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BUREAU GRAVIMETRIQUE INTERNATIONAL

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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.

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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 only reach you by mail, in many cases.

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 extra charges (with respect to usual cost - see § 3.3.2.). 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 :

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

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*

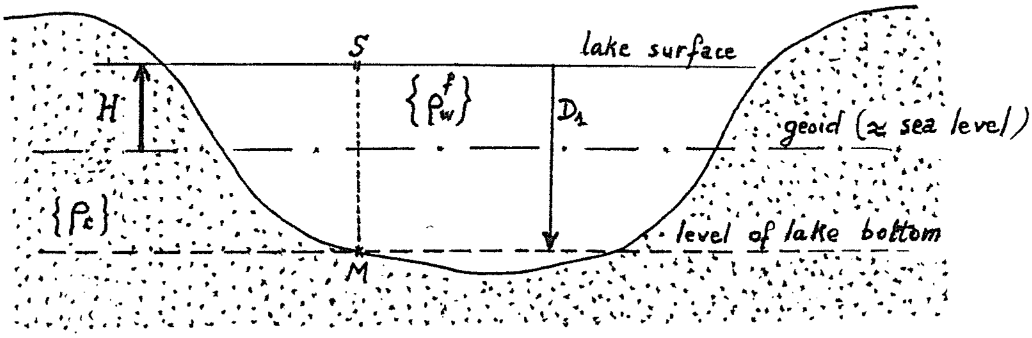
Formulas :

* *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	$FA = g + 2k\rho_c D_2 + \Gamma(H - D_2) - \gamma_o$ $BO = FA - k\rho_c H$
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 have been effective January 1, 1991 and may 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

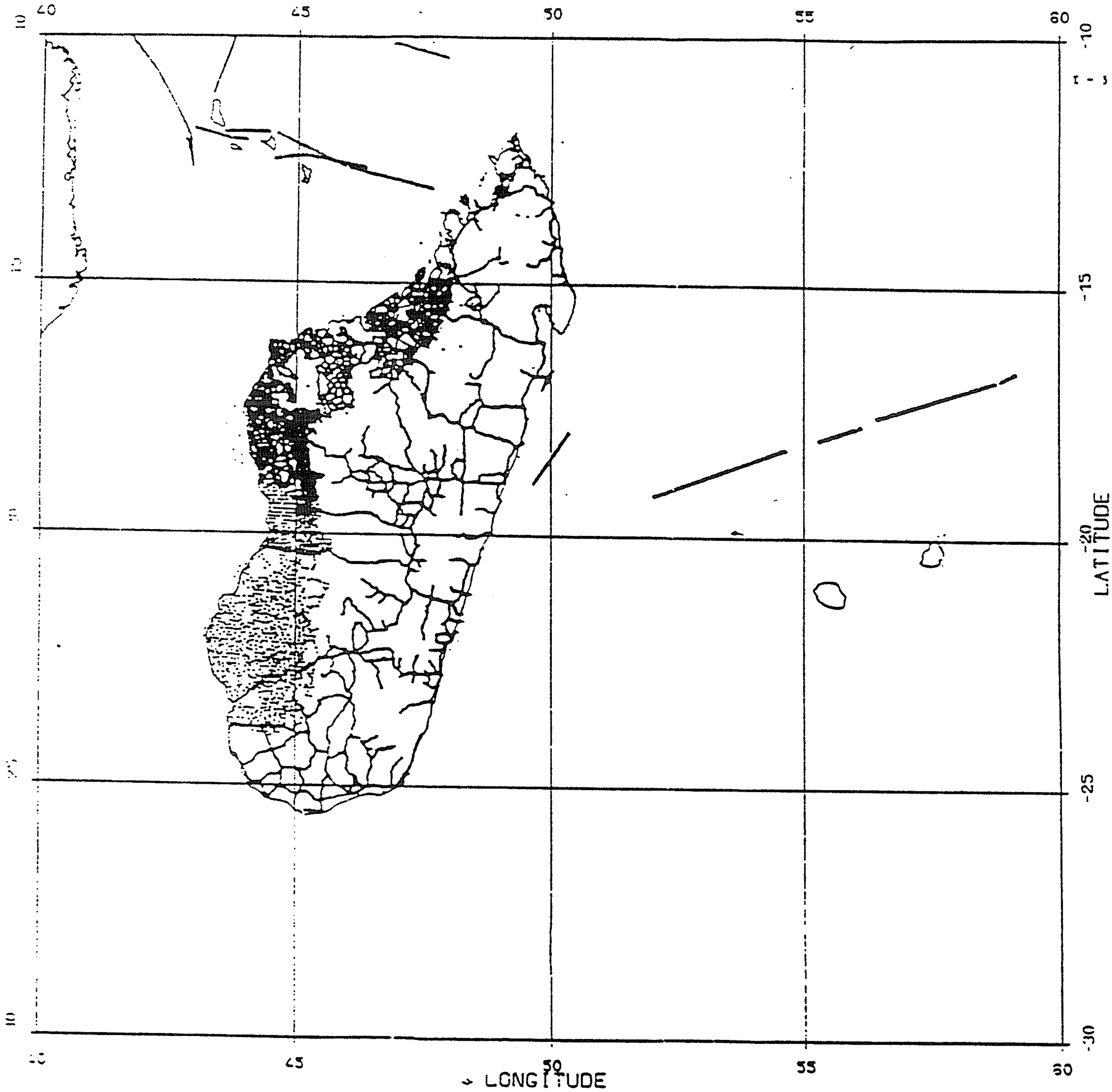
THE UNIFICATION OF THE GRAVITY NETS
OF AFRICA (Vol. 1 and 2) 1979 — 150 FF

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

. Colour copy : price according to specifications of request.

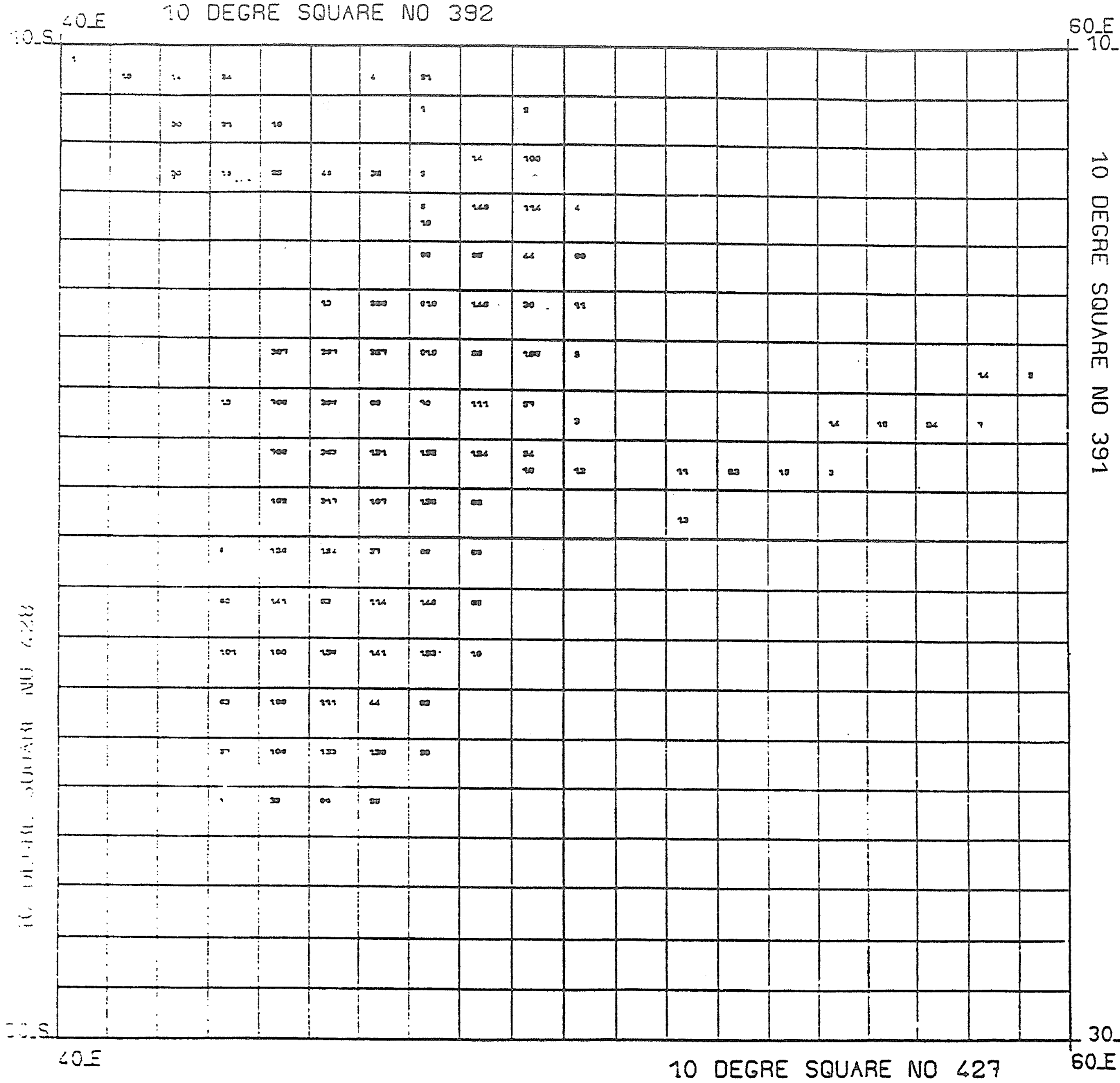
Mailing charges will be added for air-mail parcels when "Air-Mail" is requested)

Map 1. Example of data coverage plot



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

REPRESENTATION OF EARTH AND SEA GRAVIMETRIC STATIONS



4. PROVIDING DATA TO B.G.I.

4.1. Essential Quantities and Information for Gravity Data Submission

1. *Position of the site :*

   - latitude, longitude (to the best possible accuracy),
   - elevation or depth :
   *. for land data : elevation of the site (on the physical surface of the Earth)***
   . for water stations : water depth.

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

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

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.

**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.

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.

Part II

PAPERS PRESENTED AT 13th INTERNATIONAL GRAVITY COMMISSION received after deadline

RESULTS OF 3rd INTERNATIONAL COMPARISON OF ABSOLUTE GRAVIMETERS IN SÈVRES 1989

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12. Institute di Metrologia "G.Colonnetti", 10135 Torino, Strada Delle Casse 73, Italia (Italian Absolute Gravimeter);
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+) Editor

Summary

In the autumn of 1989 in Sèvres, the 3rd International Comparison of Absolute Gravimeters was carried out with the participation of gravimeters from ten countries: Austria, Canada, China, Finland, Germany, Italy, Japan, USA, USSR and IBPM (Sèvres, France). On six different pillars 19 independent absolute determinations were conducted; after using relative instruments, these measurements were reduced to one point. A comparison of all measurements has shown that the complete average square error of the determination of absolute gravity value by one instrument reached ±7.1 mcgal. The determination of its changes on the same pillar is possible with an error of less than 2 mcgal. However, one discrepancy of 23 ± 7.8 mcgal was noted between two instruments. When setting up the global gravimetric network of the 1st order to achieve the accuracy of about ±3-4 mcgal, it is necessary to make these measurements by a group of absolute gravimeters of no less than 4-5 instruments.

INTRODUCTION

As a result of the 2nd International Comparison of Absolute Gravimeters (ICAG) carried out in 1985 in Sèvres several instruments were found to show notable systematic errors which occasionally reached a few tens of mcgals /1/. This circumstance and the intention to set up in the nearest future the World Gravimetric Basestation Network with ±3-5 mcgal precision resulted in a Resolution of the International Gravimetric Commission (IGC), adopted at the General Assembly (IAG) (Vancouver,1987), to the effect that such comparisons should be carried out systematically every 3-4 years. At that meeting it was decided to hold the next one in 1988, and a Working Group 6 (WG 6 IGC) "Comparison of absolute gravimeters", chaired by Prof. Yu.D. Boulanger, was set up.

