneities of the continental and oceanic lithosphere. Together with height information and regional tomography, e.g. (Spakman, 1988) a much deeper understanding of tectonic processes should be obtainable. If one would even succeed, so to say, in striping off the lithosphere part of the gravity field, global seismic tomography together with the remaining long and medium wavelength part of the gravity field would represent two completely independent global data sets that will provide invaluable constraints on modelling core and mantle processes.

Example 4: Physical Oceanography.

Probably the most fascinating applications of the results of ARISTOTELES are obtained in the field of physical oceanography. Satellite altimetry proved to be very successful for measuring the variations of the ocean surface. Altimetry in combination with a precise geoid - as derived from ARISTOTELES - will be even more powerful. It shall deliver global dynamic ocean topography. From it global surface circulation and its variations in time can be computed. This results in a completely new dimension of ocean modelling. Had in the past circulation to be derived from sparsely scattered ship measurements, it is now available globally, and with a high repetition rate. Circulation allows the determination of transport processes of e.g. plankton or polluted material. But, even more important, it also maps surface heat transport. Heat transport and exchange is still not well understood but of major importance for understanding climate processes, compare e.g. (IAPSO, 1985) or (Hibbs & Wilson, 1983). This leads us to our last example.

Example 5: Earth System.

There is a growing awareness of global environmental problems, whether it is the CO_2 question, the rapid decrease of rain forests, or global sea level changes. More and more it is agreed upon that the Earth has to be viewed upon as one complicated system, with sophisticated and not yet understood interactions of the dynamic Earth with its oceans, ice, atmosphere, and biosphere. What is the role of ARISTOTELES in this context? ARISTOTELES does not, for instance, tell us whether sea level rises or falls. This has to be studied from long records of tide gauges measurements, linked into one monitoring system, see (Wyrtki & Pugh, 1984), but it is essential to bring them into one system and make sea level records comparable in different parts of the world. In combination with altimetry it will also, so to say, establish a global field of tide gauges at the open sea, from which the redistribution of water masses can be derived. In short, as part of the complicated system, called Earth, the gravitational field and the geoid can be viewed as an almost static reference for many rapidly changing processes and at the same time as a "frozen picture" of tectonic processes that evolved over geological time spans.

References.

Barlier, F., C. Berger: Rapid Density Fluctuations - Statistical Applications to Gradiometry, WP140 in: Study on Precise Gravity Field Determination Methods and Mission Requirements, ESA Contract no. 7521/87/F/FL, 1989.

Bernard, A.: The GRADIO Spaceborne Gravity Gradiometer: Development and Accommodation, in: Proc. Chapman Conference on Progress in the Determination of teh Earth's Gravity Field, 184-187, Fort Lauderdale, 1988.

Bertotti, B.: Twin Probes for Space Geodesy, in: Proc. European Workshop on Space Oceanography, Navigation and Geodynamics, ESA SP-137, 169-170, 1978.

Colombo, O.L.: High Resolution Analysis of Satellite Gradiometry, in: Proc. Chapman Conference on Progress in the Determination of the Earth's Gravity Field, 188-192, Fort Lauderdale, 1988.

Falk, G., W. Ruppel: Mechanik, Relativität, Gravitation, Springer, Berlin, 1973.

Gravity Workshop: Geophysical and Geodetic Requirements for Global Gravity Field Measurements 1987-2000, Geodynamics Branch, NASA, Colorado, 1987.

Hibbs, A.R., W.S. Wilson: Satellites Map the Oceans, IEEE Spectrum, 46-53, 1983.

IAPSO Advisory Committee on Tides and Mean Sea Level: Changes in Relative Mean Sea Level, EOS, Transactions AGU, 66, 45, 754-756, 1985.

Kaula, W.M.: Geophysical Inferences from Statistical Analysis of the Gravity Field, in: The Changing World of Geodetic Science, ed.: U.A. Uotila, vol. I, 119-141, Dept. Geodetic Science, 250, Ohio State University, Columbus, 1977.