Ten countries expressed their wish to participate: Austria, Canada, China, Finland, Germany, BIPM (Sèvres), Italy, Japan, USA, and USSR. At the first meeting of WG 6 in June 1988 in Paris, however, it became clear that many instruments will not be ready in 1988 and the comparison was postponed to the autumn of 1989.

Prof. F.Giacomo, the then Director of BIPM, attended the Meeting and invited the participants to hold the comparison in Sèvres in the end of November-December 1989. This invitation was gratefully accepted.

Since BIPM cannot simultaneously accomodate and provide normal conditions for operation of such a large number of instruments, it was decided to carry out measurements by two groups: the first group during the third decade of November and the second group in the first decade of December 1989. In the interval between them it was planned to conduct measurements of relative gravimeters to establish a high-precision microgravimetric network and measurements of vertical gradients over pillars. Prof. E.Groten and Dr. M.Becker have kindly agreed to prepare and conduct these measurements.

RELATIVE MEASUREMENTS

The gravity value is determined by an absolute gravimeter at the so-called effective height over the pillar h, on which the gravimeter is mounted. Its magnitude depends on the type of the instrument and the manner in which it is mounted. During the 3rd ICAG the h heights were always determined from the upper surface of the metallic disc inserted in the pillar. At their centres, special markings are placed to fix the exact place of gravimeter installment.

In order to compare the absolute gravimeters, it is necessary to reduce to one point the measured gravity values g(h) at effective height h. Point A(0.05), situated at the height of 5 cm over the marking on pillar A, was chosen as such a point.

In laboratory, where concentrations of exciting masses are often located in immediate vicinity to a pillar, the variations of the vertical gradient W_{zz} with height are non-linear. Fig.1 shows W_{zz} values as functions of height over the pillar. This plot is calculated theoretically with allowance for the real size and mass of A3 pillar. Consequently, particular attention should be paid to the determination of reduction of the observed g(h) values to the surface of the pillar or to point A(0.05).

Since the observations with different absolute gravimeters take place at different heights, the establishment of high-precision ties of h with point A(0.05) when comparing many instruments would have required a rather large amount of work with relative gravimeters. Taking into account the circumstance that in the 0.800-1.200 m interval of heights W_{zz} practically changes by linear law and the effective heights of all participating absolute gravimeters lie within 0.580-1.178 m, their average height being 0.844, the following scheme was suggested and carried out for reduction of the measured g(h) values to point A(0.05).

A group of relative gravimeters at all points carefully measured Δg between points h=0.85 and h=1.25, thus making it possible to determine the average value of the vertical gradient W_{zz}(0.85-1.25) with an accuracy no less than 10 Eötvös. This procedure produced a reliable reduction of g(h) to the point at height 0.85 m. Fig. 1 shows that even if h maximally deviates from h=0.85 (Japan), the reduction to point (A(0.85) had the error of less than 0.5 mcgal.

To reduce g(h=0.85) to point A(0.05), the same group of gravimeters carried out ties of this point with points h(0.85) over pillars A, A1, A2, A3 and A8. These ties were made with errors less than ±1 mcgal, thus allowing to assume the average value of the total error equal to ±1.2 mcgal when estimating the accuracy of determination of reductions from g(h) with gA(0.05) for all points.

Figs 2 and 3 show the schemes of all ties and a scheme of reduction of g(h) to different points. The tie A(0.00) with A5(0.00) is particularly interesting (Fig.4). Its necessity became apparent only after the completion of work with relative gravimeters. Therefore, for this tie and for the determination of W_{zz}(A5) the results of measurements made in 1985 were used. In his paper /2/ M.Becker describes in detail the procedure of relative measurements.

ABSOLUTE DETERMINATIONS

The observations with absolute gravimeters proceeded as follows. As soon as the gravimeter was mounted on the pillar and put into operation, the testing measurements were made. If no defects were observed, then a series of drops was carried out. The number of drops in a series depended on the type of instrument, i.e., from a few to several tens and even hundreds of drops. After each series the instrument was stopped, partially adjusted and then put into operation again. The number of drops and the number of series were determined by conditions of observations and the capacities of the instrument.

As it was mentioned earlier, the absolute measurements were divided into two groups. The first group included instruments from Austria, China, Italy, IBPM and Finland and operated from 13 till 21 November; the second group had instruments from China, Canada, Germany, USA and USSR, and later additionally the Japanese instrument from 27 November till 8 December 1989. From 22 till 26 November the relative gravimeters operated. The preliminary results of the calibration performed were reported to and discussed at the IGB meeting (Toulouse, September, 1990) and were recommended for publication in Bull. d'Inform. IGB. However, later on October 9, Yu.D.Boulanger received the telex. It was as follows: October 9, 1990-MP/LD. Dear Professor Boulanger, 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. With best wishes, T.J.Quinn, Director BIPM (Communicated by TELEX).

It made us exclude the data obtained by BIPM instrument from the final processing and reprocess anew the entire set of observations obtained by absolute gravimeters.

Table 4 gives the final results of absolute determinations of absolute gravity value were obtained from six different pillars and 43. 893 drops were processed.

Corrections for the tidal changes of g were introduced into all absolute determinations according to the data calculated by Prof. A.Sakuma, as also corrections for the atmospheric mass attraction and for the pole coordinates from the formulas published in /3/.

In Table 2, in the succeeding Tables and also in the Appendixes the following indices are used:

- k - number of drops in a series;
- K - total number of drops adopted for precessing;
- n - number of series;
- h - effective height of the instrument over the metallic disc on the pillar;
- g(h) - absolute gravity value at effective height h corrected by all corrections except correction for height;
- m - mean square error of determination by a single drop by convergence of results in this series;
- $\bar{m}$ - its average value for this instrument;
- m_0 - mean square error of g(h) determination from one series by convergence of series;
- M' - mean square error of g(h) determination in a given series by k drops;
- $\bar{M}'$ - its mean value for this instrument;
- M_0 - mean square error of determination of g(h) average value from n series (incidental error of determination of $\bar{g}$(h) by this instrument);
- M - total error of $\bar{g}$(h) determination at effective height;

M_A - total error of $\bar{g}(h)$ determination reduced to point A(0.05);

Δg_1 - value of reduction of the measured g(h) value to point h=0.85 m;

Δg_2 - reduction value of gravity from point h=0.85 m to point A(0.05);

Δg_3 - reduction value of measured g(h) value to point h = 0.05 m on the same pillar;

Δg_R - Δ g value between points h = 0.05 m on the given pillar and point A(0.05); (See Fig.3).

The complete error M was determined as the squared sum of incidental error M_0 and the sum of systematic errors $\mathcal{E}$ obtained from engineering-physical calculations and specialised laboratory research carried out by the holders of the instruments. Table 3 gives the values of errors $\mathcal{E}$;

$$M = \pm (M_0^2 + \sum \mathcal{E}^2)^{1/2}$$

The full error M_A of $\bar{g}(h)$ determination, reduced to point A(0.05), was determined as the squared sum of M error and of the errors of Δg_1 and Δg_2 determinations, the values of which were assumed on the average equal to ±1.2 mcgal.

As deduced from Table 2, the maximal divergence this time was observed between the instrument (980 925 963.8 ± 5.8 mcgal) and the USSR instrument (980 926 986.9 ± 4.4 mcgal). The difference amounts to 23.1 ± 7.3 mcgal, which indicates the presence of systematic errors unaccounted for and considerably exceeding the errors attributed to the results of measurements by the holders of the instruments (Table 3).

By convergence of 18 independent measurements, the mean square error of absolute gravity determination by one instrument was found to be equal to:

$$\sigma = \pm 7.6 \text{ mcgal.}$$

If this value is compared to the value of error M_A = ±4.1 mcgal, it becomes apparent that the effect of systematic errors (Table 3), was on the average reduced by

$$(\sigma^2 - M_h^2 - M^2_{\Delta g})^{1/2} = (7.6^2 - 3.9^2 - 1.2^2)^{1/2} = \pm 6.4 \text{mcgal}$$

A similar result was independently obtained from the comparison of a group of instruments on one and the same pillar at the height h = 0.85. This kind of group measurements was conducted on five pillars with three or four instruments. Table 5 shows the results of this comparison. In this case, the mean value of error in the determination of the absolute gravity value was

$$\sigma = \pm 7.1 \text{ mcgal}$$

The data in this Table imply that the error in the determination of the average g value by a group of instruments composed of three or four gravimeters on five pillars is consistently characterised by the value ±4.0 mcgal (±1.0 mcgal).

As a result of measurements by seven gravimeters the absolute g value was determined by one and the same instrument at two or three points. This procedure allowed us to compare ten Δ g values measured by absolute and relative gravimeters (Table 6). From these data it follows that the error of Δ g measurement by absolute gravimeters was $M_{\Delta g}$ = ±2.9 mcgal, i.e. much less than the complete error of g determination M = ±7.1mcgal.

This result is not unexpected because a part of the unintroduced systematic errors is excluded when measuring Δ g difference, if the external conditions change only slightly during the displacement of instrument.

Finally, let us discuss the possibility of the appearance of group systematic errors when using gravimeters of one type of construction. Eleven out of 18 absolute determinations (Table 2) were carried out by gravimeters constructed by Prof. D.Faller and eight gravimeters were of different other systems. Table 7 shows results of such group measurements. Two values of $\bar{g}_A$ were obtained:

from measurements by gravimeters of Prof. D.Faller's construction:

$\bar{g}_A$ = 980 925 977.1 ± 2.1; σ = ±6.9 mcgal

from measurements by gravimeters of other systems:

$\bar{g}_A$ = 980 925 975.4 ± 3.3; σ = ±8.8 mcgal.

The difference between these two groups amounts to only 1.7 ± 3.9 mcgal, i.e., the systematic effect between groups was not observed. Moreover, the error in measurements by JILAG instruments was on the average less by one third than that of other instruments.

The accomplished measurements have revealed certain factors influencing the accuracy of absolute gravity determinations. The Figure shows values of two corrections which were introduced by the authors of measurements in the process of their final interpretation, i.e., corrections for the motion of the pole and for atmospheric mass attraction.

The plot implies that the first correction was computed with sufficient accuracy and the error of its values does not exceed 0.2 mcgal, whereas a comparison of corrections for atmospheric mass attraction indicates that their determination is unsound. If during the observations of the 1st group of instruments their accuracy was of the order of 1-2 mcgal, the measurements in December of the 2nd group took account of this correction with less assurance because the practically concurrent measurements of instruments produce a scattering of their values reaching 3-4 mcgal.

Taking into consideration this experience, in later operations with absolute gravimeters it is necessary to determine the values of the atmospheric pressure and air temperature for each series. And still this is not all. The determination of this correction requires the knowledge of not only atmospheric pressure at the point of installation of the gravimeter, but the average integral value of air pressure and temperature over the area of at least 250-300 km in radius.

As mentioned already, the observations were carried out with two groups of instruments from 16 to 20 November and from 28 November to 7 December 1989. The interval was 12.5 days. The results of observations of both groups are given in Fig. 4. Their ranalysis reveals a systematic difference between their average values:

1st group: 6 measurements of $\bar{g}$ = 980 925 968.3±1.7 mcgal
2nd group: 12 measurements of $\bar{g}$ = 980 925 978.6±1.8 mcgal
10.3±2.5 mcgal.

By assuming g changes as linear, the diurnal gravity variations at the time of comparison was 0.9 ± 0.2 mcgal/day. This value is statistically quite significant and confirms once

again that the gravity field of the Earth is "noisy" in a wide band of frequencies.

It is difficult to suggest the causes of this phenomenon. Perhaps it is the effect of unstable weather, or a result of changes in the hydrogeological regime in the region of Sèvres. Therefore in future, when conducting comparisons of absolute gravimeters, it is particularly necessary, if they take a certain period of time, to take special measures to record the gravity field variations by using probably crycgenic gravimeters having rather high sensitivity and zero stability.

Three international comparisons of absolute gravimeters were carried out in Sèvres: the first in 1981, the second in 1985, and the third, discussed here, in 1989. The first comparison produced five independent determinations, the second seven, and the third eighteen. A comparison of the average error in gravity determinations by one instrument indicates that error σ in 1989 was reduced to a half of the errors obtained (Table 8) previously.

This Table also shows that the gravity value in Sèvres increased by 16.2 ± 7 mcgal during the first four years, and decreased by 9.8 ± 5.6 mcgal during the second four-year period. The changes are not large but statistically meaningful.

It should be noted that these gravity changes similar in phase and sign were simultaneously recorded in Potsdam and Ledovo (Moscow) with periods close to eleven years. These results prompt a suggestion that the observed phenomenon may be global whose periodicity coincides with the period of solar activity (Fig.7).

CONCLUSIONS

The data, collected as a result of the 3rd International Comparison of Absolute Gravimeters, allow us to draw the following conclusions:

1. The total mean square error of determination of absolute gravity value with one instrument by convergence of 18 measurements reduced to one point is found to be σ =±7.6 mcgal.
2. Same by convergence of measurements accomplished on one and the same pillar with different instruments amounted to σ =±7.1 mcgal.

3. Same by convergence of measurements of differences in gravity values between pillars carried out by absolute and relative gravimeters is equal to ±2.9 mcgal.
4. Same from the estimations of authors of measurements with allowance for all systematic errors known to them is ±4.3 mcgal.
5. The absence of notable systematic difference was established between measurements carried out by a group of JILA gravimeters (eleven measurements) and those conducted by a group of instruments of other types of construction (eight measurements). The difference is 1.7 ± 3.9 mcgal.
6. By convergence of measurements, carried out by groups of three or four absolute gravimeters, the error of determination of the mean gravity value on five pillars has a persistent value of ±4.0 mcgal (±1.0 mcgal).
7. The modern level of accuracy of absolute gravimeters makes it possible to set up a World Gravimetric Network of the First Order with a single gravimeter operating at a level of ±7-8 mcgal whereas with a group of instruments (3 or 4) the accuracy of the network may reach ±4 - ±5 mcgal.

* * *

In conclusion authors would wish to express deep gratitude to Prof.T.Quinn, the now Director of BIPM, for kindly inviting the 3rd International Comparison of Absolute Gravimeters to BIPM in Sèvres, and to Prof. A.Sakuma for the excellent preparation and organisation not only of the measurements but of providing participants with the necessary means and facilities, including the possibility to compare the lasers of gravimeters with the international standard.

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

Yu.D.Boulanger

December 1990, Moscow

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1. Yu.D.Boulanger, J.Faller, E.Groten et al. Results of the Sekond International Comparison of Absolute Gravimeters in Sèvres 1985, BGI, Bulletin d'Information, No 59, 1986, pp89 - 103.

2. M.Becker, B.Bernard et al. Relative Gravity Measurements et the 3-rd International Comparison of Absolute Gravimeters, BGI, Bulletin d'Information (in press).

3. G.Boedecker. International Absolute Gravity Basestation Network (IAGBN). Absolute Gravity Observation Data Processing Standarts and Station Documentation, BGI, Bulletin d'Information, No 63, 1988, pp. 51 - 57.

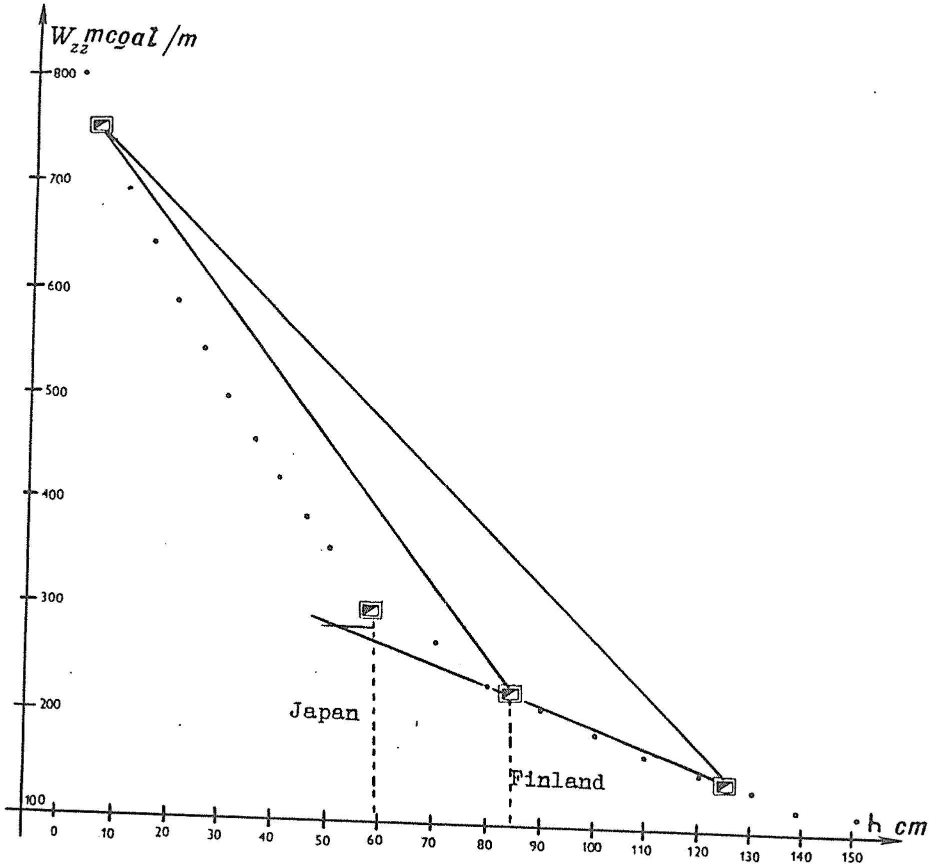

Fig. 1 Variation of vertical gradient above point A_3.

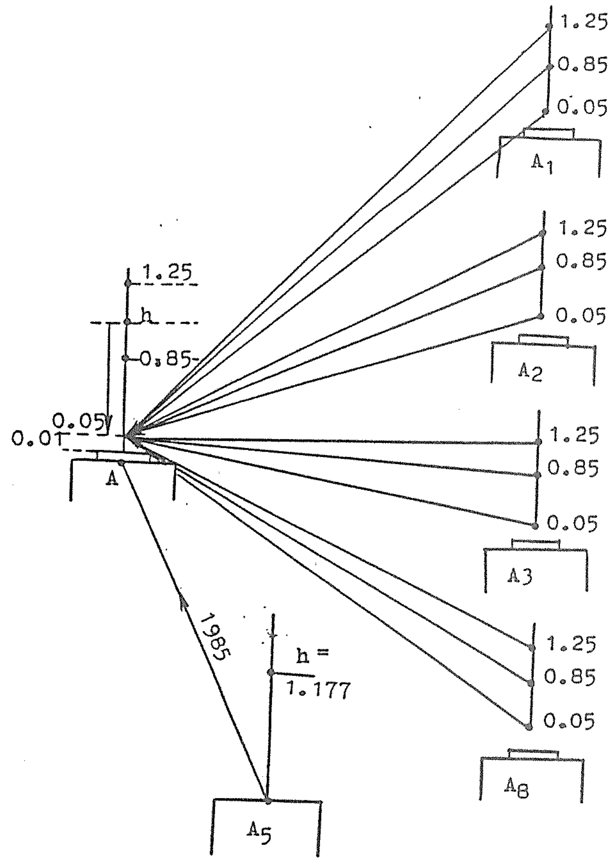

Fig.2. Relative gravity measurements.

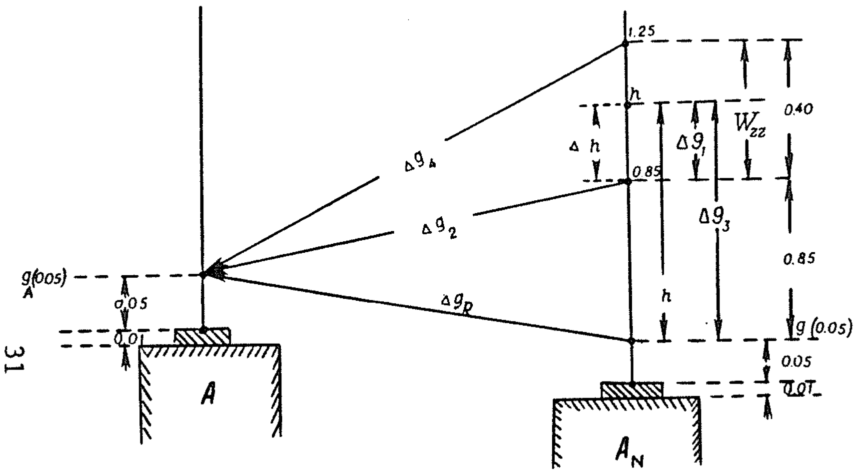

Fig. 3. Transfer of measurment results from micronet points to point A (0.05)

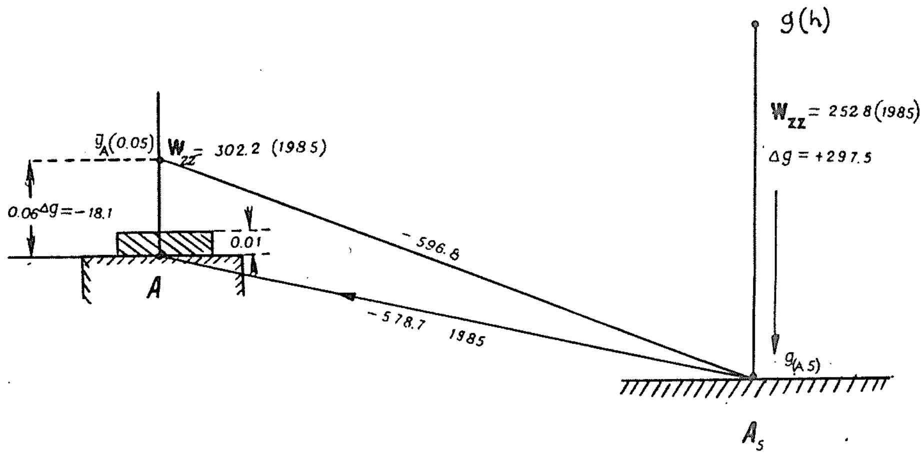

Fig.4. Method of results transfer from point A_5 to point A.