Lambeck, K.: ARISTOTELES: A European Space Agency mission for the Study of the Earth's gravity field, Report for ESA, Canberra, 1989.

Marussi, A.: Intrinsic Geodesy, Springer, Berlin, 1985.

Misner, Ch.W., K.S. Thorne, J.A. Wheeler: Gravitation, Freeman and Company, San Francisco, 1973.

Paik, H.J., J.-P. Richard: Development of a Sensitive Superconducting Gravity Gradiometer for Geological and Navigational Applications, NASA Contractor Report 4011, NASA, 1986.

Rapp, R.H.: The $1^0 \times 1^0$ Mean Anomaly Field of the Earth and Prospects for Its Improvement, in: proc. 4th Intern. Symposium Geodesy and Physics of the Earth, part II, p. 431-455, Karl-Marx Stadt, 1980.

Rummel, R.: Geodesy's Contribution to Geophysics, Interdisciplinary Science Reviews, 9, 2, 113-122, 1984.

Rummel, R.: The Earth's Gravity Field, Proc. ESA Special Workshop on 'Solid Earth Science & Application Mission for Europe', 69-76, ESA SP-1080, 1986.

Rummel, R.: Satellite Gradiometry, Lecture Notes in Earth Sciences, vol. 7, Mathematical and Numerical Techniques in Physical Geodesy, ed. H. Sünkel, 318-363, Springer, Heidelberg, 1986.

Sacerdote, F., F. Sansó: Some Problems Related to Satellite Gradiometry, Bulletin Géodésique, 1989 (in print).

Soffel, M., E. Gill, H. Ruder, M. Schneider: Relativistic Theory of Gravimetry and Gradiometry, Proc. of IAG symposia, vol. I, 101-105, Vancouver, 1987.

Spakman, W.: Upper Mantle Delay Time Tomography, Instituut voor Aardwetenschappen, 53, Rijksuniversiteit Utrecht, 1988.

Wyrtki, K., D. Pugh: Plan for a Global Sea Level Network, IOC/CCCO Publication INF-563, 1984.

INVERSION OF AN OVERDETERMINED BOUNDARY VALUE PROBLEM THEORY AND RESULTS

F. Migliaccio, F. Sanso, M. Brovelli

I.T.M., Milano, Italy

At ITM several problems have been considered to set up a possible line of reduction of data taken by an orbiting gradiometer (Aristoteles) following the traditional geodetic approach to B.V.P. : these problems have led us to confront difficult theoretical questions, as well as, specially in the last part of the contract time, to perform simulations demonstrating the predicted behaviour in the estimation process.

More specifically the following questions have been addressed :

(1) how to treat the attitude problem :

1A) the possible use of invariants has been proposed, in case a full components gradiometer is available, with particular regard to the singularity of linearized equations in the spherical approximation case ;

1B) an error analysis has been assessed to prove that with existing gravity models one can hope to have information on ω_y at the level of accuracy of 2 E.U. roughly ;

(2) how to treat a B.V.P. with more data than necessary (e.g. more than one tensor component) :

2A) it has been proved that the correct theoretical tool is the analysis of overdetermined B.V.P., which is a very recent theoretical achievement, presupposing that data are affected by a white noise, possibly varying from point to point ; the method allows for the simultaneous treatment of several components, particularly T_{zz}, T_{zy} ; the structure of error degree variances has been derived under simple hypothese ;

2B) a particular care should be taken when treating boundary value operators which are not diagonal in the spherical harmonic representation, like the T_{yy} case ; in this case the new concept of biorthogonal sequencies seems to be the most appropriate ;

3) comparison and numerical experiments ;

3A) a theoretical comparison between the B.V.P. approach and a pure least squares approach with a truncated model has been set up, giving arguments that allow to predict for the latter a certain degree of bias in the estimates of the potential coefficients, due to higher coefficients not accounted for in the model ; the B.V.P. approach on the contrary should not be effected by the same phenomenon ;