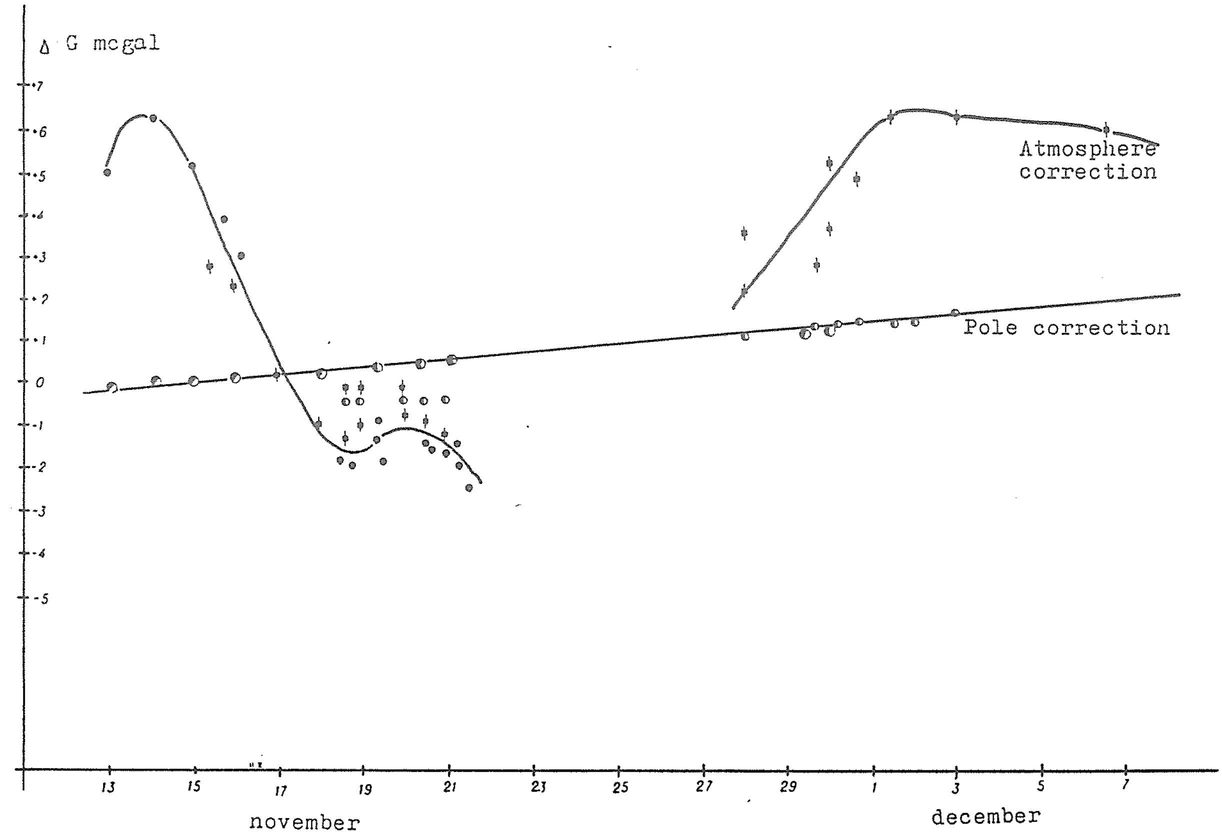

Fig.5 Correction for Pole motion and atmosphere

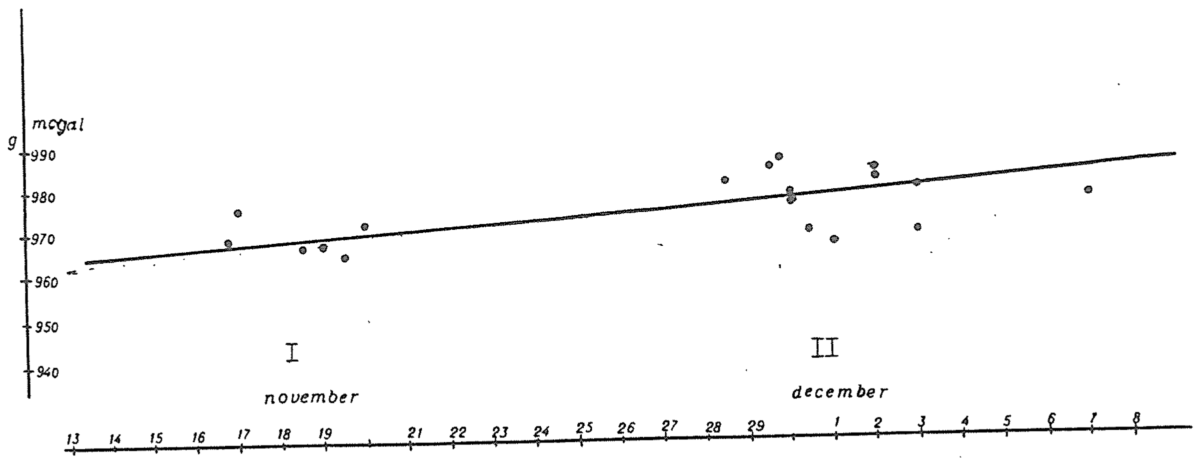

Fig. 6 Change of gravity value at Sèvres.

Table 1

Results of relative measurements for establisment of microgravimetric network

Pillars	Differences of gravity values		
	At height h = 0.05	$g_h(0.05)-g_h(0.85)$	$g_h(0.05)-g_h(1.25)$
	m c g a l		
A	-	+ 248.9	+ 369.8
A - A1	+ 11.1	+ 257.4	+ 377.6
A - A2	- 5.2	+ 242.4	+ 365.8
A - A3	+ 72.5	+ 310.2	+ 426.4
A - A8	- 558.9	- 354.2	- 257.7
A - A5+	- 593.8	-	-

+ From measurements data of 1985 year at heights h = 0.00 m

Table 2

Accidental errors of measurements

Country	Point	n	K	$\overline{m}$	m_o	M'	M_o	M_h	M_A
				m c g a l					
Austria	A2	5	5020	± 38.6	± 2.7	± 1.4	± 1.5	± 4.2	± 4.5
	A8	5	6057	38.5	2.6	1.6	1.2	4.2	4.4
Canada	A	144	3600	-	-	-	0.4	1.4	1.8
	A1	160	4000	-	-	-	0.6	1.4	1.8
	A3	73	1825	-	-	-	0.8	1.4	1.9
China	A1	34	1411	218.	(29.4)	(31.1)	5.0	6.3	6.4
	A5	35	1417	205.	(41.1)	(32.5)	6.9	7.9	8.0
Finland	A8	74	3700	-	6.0	-	0.7	3.4	3.6
	A2	26	1300	-	4.1	-	0.8	3.4	3.6
	A3	75	3750	-	4.3	-	0.5	3.3	3.5
Germany	A1	5	1436	64.2	7.3	3.7	3.3	4.7	4.8
	A3	11	3156	102.7	6.1	11.2	3.4	4.7	4.8
IBPM	A	-	-	-	-	-	-	-	-
Italy	A3	6	119	16.0	4.5	3.8	1.8	5.0	5.4
Japan	A2	2	43	112.	-	-	(9.0)	(17.9)	(17.9)
	A8	7	210	112.	-	-	(14.0)	(14.0)	(14.1)
U S A	A2	20	4727	20.1	1.9	1.3	0.4	2.8	3.0
USSR	A	11	1019	124.	6.8	13.0	2.1	4.2	4.4
	A3	14	1103	79.	11.1	8.9	3.0	4.5	4.7
	n = 707			$\overline{m}_o = \pm 5.2$		$\overline{M}_o = \pm 2.0$			$\overline{M}_A = \pm 4.2$
	K = 43893							$\overline{M}_h = \pm 3.9$	

Table 3

Errors in measurements of absolute gravimeters (mcgal)

Sources of errors	Austria	Canada	China	Finland	Germany	IBPM	Italy	Japan	USA	USSR	Mean
± (mcgal)	±	±	±	±	±	±	±	±	±	±	±
Error of wave of laser	1.0	0.2	1	1.0	1.0	-	2	2	1.0	2	1.2
Influence of magnetic forces	0.5	0.1	2	0.5	0.5	-	-	-	0.5	1	0.7
Influence of electrostatics	1.0	0.1	-	1.0	1.0	-	3	-	1.0	0	1.0
Influence of optical effects	1.5	0.5	-	1.0	1.0	-	-	4	1.0	2	1.6
Influence of pressure in the chamber	1.0	0.1	3	1.0	1.0	-	-	-	-	0	1.0
Influence of unstable frequencies	0.5	0.2	-	0.5	0.5	-	-	-	0.5	1	0.5
Influence of body rotation	1.0	0.8	-	1.0	1.0	-	2	3	1.0	0	1.2
Influence of traslation	1.0	0.1	1	1.0	1.0	-	2	-	1.0	-	1.0
Temperature effects	1.5	0.2	-	1.0	1.0	-	-	-	1.0	0	0.8
Back effects	1.5	0.7	-	0.7	0.7	-	-	-	0.5	0	0.7
Time interval determination	1.5	0.3	-	0.5	-	-	-	-	0.5	1	0.8
Deflection from vertical	1.0	0.3	-	0.5	0.5	-	2	1	0.5	0	0.7
Delay	-	-	-	0.5	1.0	-	-	-	0.5	0	0.5
Attraction of apparatus	-	-	-	0.5	0.5	-	-	-	0.5	0	0.4
Accidental errors M_o	1.2	0.6	5.9	0.7	3.4	-	1.8	(15)	0.4	2.8	2.1
Total errors M_h	4.2	1.4	7.1	3.1	4.6	-	5.3	(16)	2.8	4.3	4.1
Error redactions to pillar A	1.2	1.0	1.2	1.2	1.2	-	2.2	1.2	1.2	1.2	1.3
Total errors of absolute values g at pillar A(0.05) M_A	4.3	1.8	7.2	3.3	4.8	-	5.8	(16)	3.0	4.5	4.3

Table 4

Results of comparison of absolute gravimeters

Country	Point	g(h) mcgal	M_h	h m	Δ h m	W_{zz}	Δg_1	Δg_2 mcgal	$g_A(0.05)$	M_A
Austria	A2	980 925 746.1	± 4.2	0.840	- 0.010	308.5	- 3.1	+ 242.4	980 925 985.4	± 4.4
	A8	926 337.2	± 4.2	0.840	- 0.010	242.8	- 2.4	- 354.2	80.6	± 4.4
Canada	A	925 714.5	± 1.4	0.910	+ 0.060	302.2	+ 18.1	+ 248.9	81.5	± 1.8
	A1	925 706.5	± 1.4	0.910	+ 0.060	300.5	+ 18.0	+ 257.4	82.0	± 1.8
	A3	925 651.3	± 1.5	0.910	+ 0.060	290.5	+ 17.4	+ 310.2	78.9	± 1.9
China	A1	925 611.8	± 6.3	1.178	+ 0.328	300.5	+ 98.6	+ 257.4	67.8	± 6.4
	A5	926 267.6	± 7.9	1.177	+ 0.327	252.8	+297.5	- 596.8	68.3	± 8.0
Finland	A8	926 326.2	± 3.1	0.833	- 0.017	242.8	- 4.1	- 354.2	67.9	± 3.3
	A3	925 729.7	± 3.1	0.834	- 0.016	308.5	- 4.9	+ 242.4	67.2	± 3.3
	A1	925 717.5	± 3.0	0.834	- 0.016	300.5	- 4.8	+ 257.4	70.1	± 3.2
Germany	A1	925 729.0	± 4.7	0.795	- 0.055	300.5	- 16.5	+ 257.4	69.9	± 4.8
	A3	925 688,5	± 4.7	0.801	- 0.049	290.5	- 14.2	+ 310.2	84.5	± 4.8
Italy	A3	925 631.0	± 5.3	0.926	+ 0.076	290.5	+ 22.1	+ 310.2	63.8	± 5.8
Japan	A2	925 819.8	±17.9	0.581	- 0.269	308.5	- 83.0	+ 242,4	70.0	(±17.9)
	A8	926 397.1	±14.0	0.581	- 0.269	242.8	- 65.3	- 354.2	77.6	(±14.1)
U S A	A2	925 780.7	± 2.8	0.907	+ 0.057	308.5	+ 17.6	+ 242.4	80.7	± 3.0
USSR	A	925 697.5	± 4.2	0.984	+ 0.134	302.2	+ 40.5	+ 248.9	86.9	± 4.4
	A3	925 636.1	± 4.5	0.986	+ 0.136	290.5	+ 37.8	+ 310.2	84.1	± 4.7

$\bar{g}^A(0.05) = 980\ 925\ 976.5 \pm 1.8$

n = 18 $\quad \sigma = \pm 7.6$

Table 6

Comparison of Δg measured by absolute and relative gravimeters (mcgal)

Country		g(h)		Δg_1	Δg_3	g(h=0.05)		Diff.	Δg_{AG}		Δg_R		d	M_d
		980				980								
Austria	A2	925 746.1	± 4.2	- 3.1	247.6	925 990.6	± 4.4	A2-A8	-543.9	± 6.1	-553.7	±1.2	- 8.8	± 6.2
	A8	926 337.2	4.2	- 2.4	204.7	926 539.5	4.4							
Canada	A	925 714.5	1.4	+18.1	248.9	925 981.5	1.8	A -A1	+ 10.7	2.3	+ 11.1	1.2	+ 0.4	± 2.6
	A1	706.5	1.4	+18.0	246.3	970.8	1.8	A1-A3	+ 64.4	2.5	+ 61.4	1.2	- 3.0	± 2.8
	A3	751.3	1.5	+17.4	237.7	906.4	1.9	A -A3	+ 75.1	2.6	+ 72.5	1.2	- 2.6	± 2.9
China	A1	925 611.8	6.3	+98.6	246.3	925 956.7	6.4	A1-A5	-589.4	10.2	-593.8	1.2	- 4.4	±10.3
	A5	926 267.6	7.9	+82.7	196.9	926 546.1	8.0							
Finland	A2	925 729.7	3.4	- 4.9	354.2	926 079.3	3.3	A2-A8	-551.6	4.7	-553.7	1.2	+ 2.1	± 4.9
	A8	926 326.2	3.4	- 4.1	309.0	630.9	3.3	A2-A1	- 19.4	4.7	- 16.3	1.2	+ 3.1	± 4.9
	A1	925 717.5	3.3	- 4.8	246.3	925 959.9	3.2	A1-A8	-570.0	4.6	-570.0	1.2	+ 1.0	± 4.8
Germany	A1	925 729.0	4.7	-16.5	246.3	925 958.8	4.7	A1-A£	- 46.8	6.8	- 61.4	1.2	(+14.6)	± 6.9
	A3	688.5	4.7	-14.2	237.7	912.2	4.9							
Japan	A2	925 819.8	17.9	-83.0	247.6	925 983.7	17.9	A2-A8	-552.8	23.0	-553.7	1.2	- 0.9	(±23.0)
	A8	926 397.1	14.0	-65.3	204.7	926 536.5	14.0							
USSR	A	925 657.5	4.2	+40.5	248.9	925 986.9	4.4	A -A3	+ 75.3	6.4	+ 72.5	1.2	- 2.8	± 6.5
	A3	636.1	4.5	+37.8	237.7	911.6	4.7							

n = 10

$(\sum d^2 : 2n)^{\frac{1}{2}} = \pm 2.9$ mcgal

$\bar{M}_d = \pm 5.3$

Table 5

Results of group measurements at height h = 0.85 m

	Country	g(h)	Δg_1	g(0.85)	$\bar{g}$(0.85)	M	σ
		m c g a l					
		980		980	980		
1. A	Canada	925 714.5	+ 18.1	925 732.6	925 735.3	± 2.7	± 3.8
	USSR	697.5	+ 40.5	738.0			
2. A1	Canada	925 706.5	+ 18.0	925 724.5	925 715.0	± 3.2	± 6.4
	China	611.8	+ 98.6	710.4			
	Finland	717.5	- 4.8	712.7			
	Germany	729.0	- 16.5	712.5			
3. A2	Austria	925 745.5	- 3.1	925 742.4	925 734.7	± 5.2	± 9.0
	Finland	723.7	- 4.9	724.8			
	Japan	819.8	- 83.0	736.8			
4. A3	Canada	925 651.3	+ 17.4	925 668.7	925 667.7	± 4.8	± 9.6
	Germany	688.5	- 14.2	674.3			
	Italy	631.6	+ 22.1	653.7			
	USSR	636.1	+ 37.8	673.9			
5. A8	Austria	926 337.5	- 2.4	926 335.1	926 329.7	± 3.9	± 6.8
	Finland	326.2	- 4.1	322.1			
	Japan	397.1	- 65.3	331.8			

$\bar{M} = \pm 4.0$ ($\pm$ 1.0)

$\bar{\sigma} = \pm 7.1$

Table 7

Comparison of results of measurements by different types gravimeters

Absolute gravity values at point A(0.05)					
JILA gravimeters			Gravimeters of other type		
		m c g a l			m c g a l
Austria	A2	980 925 985.4 ± 4.4	China	A1	980 925 967.8 ± 6.4
	A8	80.6 ± 4.4		A5	68.3 ± 8.0
Canada	A	81.5 ± 1.8	Italy	A3	63.8 ± 5.8
	A1	82.0 ± 1.8	Japan	A2	79.2 ± 17.9
	A3	78.9 ± 1.9		A8	77.6 ± 14.1
Finland	A8	67.9 ± 3.3	USSR	A	86.9 ± 4.4
	A2	67.2 ± 3.3		A3	84.1 ± 4.7
	A1	70.1 ± 3.3			
Germany	A1	69.9 ± 4.8			
	A3	84.5 ± 4.8			
U S A	A2	79.7 ± 3.0			
n = 11;		$\bar{g}_1$=980 925 977.1 ± 2.1	n = 7;		$\bar{g}_2$=980 925 975.4 ± 3.3
		σ_1 = ± 6.9			σ_2 = ± 8.8

$\bar{g}_2 - \bar{g}_1 = - 1.7 \pm 3.9$ mcgal

Table 8

Temporal changes of absolute gravity value at point A3(h = 0.000)

Epoch	g_{A3}(h=0.000)	M	σ	n
	m c g a l			
1981	980 925 915	± 4.6	± 10.2	5
1985	31.2	± 5.3	14.0	7
1989+)	21.4	± 1.8	7.6	18

+) With allowance for height differences at of comparison: $(0.010 + 0.050)W_{zz}$ = 17.4 mcgal

Appendix 1

PARTICIPANTS

of 3-th Comparison of Absolute Gravimeters
Sèvres, 1989

1. A u s t r i a

Institution: University of Vienna, Institute for Metrology and Geophysics, Hohe Warte 38, A-1190 Wien; telex: 131837; fax: 222/369 12 33.
Instrument: Absolute gravimeter JILA-6
Group leader: Dr.D.Ruess, Federal Office for Metrology and Surveyng Schiffamtsgasse 1-3, A-1025 Wien; telex: 115468 BCVWN A; fax: 222/216 10 62.
Operators: Dr.D.Ruess.

2. C a n a d a

Institution: Geological Survey of Canada, 1 Observatory Crescent Ottawa Ontario, Canada K1A 0Y3; telex: 0533117 EMAR OTT.
Instrument: Absolute gravimeter JILA-2.
Group leader: Dr. J.Liard (the same address).
Operators: Dr. J.Liard, N.Courtier (the same address).

3. C h i n a

Institution: National Institute of Metrology, Mechanical Division, Beijing, PRC,
Instrument: Absolute gravimeter, constructed in PRC.
Group leader: Prof. Guo You - Guang (the same address).
Operators: Huang Da - Lun, Feng Youg - Yuan, Zhang Guang - Yuan, Li De - Xi (the same address).

4. F i n l a n d

Institution: Finnish Geodetic Institute, Ilmalankatu 1A, SF-00240, Helsinki, fax: 358-0-414 946.
Instrument: Absolute gravimeter JILA.
Group leader: Dr.J.Mäkinen (the same address).
Operators: Dr. J.Mäkinen, A.Vänskä (the same address).

5. G e r m a n y

Institution: Institute für Erdmessung, Universität Hannover, Nienburger Str. 6, D-3000, Hannover 1; telex: 923868 UNIHN D, fax: (0511) 762 4006.
Instrument: Absolute gravimeter JILA-
Group leader: Prof.Dr.-Ing.W.Torge (the same address).
Operators: Dipl.Ing. M.Schnüll, Dipl.Ing. R.Röder, Dipl.Ing. L.Timmer.

6. I t a l y

Institution: Instituto di Metrologia "G.Colonnetti", 10135 Torino, Strada Delle Casse 73; telex: 212209 IMGCTO I, fax: (011) 346761.
Instrument: Absolute gravimeter Instituto "G.Colonnetti".
Group leader: Dr.G.Cerutti (the same address).
Operators: L.Camizzo, Dr.G.Cerutti (the same address), Dr.I.Marson (Universitet di Trieste, Instituto Miniere e Geofisica Applicate).

7. I B P M

Institution: Bureau International des Poids et Mesure, Pavillon de Breteul, F-92312 Sèvres CEDEX, telex: BIPM 201067 F; fax: (33) 145342021.
Instrument: Absolute gravimeter of IBPM.
Group leader: Prof. A.Sakuma (the same address).
Operators: Prof. A.Sakuma.

8. J a p a n

Institution: National Astronomical Observatory, Mizusawa 2 - 12 Hosigaoka, Mizusawa, Iwate 023; telex 837628; fax: 0197 - 23 - 5156.
Instrument: Absolute gravimeters, constructed in Japan.
Group leader: Prof. M.Ooe, (the same address).
Operators: Prof. M.Ooe, prof.T.Tsubokawa, H.Hanada, S.Tsurzuta (the same address).

9. U S A

Institution: National Geodetic Survey, 11400 Rockville Pike, Rockville
MD 20852 fax: 301 468 5714.

Instrument: JILA gravimeter.

Group leader: Dr.G.Peter (the same address).

Operators: Dr.G.Peter, B.Bernard, J.Fried (the same address).

10. U S S R

Institution: Institute of Automatics and Electrometry, Siberian Branch of Academy of Sciences of the USSR, Novosibirsk 630090, USSR.

Instrument: GABL USSR gravimeter.

Group leader: Prof.Yu.Boulanger, Institute of Physics of the Earth
Moscow D-242, Bol.Grusinskaia str.10.

Operators: Dr.S.Scheglov (the same address), Dr.G.Arnautov, E.Kalish, Yu.F.Stus, W.Tarasuk (Inst.of Automatics and Electrometry).

Appendix 2

RESULTS OF DETERMINATION OF ABSOLUTE GRAVITY VALUES
Sèvres, 1989

1. A u s t r i a

Point A8

h = 0.840 m $W_{zz}(1.25 - 0.85)$ = 242.8 mcgal/m

Series	Date	U T mid mom.	k	m (mcgal)	M´ (mcgal)	g(h)
1	1989 11 18	15^h25^m	113	± 39.4	± 3.2	980 926 340.2
2	19	04 25	2290	41.8	0.8	38.6
3	19	23 25	1711	39.2	0.9	37.7
4	20	12 55	462	38.0	1.7	33.1
5	20	23 25	1481	34.3	0.9	36.8

n = 5 K = 6057 $\bar{g}(h)$= 980 926 337.5

$\bar{m}$ = ± 38.5 M = ± 1.6

m_o = ± 2.6 M_o= ± 1.2

Point A2

h = 0.840 m $W_{zz}(1.25 - 0.85)$ = 308.5 mcgal/m

Series	Date	U T mid mom.	k	m (mcgal)	M´ (mcgal)	g(h)
1	1989 11 15	14^h56^m	115	± 40.7	± 3.7	980 925 743.7
2	16	00 05	800	30.8	0.9	47.3
3	16	23 10	1367	29,2	0.8	46.8
4	17	22 25	1369	31.4	0.7	47.6
5	27	23 55	1369	40.7	1.0	41.2

n = 5 K = 5020 $\bar{g}(h)$ = 980 925 746.1

$\bar{m}$ = ± 38.6 M´= ± 1.4

m_o= ± 2.7 M_o= ± 1.2

2. C a n a d a

Point A

Date: 1989.12.02; h=0.910 m; $W_{zz}(1.25 - 0.85)$ = 302.2 mcgal/m

n = 144; K = 3000; M = ± 1.4 mcgal, M_o= ± 0.4 mcgal

g(h) = 980 925 714.5 ± 1.4 mcgal

Point A3

Date: 1989.11.30; h=0.910 m; $W_{zz}(1.25 - 0.85)$ = 290.5 mcgal/m

n = 160; K = 4000; M = ± 1.6 mcgal; M_o= ± 0.8 mcgal

g(h) = 980 925 651.3 ± 1.6 mcgal

Point A1

Date: 1989.11.28; h = o.910 m; $W_{zz}(1.25 - 0.85)$ = 300.5 mcgal/m

n = 7; K = 1825; M ± 1.4 mcgal; M_o= ± 1.4 mcgal

g(h) = 980 925 706.6 ± 1.4 mcgal

3. China

Point A1

h = 1.178 m W_{zz} = (1.25 - 0.85) = 300.5 mcgal/m

Series	Date	U T	k	m	M′	g(h)
				mcgal		
1	1989 11 15	11^h13^m - 11^h28^m	40	±227	±36	980 925 610
2		21 22 - 21 35	40	225	36	643
3		21 44 - 21 59	41	200	31	604
4		23 25 - 23 38	38	197	32	637
5	16	00 00 - 00 15	46	177	26	647
6		01 09 - 01 23	42	206	32	618
7		02 19 - 02 32	45	178	26	571
8		03 54 - 04 08	39	224	36	585
9		05 38 - 05 51	41	212	33	632
10		06 21 - 06 35	40	222	35	550
11		06 45 - 07 00	41	246	38	604
12		07 05 - 07 20	39	195	31	610
13	18	09 11 - 09 25	44	187	28	597
14		09 39 - 09 53	48	198	29	652
15		11 53 - 12 08	45	209	32	586
16		12 19 - 12 32	44	242	36	610
17		14 26 - 14 40	39	186	30	620
18		14 53 - 15 05	43	223	34	605
19		16 44 - 16 58	43	232	35	588
20		17 07 - 17 20	44	222	33	626
21		17 29 - 17 42	40	240	38	642
22		18 09 - 18 22	47	207	30	592
23	19	10 09 - 10 23	44	219	33	612
24		10 57 - 11 10	43	214	33	653
25		17 21 - 17 35	45	208	31	532
26		17 41 - 17 55	44	229	35	590
27		19 10 - 19 23	45	207	31	600
28		19 29 - 19 43	44	206	31	621
29	20	15 16 - 15 30	38	264	43	642
30		15 37 - 15 50	30	260	47	623
31		16 59 - 17 12	40	228	36	649
32		17 13 - 17 26	29	252	47	636
33		17 29 - 17 42	40	215	34	640
34	20	17 45 - 17 58	40	269	43	571

n = 34 K = 1411 $\bar{g}(h)$ = 980 925 611.7 ± 5.0

Correction for Pole + 0.1

Final value $\bar{g}(h)$ = 980 925 611.8 ± 5.0 .