3B) a numerical experiment of least squares adjustment up to degree 89 (only odd degrees) for a field generated with odd degrees up to 101, has proven that the effect indeed takes place, in the quadratic average affecting significantly only degrees 85,87 ; however for specific particular orders the bias can be very significant down to degree 71 and we still find individual coefficients which are strongly biased for order zero and very small degrees ;

3C) a numerical experiment of gravity field reconstitution from T_{zz} at 200 km has shown a significant agreement with the theoretically predicted errors. Figure 1 shows the theoretical cumulative error on the geoid height, to be compared with the empirical error computed from the numerical experiments (Fig. 2 and 3 - on figure 2 the theoretical curve is shown multiplied by a factor of 1.4 which is the ratio between the theoretical noise and the one actually used).

To conclude we can say that the B.V.P. approach has been shown to be a handable tool to treat gradiometric data, under certain simplifying hypotheses, among which the most intriguing is probably that the whole surface of a sphere (at satellite altitude) has been surveied.

Fig. 1

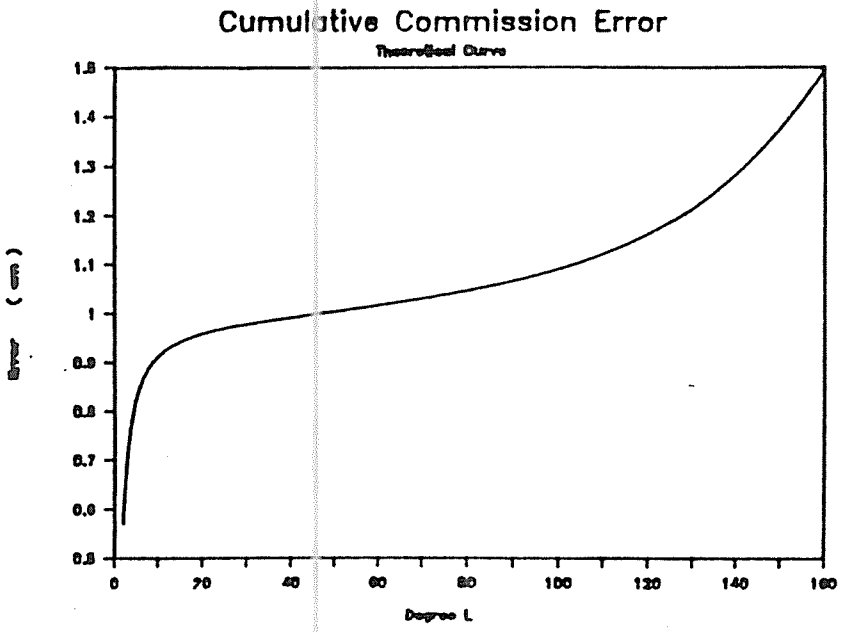


Fig. 2

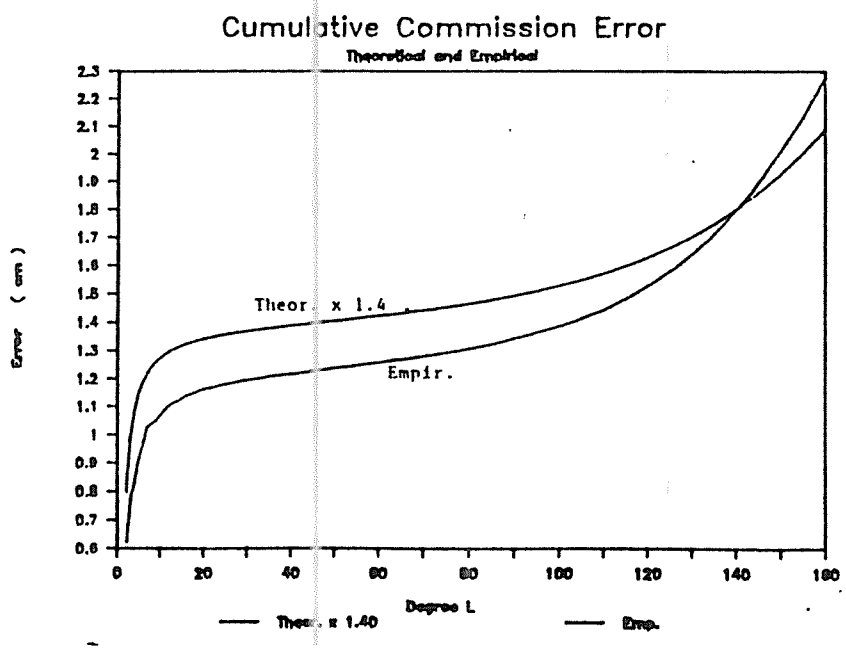
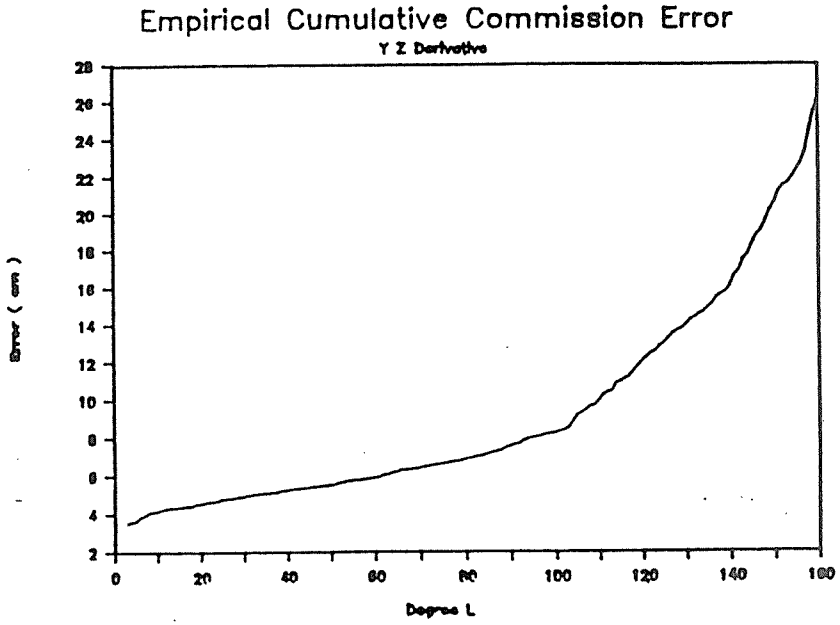


Fig. 3



METHODS OF GLOBAL RECOVERY OF HARMONIC COEFFICIENTS FROM SGG IN THE GENERAL CASE

G. Balmino, J.P. Barriot

Bureau Gravimétrique International, Toulouse, France

The effort was aimed at the global recovery of a large set of coefficients of the Earth gravitational potential expanded in series of harmonic functions, from real (simulated) measurements of some components of the gravity gradient tensor in satellite axis, with no peculiar geometry nor regular temporal distribution. Compared to the semi-analytical approaches described in the other workpackages of this task, this is a "brute force" technique, very costly in computer time and resources.

Recognizing the dependence of the instrument accuracy on the bandwidth, it is first proposed to take account of a long wavelength reference model of the best available quality to cope with the low frequency errors of the gradiometer, also to use calibration areas with dense reliable gravity informations.

The strategy is then to write one observations equation for each measurement, which relates the observable (one or several components of the gravity gradient tensor) in satellite axis, to the spherical harmonics to be determined (in practice above the cut-off frequency of the reference model). The solution of this large system is obtained in the least squares sense.

To do so, we form the normal equation (by blocks) and use a special implementation of the Cholesky algorithm to solve the system. Optimizing techniques based on the vectorization of operations (whenever possible) were used and specific software developed.