$\bar{m}$ = ± 218 mcgal $\bar{M}'$ = ± 34.1 mcgal

m_o = ± 29.4 mcgal M_o = ± 5.0 mcgal

3. China

Point A5

h = 1.177 m W_{zz}(1.177 - 0.000) = 252.8 mcgal/m

Series	Date	U T	k	m	M′	g(h)
				mcgal		
1	1989 11 21	16^h40^m - 16^h55^m	38	±197	± 32	980 926 301
2		17 04 - 19 19	38	244	40	327
3		17 24 - 17 39	47	229	33	245
4		17 40 - 17 52	42	203	31	201
5		17 53 - 18 05	46	219	32	271
6	27	14 27 - 14 57	42	226	35	300
7		15 17 - 15 32	34	208	36	233
8	29	11 17 - 11 32	37	182	30	236
9		11 33 - 11 48	34	238	41	260
10		12 12 - 12 27	37	144	24	209
11		12 27 - 12 40	42	194	30	323
12		12 55 - 13 08	44	236	36	270
13	30	10 37 - 10 50	39	189	30	287
14		10 56 - 11 10	44	244	37	252
15		11 13 - 11 27	45	209	31	278
16		14 17 - 14 30	38	234	38	315
17		14 34 - 14 47	43	226	34	221
18		14 48 - 15 02	46	267	39	294
19		15 03 - 15 18	37	205	34	233
20		15 22 - 15 35	36	226	38	277
21		16 48 - 17 01	37	242	40	359
22		17 02 - 17 15	43	195	30	219
23	12 01	13 15 - 13 28	34	228	39	267
24		15 02 - 15 15	34	219	38	179
25		15 29 - 15 42	40	236	37	284
26		15 46 - 16 00	45	196	29	241
27		16 22 - 16 35	39	191	30	333
28	02	10 27 - 10 40	45	169	25	221
29		10 45 - 10 58	48	158	23	283
30		11 00 - 11 13	45	159	24	247
31		11 14 - 11 27	45	183	27	320
32		11 27 - 11 42	48	151	22	292
33		11 42 - 11 55	47	193	28	253
34		11 56 - 12 10	28	180	34	239
35	02	13 48 - 14 01	30	169	31	259

n = 35; K = 1417 $\bar{g}(h)$ = 980 926 266.5

Correction for Pole 1.1

Final value $\bar{g}(h)$ = 980 926 267.6

$\bar{m}$ = ± 205 mcgal $\bar{M}'$ = ± 32.5 mcgal

m_o = ± 41.1 mcgal M_o = ± 6.9 mcgal

4. F i n l a n d

Point A8

h = 0.833 m $W_{zz}(1.25 - 0.85)$ = 242.0 mcgal/m

==

Date: 1989.11.15 $18^h30^m00^s$ - 11.18 $08^h09^m18^s$; n = 74; K = 3700

$\bar{g}(h)$ = 980 926 326.2 ± 0.7 mcgal

m_o = ± 6.0 mcgal M_o = ± 0.7 mcgal

Point A2

h = 0.834 m $W_{zz}(1.25 - 0.85)$ = 242.8 mcgal/m

==

Date: 1989.1'.18 $19^h00^m00^s$ - 11.19 $07^h39^m17^s$; n = 26; K = 1300

$\bar{g}(h)$ = 980 925 729.7 ± 0.8 mcgal

m_o = ± 4.1 mcgal M_o = ± 0.8 mcgal

Point A1

h = 0.834 m $W_{zz}(1.25 - 0.85)$ = 300.5 mcgal/m

==

Date: 1989.12.02 $14^h19^m00^s$ - 12.04 $07^h39^m18^s$; n =75; K = 3750

$\bar{g}(h)$ = 980 925 717.5 ± 0.5 mcgal

m_o = ± 4.3 mcgal M_o = ± o.5 mcgal

5. G e r m a n y

Point A1

h = 0.795 m   Wzz(1.25 - 0.85) = 300.5 mcgal/m

Series	Date	k	m	M'	g(h)
			m c g a l		
1	1989 11 30	285	+/- 72.6	+/- 4.3	980 925 732.7
2	1989 11 30	282	67.2	4.0	730.7
3	1989 11 30	290	54.5	3.2	737.1
4	1989 11 30	290	49.4	2.9	727.6
5	1989 12 01	289	73.1	4.3	717.6

n = 5   K = 1436 $\bar{g}(h)$ = 980 925 729.0 +/- 3.3

$\bar{m}$ = +/- 64.2 $\bar{M}'$ = +/- 3.7

mo= +/- 7.3   Mo = +/- 3.3

Point A3

h = 0.801 m   Wzz(1.25 - 0.85) = 290.5 mcgal/m

Series	Date	k	m	M'	g(h)
			m c g a l		
1	1989 11 28	290	+/-102.2	+/- 6.0	980 925 695.3
2	1989 11 28	290	93.7	5.5	702.1
3	1989 11 28	289	91.8	5.4	695.8
4	1989 11 29	285	119.9	7.1	682.2
5	1989 11 29	288	129.0	7.6	706.4
6	1989 11 29	289	117.3	6.9	690.0
7	1989 11 29	286	111.6	6.6	692.5
8	1989 11 29	283	114.4	6.8	676.2
9	1989 11 29	284	89.3	5.3	679.5
10	1989 11 29	284	80.9	4.8	683.5
11	1989 11 30	288	79.8	4.7	670.0

n = 11   K = 3156 $\bar{g}(h)$ = 980 925 688.5 +/- 3.4

$\bar{m}$ = +/- 102.7 $\bar{M}'$ = +/- 11.2

mo= +/- 6.1   Mo = +/- 3.4

6. I t a l y

h = 0.926 m $W_{zz}(h - 0.05)$ = 290.5 mcgal/m

Series	Date	U T	k	m	M´	g(h=0.05)
				m c g a l		
1	1989.11.18	12^h42^m - 14^h09^m	18	±16.7	±3.9	980 925 882.5
2		15 21 - 17 27	25	18.3	5.8	94.8
3	19	08 24 - 10 59	21	15.0	3.3	89.5
4	20	09 56 - 10 56	16	15.3	3.8	85.5
5	21	00 30 - 10 57	29	14.9	2.8	90.2
6		13 38 - 15 33	10	16.1	5.1	92.4

n = 6;   K=119 $\bar{g}$(h=0.05)=980 925 889.2

$\bar{m}$ = ± 16.0 mcgal

$\bar{m}_o$= ± 4.5 mcgal $\bar{M}'$± 3.8 mcgal M_o= ± 1.8 mcgal

7. J a p a n

Point A8

h = 0.581 m $W_{zz}(1.25 - 0.85)$ = 242.8 mcgal/m

Series	Date	U T	k	g(h) mcgal	
1	1989.11.27:	16^h40^m - 28: 07^h00^m	43		980 926 392
2	28:	14 40 - 28: 17 21	7	Corr.Attr. of Atmosph.	+ 4.0
3	29:	14 34 - 30: 04 22	54		
4	30:	17 25 - 30: 18 03	5	Pole corr.	+ 1.1
5	12.01:	19 56 - 02: 05 27	55	Final value	980 926 397.1
6	02:	14 44 - 02: 16 43	11		
7	06:	19 19 - 06: 00 19	35		

n = 7   K = 210 M_o = ± 14 mcgal

Point A2

h = 0.581 m $W_{zz}(1.25 - 0.85)$ = 308.5 mcgal/m

Series	Date	U T	k	g(h) mcgal	
1	1989.12.06:	20^h00^m - 07: 08^h19^m	23		980 925 812
2	07:	22 53 - 08: 08 31	20	Corr.Attr. of Atmosph.	+ 6.0
				Pole corr.	+ 1.8
				Final value	980 925 819.8

n = 2   K = 43; M_o= ± 17 mcgal

8. U S A

Point A2

h = o.907 m W_{zz}(1.25 - 0.85) = 308.5 mcgal/m

Series	Date	U T	k	m	M'	g(h)
				mcgal		
1	1989.12.02:	13^h00^m - 16^h45^m	232	± 23.0	± 1.5	980 925 720.2
2		15 00 - 15 45	229	22.3	1.5	19.2
3		17 00 - 17 45	238	22.3	1.4	21.8
4		21 00 - 21 45	233	23.0	1.5	18.3
5		23 00 - 23 45	238	17.7	1.1	19.0
6	03:	01 00 - 01 45	237	14.9	1.0	19.0
7		03 00 - 03 45	239	13.0	0.8	19.1
8		05 00 - 05 45	239	15.7	1.0	19.4
9		11 00 - 07 45	238	20.8	1.3	19.1
10		13 00 - 13 45	234	20.3	1.3	15.3
11		15 00 - 15 45	234	20.4	1.3	16.1
12		17 00 - 17 45	236	20.4	1.3	16.1
13		19 00 - 19 45	232	15.8	1.0	16.4
14		21 00 - 21 45	233	15.1	1.0	18.4
15		23 00 - 23 45	239	15.8	1.0	16.3
16	04:	01 00 - 01 45	237	18.2	1.2	15.9
17		03 00 - 03 45	237	17.5	1.1	16.4
18		05 00 - 05 45	242	24.3	1.6	19.5
19		07 00 - 07 45	239	28.3	1.8	14.5
20		09 00 - 09 45	241	35.2	2.3	18.2

n = 20 K = 4727 $\bar{g}$(h) = 980 925 718.0

$\bar{m}$ = ± 20.1 mcgal $\bar{M}'$= ± 1.3 mcgal

m_o= ± 1.9 mcgal M_o= ± 0.4 mcgal

9. U S S R

Point A

h = 0.984 m W_{zz}(1.25 - 0.85) = 302.2 mcgal/m

Series	Date	U T	k	m	M'	g(h)
				mcgal		
1	1989.11.29:	17^h55^m - 18^h10^m	80	± 125	±14	980 925 704
2		18 15 - 18 30	80	125	14	686
3		18 50 - 19 05	80	125	14	692
4		19 15 - 19 30	80	143	16	687
5		20 20 - 20 40	100	130	13	702
6		20 50 - 21 10	100	100	10	698
7		21 20 - 21 40	99	119	12	696
8		21 30 - 22 10	100	120	12	698
9		23 10 - 23 30	100	130	13	699
10		23 40 - 24 00	100	130	13	705
11	30:	00 20 - 00 40	100	120	12	706

n = 11; K = 1019 $\bar{g}$(h) = 980 925 697.5

$\bar{m}$ = ± 124 mcgal $\bar{M}'$= ± 13.0 mcgal

m_o= ± 6.8 mcgal M_o= ± 2.1 mcgal

9. U S S R

Point A3

h = 0.986 m $\qquad W_{zz}(12.5 - 0.85) = 290.5$ mcgal/m

Series	Date	U T	k	m	M′	g(h)
				m c g a l		
1	1989.12.01:	$20^h05^m - 20^h20^m$	75	±87	±10	980 925 644
2		23 20 - 23 35	75	87	10	630
3		23 45 - 23 59	75	78	9	652
4	02:	00 10 - 00 25	80	89	10	657
5		00 40 - 00 55	79	80	9	622
6		01 05 - 01 20	80	89	10	630
7		01 30 - 01 45	80	72	8	616
8		01 55 - 02 10	80	72	8	644
9		02 20 - 02 35	79	62	7	630
10		02 45 - 03 00	80	80	9	639
11		03 10 - 03 25	80	80	9	637
12		03 35 - 03 50	80	72	8	628
13		04 00 - 04 15	80	72	8	636
14		04 25 - 04 40	80	80	9	640

n = 14; $\qquad$ K = 1103 $\qquad \bar{g}(h) = 980\ 925\ 636.1$

$\bar{m} = \pm 78.6$ mcgal $\qquad M' = \pm 8.9$ mcgal

$m_o = \pm 11.1$ mcgal $\qquad M_\delta = \pm 3.0$ mcgal

Canada's contribution to the 1989 International Comparison of Absolute Gravimeters at the BIPM: Instrumental Improvements and Analytical Approach

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ABSTRACT

A summary of instrumental improvements brought to the JILA-2 absolute gravimeter (Canada) as well as analytical techniques is presented. Special emphasis is put on two aspects of measuring absolute gravity with a falling mass, namely that the equation of motion must include the vertical gravity gradient, and that lasers with two wavelengths used to monitor the falling mass may contain a high frequency leakage. In the first case, a position error of about 2 cm can occur without the proper gradient function, and in the second case, the mean gravity value based on two wavelengths can be off by more than 5 μGal without the proper leakage corrections. Other corrections presented are: temperature compensation for laser wavelengths and standard external corrections agreed upon at the 1989 International Comparison of Absolute Gravimeters.

INTRODUCTION

The Geological Survey of Canada (GSC) participated in the International Comparison of Absolute Gravimeters (ICAG) in the laboratories of the Bureau International des Poids et Mesures (BIPM), Sèvres, France, in the latter part of 1989. This was a unique opportunity for ten instruments from ten different countries to determine the accuracy of such instruments through nearly simultaneous measurements at a few co-located sites. A few participants were also able to observe at more than one point, in addition to what was originally planned. In particular, we (GSC) observed at BIPM sites A, A1 and A3 over a period of 7 days.

We take this opportunity to present a summary of our hardware configuration, observation philosophy, analysis method and known systematic effects as applied to the ICAG campaign.

Hardware Configuration

The GSC instrument, JILA-2 (Zumberge 1981), originally built by the Joint Institute of Laboratory Astrophysics , University of Colorado in Boulder, was modified extensively since 1985 when it was first received in our laboratories. The instrument was made up of 7 major pieces of equipment: a roughing pump for acquiring start-up vacuum, a dropping chamber, a vibration isolation system called a super spring, a laser interferometer base, a HP9816 (HP200) computer and two racks of electronic equipment (see Table 1). We performed most of the modifications between 1985 and 1987, after doing a series of tests with our instrument.

Tables 2-A and 2-B give a summary of the modifications and improvements brought to our instrument. Additional equipment is also listed. An important change done in 1987 was the replacement of the HP200 computer with a HP300 computer which has more memory (2 Mbyte) and runs faster than the previous unit. The operating language was changed from HPL to HP BASIC 5.0 which is more powerful and more easily understandable to the uninitiated. The controlling software was re-written in its entirety. In 1988, a tape cartridge unit was added to record all the fringe data (times associated with each fringe of a drop) for later analysis. Because the instrument contains more equipment, two racks were added to the original electronic racks. The instrument has been used in this configuration more or less since then.

Many modifications are self explanatory but some need more details. For example, the behavior of the dropping chamber with the original tripod was studied to see if it moved during a measurement. We needed to know if the window of the chamber, which acts as a vacuum-air interface, was stable enough optically so as not to introduce noise in the position of the fringes measured during each drop (Peter et al. 1990). The difference in index of refraction between air and vacuum is large enough so that a window displacement at the bottom of the chamber will lead to an offset of over 4 wavelengths/cm. Since our requirements demand a resolution of one thousandth of a fringe or less, any window displacement greater than 40 μm starts to degrade the quality of the measurement and potentially add a systematic error to the results. We determined that the bracing of the tripod and the footing of each leg could both be improved to reduce any vertical displacement of the chamber.

We used a geophone on top of the chamber to monitor its movement during a drop. The signal analyser (Table 2B) was used to capture the chamber response. With such a system, we were able to test different chamber-tripod configurations in order to obtain an optimum instrument geometry.

The original angle of the tripod legs was set at about 45° from the vertical. This angle sets the feet of the tripod far apart which allows the chamber to vibrate over the duration of a drop. The period of vibration can last as long as the time it takes for the mass to drop (200 ms). Furthermore, whenever the legs have to be brought closer to the chamber (angle less than 45° off vertical), the original leg braces no longer provide a rigid horizontal constraint, hence the chamber is more susceptible to oscillations. A new set of braces were designed to maintain rigidity at all leg angles.

The original feet of the tripod are made up of a set of three adjustable brass receptacles (pads) into which the rounded ends of the tripod legs are inserted. Each pad has a shallow groove designed to receive each tripod leg for easy adjustment. It was determined that the chamber moved slightly during a drop because the grooves allowed the rounded ends of the legs to slide in and out. Since these grooves can be removed from the pads leaving only a conical depression, tests showed that the chamber vibrated less with the rounded ends of each leg inserted in these depressions.

We also inserted a Viton O-ring underneath each brass pad in order to provide a more stable contact with the floor. Tests showed that this addition alone helped considerably to reduce chamber vibrations. These vibrations were absorbed over a period of about 40 ms which is much shorter than the drop time.

We decided on a final chamber-tripod configuration where new braces with positive clamping were put in place, O-rings were kept as permanent parts of the brass pads and the tripod legs were kept as close as possible to the chamber without touching the interferometer base underneath the apparatus. It was found that the chamber vibrations were reduced considerably so as not to introduce fringe offsets during the 200-ms period of the drop. Figure 1 illustrates chamber velocities (the geophone records velocity) before and after the improvements have been performed.

Since the analysis of the position of the falling mass starts 32 ms after the initiation of the drop, and since nearly all chamber vibrations are absorbed by 40 ms with the new arrangement, we consider that essentially no bias is introduced into the position of the falling mass.

However, because the chamber-tripod arrangement is more rigid than before, we are concerned that chamber vibrations will be more readily transmitted into the ground through recoil, and thus disturb the interferometer underneath the instrument. In fact, J. E. Faller has expressed such a concern during the ICAG meeting at the BIPM in November, 23rd, 1989, and G. Peter (Peter et al. 1990) has reported on this subject.

The design of the JILA instrument calls for an interferometer in which the two arms of the interfering laser beam have a horizontal segment of 20 cm (Fig. 2) between two vertical parallel paths. It becomes evident that any relative displacement between one mirror (the beam-splitter for instance) and the other will introduce an offset in the fringe positions. A relative displacement of only 1 nanometer is sufficient to give an error of one thousandth of a fringe (equivalent to about 1 μGal). Any vibration that is systematic with the drop because of ground transmission needs to be avoided or reduced to a minimum. Since they have a different instrument configuration (different instrument modifications, installation etc...) G. Peter et al. (JILA-4) have designed an analysis procedure to reduce such systematic effects. This procedure is extremely useful when the gravity site is located on a "flexible" surface such as concrete floors normally found in the basement of buildings.

At the Geological Survey of Canada, we have tended to install gravity sites directly on bedrock or on piers firmly anchored to bedrock. Because past glaciations have cleared the Canadian landmass of overburden in many places, access to bedrock is relatively easy, especially in the northern latitudes. This choice of sites has generally isolated us from recoil problems since bedrock does not yield to chamber vibrations. Tests with the geophone mentioned above have also shown that at such sites as opposed to "soft" floors, the instrument barely moves during a drop. We will briefly address the ground vibration problem later in this report.

Observation Philosophy

Measurements are done automatically by the computer once the instrument has been installed in its optimal configuration. Instrumental and geophysical considerations have governed what sort of data are captured and analyzed, what external parameters are recorded and how the measurements are grouped.

First, since the mass falls within an enclosure called a drag-free chamber, there is a short period of time when the mass is close to its resting point. Once it has risen away relative to this point, it hovers at a fixed distance for the duration of the drop (Zumberge 1981, p43). When the drag-free chamber nears the end of its travel, the mass is again brought close to its resting point before finally stopping at a pre-determined spot. The time it takes to reach the hovering distance is 32 ms and the hovering time interval has been set at 188 ms. Thus, since there are fringes being generated prior to the hover interval, any fringes before 32 ms are ignored since residual electrostatic forces could have an effect on the falling mass when it is close to the drag-free chamber. The same holds true after the mass has fallen over a 188 ms period: fringes past this time are also ignored.

The original instrument scaler counter (Table 1) recorded every 4000th fringe. Because we get only about 170 fringes in 190 ms, we changed the scaler setting so that it recorded every 1500th fringe in order to get 444 fringes in one drop. This implied that memory requirements such as computer RAM and disk space had to increase since more data were generated.

Next, drops need to be grouped in some manner since gravity can change significantly over the measurement period which can last more than one day, and subtle gravity changes occurring over a short time will not be noticed if the observations are averaged from a large data set.

No data grouping was suggested at the outset with the instrument in 1985. Some institutions preferred a set size of 100 drops while others used 250 drops. The set size is particularly important since the instrument has to operate in two wavelength modes (Niebauer et al. 1988). Since the instrument performs measurements alternatively in the "red" and the "blue" modes of the laser (low frequency and high frequency modes), this mode switching provides a convenient break in the data and as well as the set size.

Niebauer describes the frequency-stabilized lasers used in the JILA instruments as having very stable mean frequencies (mean of the red and blue modes). The individual laser modes however are not as stable as their mean. This implies that if one mode drifts in one direction, the other mode will drift in the opposite direction. For this reason, we have grouped our measurements into small sets of 25 drops where the instrument is alternately operated in the red and the blue laser modes.

Thus, laser drift in the individual modes is compensated for by this switching method and wavelength uncertainty is minimized. The average waiting time between sets from one mode to the other can vary from 2 to 5 minutes under normal conditions. A set of 25 measurements will take approximately 9 minutes to collect, thus 4 to 5 sets can be recorded over one hour. Data storage requirements have limited us in the quantity of readings we can take during one site occupation without having to change the storage medium (floppy disk). 2000 measurements, along with a copy of the controlling program which is saved for future reference, will nearly fill one 720 kb floppy disk. Our standard data structure then is 80 sets of 25 drops, with the laser alternating between red and blue modes. The observation time will vary from 16 to 24 hours depending on the chosen waiting period between sets.

The observation time of 9 minutes for one set of 25 drops may seem long compared to other absolute gravity meters because other external parameters are recorded as well during the measurements. Table 3 gives a summary of the data gathered. This information will serve later to correct for known systematic effects and to study possible correlations between gravity measurements and the status of the instrument.

Data Analysis & Systematic Effects

On the assumption that the single-drop absolute gravity values are randomly distributed, statistical analysis of this data is fairly straightforward. The average of each 25 drop set is calculated and data points within each set are rejected whenever they deviate from the mean by more than 3 standard deviations (σ). If any value is rejected, a new average is calculated along with a new σ. On a normal survey, about 30 drops out of 2000 are rejected this way. We suspect that these rejected points are mostly caused by hardware data transmission errors and not by true random fluctuations.