Many tests were performed on a C.D.C. Cyber 992 of the french space center, which validated the whole process.

The big simulations were conducted on a CRAY-2, which required to transport and adapt the software in view of some operational constraints.

The largest simulations performed used a one month, 160 km mean altitude orbit generated by very accurate numerical integration, and aimed at the recovery of a full (100 x 100) spherical harmonic model (Fig. 1) from the sole measurement of the radial component of the tensor, assuming a 10^{-2} E (10^{-11} s^{-2}) random error and an orbital error in the range of a few meters (largest at 1 cycle/rev. frequency). The gravity field is shown to be recovered with an r.m.s. error of 2 mgals (2.10^{-5} ms^{-2}) for 1° x 1° average values (Fig. 2), which is very consistent with other simulations. The dependence of the solution quality on the data coverage was also studied, as well as the numerical stability of the normal system.

This simulation, which involved more than 80 000 equations and about 10 100 unknowns, was quite costly and that is why it was not possible to derive a full (180 x 180) model. However we are confident, from our analysis, that the same algorithms and software will works as well on larger systems and that computer time in the future will be drastically reduced thanks to the constant progress in computer design and architecture.

Fig. 1- Decimal logarithm of degree variances of difference coefficients for terms of degree ≥ 3, (100 x 100) field recovered from 82944 observations.

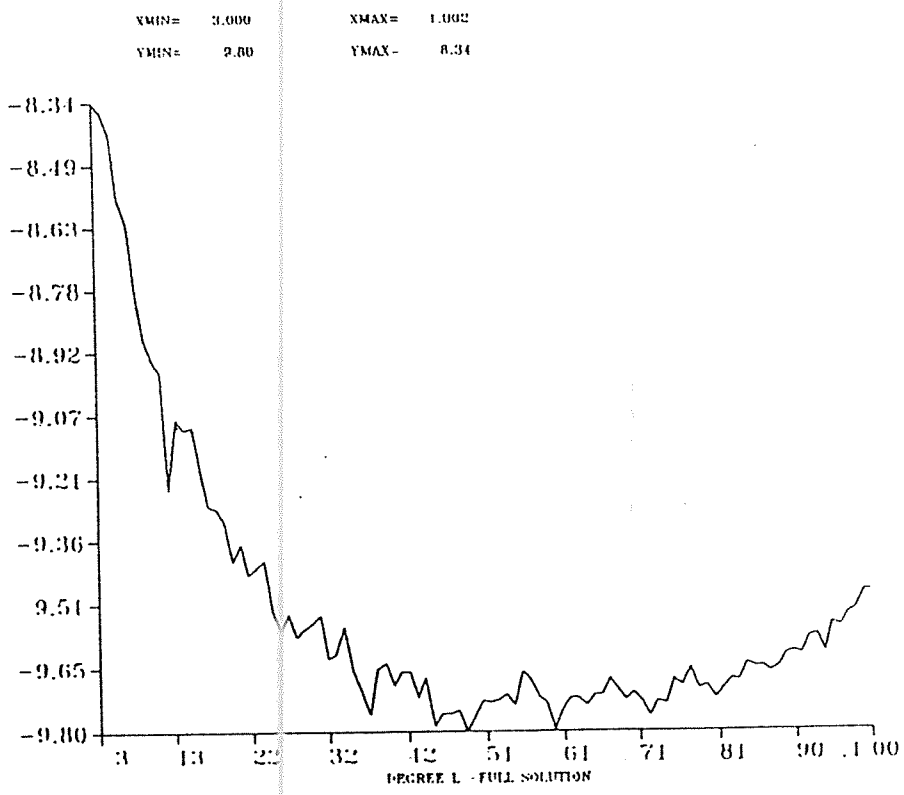


Fig. 2- Histogram of 1° x 1° gravity differences (min. = - 23 mgal, max. = 21,7 mgal, r.m.s. = 2.0 mgal).