All the 80 sets are then averaged to give the final gravity mean of a site occupation. The same rejection criterion of 3σ is used on these sets. Whole 25-drop sets are rarely rejected and occurs only when a teleseism disturbs the instrument or when ground noise changes abruptly.

Each set is corrected for known instrumental and geophysical effects. The standard corrections will be listed later. Three non-standard corrections are explained here in more detail. One correction deals with the absolute gravity measurement method itself while the last two cover poorly documented effects in geophysics influencing the laser wavelengths.

Measurement method

To achieve an accuracy of 1 μGal with absolute gravimeters that use a falling object as the sensing unit, the exact height of the gravity observation above the reference marker needs to be known to about 1 mm. The physical coordinate of the falling object can be accurately determined at a multitude of positions with the following equation,

$$X = X_o + V_o T + g T^2/2 \qquad [1]$$

where X_o is the initial position, V_o, the initial velocity, g, the value of gravity at some point in the drop, and T, the time of each fringe.

However, since this technique uses least-mean-square methods to solve for the value of gravity, the location of the gravity result will be difficult to specify _if_ equation 1 is used where the vertical gravity gradient is not included.

The accuracy of absolute gravimeters has increased over the years and for that reason we decided early on to avoid as much as possible "transferring" the observed gravity value to another height with the measured gradient since the latter usually has a standard deviation of 1 or 2 μGal. We felt that this would reduce the accuracy of gravity determinations. Our survey procedure is to measure the gravity gradient prior to absolute gravity observations and to incorporate this gradient into the least-mean-square solution for gravity. Thus, the value observed could be associated with the start of the drop.

The formal equation of motion which includes fourth order terms is

$$X = X_o (1 + \tau T^2/2) + V_o (T + \tau T^3/6) + g (T^2/2 + \tau T^4/24) \qquad [2]$$

where τ is the gradient.

Prior to May, 1988 , we had assumed that the velocity component V_o with the gradient was negligible and that the following equation of motion was sufficient,

$$X = X_o + V_o T + g (T^2/2 + \tau T^4/24) . \qquad [3]$$

With equation 3, the observed gravity value is associated with the rest point of the mass which is easily identifiable, and not with somewhere "one third of the way down" (Zumberge 1981) into the drop which is not so easily determined. Since the drop span in our instrument is of the order of 17.3 cm, the "1/3" offset is equal to 5.77 cm below the starting point. The gravity difference between a result using equation 3 and a value not corrected for the gradient is equal to this vertical offset times the gradient.

However,a problem became apparent after the Geological Survey of Canada and the National Geodetic Survey (USA, JILA-4) performed an inter-comparison at our site near Ottawa. JILA-4 was using equation 1 and JILA-2, equation 3, and the gradient transfer did not exactly adjust our respective observations. It turns out that even a relatively small initial velocity V_o cannot be ignored when solving for the value of gravity. Due to the nature of the dropping mechanism, the initial velocity V_o is seldom equal to zero so that equation 3 will usually give a distorted result since it is a simplified version of the more formal equation 2.

The "real" height associated with the value of gravity will be slightly lower than expected if equation 2 is not used. For example, in our instrument the falling mass normally has an initial velocity V_o of about 20 cm/s. The difference between a gravity value using equation 2 and a gravity value un-corrected for the gradient, corresponds to a height displacement of the order of 7.8 cm, practically 2 cm lower than expected with equation 3.

Since V_o is not exactly 20 cm/s from drop to drop and that it can range from 18 to 22 cm/s, a procedure which does not consider the gradient as part of its solution would in effect increase the scatter between observations since the apparent height of the measurements would vary from drop to drop. Computations have shown that with an un-corrected gravity value there is approximately a 1 mm error in height for every 1 cm/s so that with our velocity span above, we could have a 4 mm scatter in our observation heights. This corresponds to about 1.2 μGal assuming a normal vertical gravity gradient.

Laser wavelength

There are two aspects to the problem dealing with the laser wavelengths. The first aspect is how stable the wavelengths are with respect to changing external temperatures, and the second, is how "pure" is each wavelength.

Early in 1986, we had our laser calibrated and tested at the laboratories of the National Research Council of Canada (NRC). The laser was tested for sensitivity to atmospheric pressure, magnetic fields, external temperature, and line voltage fluctuations (Hanes 1986). The only effects found were from magnetic fields and external temperature. It turns out that the magnetic field of the super-spring (about 40 gauss at the laser) changed the mean frequency of the laser by about 0.5 MHz. Because of this effect, we now have the laser calibrated with the super-spring in place.

It was determined that the sensitivity to external temperature is not identical for each mode. For the red mode, the correction factor is

$$W(t) = Cr/(Cr + 1.5805(t - 20) - .1841(t - 20)^2) \qquad [4]$$

and for the blue mode,

$$W(t) = Cb/(Cb - 1.8944(t - 20) + .1841(t - 20)^2) \quad [5]$$

where t is the room temperature (C°) near the laser, Cr and Cb, the respective frequencies (around 473,612,681 MHz) of the red and blue modes. The correction factor on the observed gravity g_o is used so that

$$g = g_o W(t) \quad [6]$$

Since the laser was tested with temperatures ranging from 20 to 28 C°, the above correction factors are valid for this range only. We have tried to stay close to 20 C° during all our surveys in order to minimize the approximation inherent in equations 4 and 5.

The other correction that we have implemented for our laser is more subtle. The laser has been calibrated repeatedly since 1986 but when the gravity values for both modes were compared, there was always a systematic difference of about 20 μGal between the two modes (red mode results higher than the blue). By 1987, we had come to the conclusion that inter-mode leakage was the cause of the discrepancy.

Both red and blue modes are present in the laser beam at all times. Since their polarizations are orthogonal to each other, each mode can be isolated with a polarizer. The manufacturer (Newport) claims that the mode purity after the polarizer gives a leakage ratio of the unwanted mode over the wanted mode of 1/1000 (30 dB). In 1987, we set out to measure this leakage in our laser for each mode at the laboratories of the NRC. It was determined that the mode leakage ratio for the red side was 0.0017, and for the blue side, 0.0069. Furthermore, these leakage amplitudes became equal when the super-spring was removed from its mount near the laser. Clearly, this leakage was susceptible to magnetic fields but was not eliminated when a strong field was removed. We have come to call the correction to be made to the data, the beat-mode correction since it is caused by the beating of the wanted mode with a weak unwanted mode.

Beat-mode effect

The laser operates around 473.612681 THz in one of two modes separated by 720 MHz. The light intensity in the case of a weak leakage can be approximated as the sum of two amplitudes:

$$I = COS(\phi X) + \epsilon\ COS((\phi + \delta\phi)X) \qquad [7]$$

where ϕ is equal to $2\pi/\Lambda$,

Λ is the wavelength of the normal mode,

$\delta\phi$ equals $2\pi/\delta\Lambda = 2\pi\delta f/C$, with C as the speed of light and δf, the inter-mode frequency of 720 MHz which can be positive or negative

X, the fringe positions

ϵ, the leakage ratio with respect to normal mode intensity.

Expanding the equation 7, we get

$$I = COS(\phi X)\ (1 + \epsilon\ COS(\delta\phi\ X)) - \epsilon\ SIN(\phi X)\ SIN(\delta\phi\ X)$$

and if $\epsilon << 1$ then $1 + \epsilon\ COS(\delta\phi\ X) \approx 1$ so,

$$I \approx COS(\phi X) - \epsilon\ SIN(\phi X)\ SIN(\delta\phi\ X). \qquad [8]$$

this further simplifies to

$$I \approx COS(\phi X + \epsilon\ SIN(\delta\phi\ X)). \qquad [9]$$

Thus, the intensity I has the form of a phase shifted sinusoid where the phase shift is a function of position X.

Since we are using a zero crossing discriminator as our fringe detector in the determination of acceleration, we detect the positions X_i in equation 9 where

$$I = COS(\phi X + \epsilon\ SIN(\delta\phi\ X)) = 0.$$

We calculate the positions X_i where

$$\phi\ X_i + \epsilon\ SIN(\delta\phi\ X_i) = 2\pi i \qquad [10]$$

where i is an integer.

The positions X_i can be written in the form

$$X_i = 2\pi i/\phi + \alpha$$

where α is a correction term. Substituting in 10 and solving for α we arrive at

$$X_i = (\ 2\pi i - \epsilon\ SIN(2\pi i\ \delta\phi/\phi)\ )/\phi \qquad [11]$$

Positions X_i corresponding to fringe crossing points in equation 11 are expressed with respect to a position of the falling mass where the lengths of the two arms of the interferometer are equal. Since in our instrument this position lies near the end of the drop, an integer term Φ must be added to the equation to make the positions X_i refer to the start of a drop. Equation 11 then becomes

$$X_i = (2\pi i + 2\pi\Phi - \epsilon \, SIN(2\pi i \, \delta\phi/\phi))/\phi \qquad [12]$$

As the mass falls, the zeros of the fringes will be displaced by varying amounts which would not be the case if there were no leakage in the laser. Furthermore, as the separation between the chamber and the interferometer is never the same (one unit of Φ is equal to 0.5 mm when properly scaled) and that the drag-free chamber position at the start of the drop is also variable, the beat-mode effect is not a constant to be applied to all values at all stations. For a normal instrument installation, the beat-mode correction for the red side is about -4.0 μGal and +17.0 μGal for the blue side. It is obvious that the mean gravity value of the preliminary red and blue modes is not the correct value for g.

In 1988, we raised the chamber by small increments away from the interferometer base in order to verify the accuracy of equation 12 above. Figure 3 shows that the gravity difference between modes changes with height as expected. The blue mode in fact becomes higher (negative portion of plot) than the red mode 6 cm above the normal chamber position. Ironically, if the design of the instrument had moved the chamber 5 cm above the base instead of 1.3 cm, we would never have seen this effect! Thus, the relative positions of each part of the interferometer system (super-spring and chamber) must be measured meticulously at the start of the observations.

The other standard corrections that are applied to the absolute gravity observations are for atmospheric pressure, the speed of light, tidal variations (provided by the BIPM for the ICAG exercise), and polar motion (Wahr 1985).

Atmospheric pressure correction

The first-order correction for mass redistribution in the atmosphere is based on the changes in local pressure. The correction convention used is

$$g_p = 0.3 \; (p - p_n) \; \mu Gal$$

which is added to the gravity result.

The reference atmospheric pressure at a station is the normal pressure p_n which is given by

$$p_n = 1013.25 \; (1 - 0.0065 \; H \; / \; 288.15 \;)^{5.2559} \; mbar,$$

where H is the height of the station in meters above sea level (Boedecker & Richter 1984).

Speed of light correction

We have applied a velocity of light correction by simply changing the fringe times of each drop prior to data analysis. Since there is a time delay due to the finite speed of light in a vacuum between the first fringe and the last fringe, each fringe time is reduced with respect to the last fringe time:

$$T'_i = T_i - (X_i - X_n)/C \qquad i = 1,2,3,\ldots n$$

where C is the velocity of light 2.99792458E+10 cm/s and X_i, the coordinate of each fringe. For a drop duration of about 188 ms, the gravity correction is of the order of -11 μGal to be added to the gravity solution.

Ground vibration

Apart from ground noise due to the recoil of the dropping mechanism, we have briefly studied the noise level at the BIPM sites (A, A1 and A3) which comes from external sources. We have encountered situations before where ground noise was large enough to force us to discontinue measurements. Although this was not the case at the BIPM, and because the ground signal was not continuous but was dominated by noise at discrete frequencies, this led us to test some very preliminary analysis procedures on the different data sets.

When we performed the observations at the A1 site, two groups of measurements were taken.We changed instrument orientation after taking 80 gravity sets and then we re-started the measurements. The interferometer was first oriented along the pier (N-S) which is longer than its width, and then across the pier (E-W). A 2 μGal discrepancy appeared. A preliminary study which removes significant frequencies along the lines of Peter et al. have shown that the gravity values were changed for observations done with the instrument oriented along the length of long piers such as A, A1 (same pier) and A3, and were not changed when oriented across the same piers. It is too early to tell if this effect is real or an artifact of the analysis technique but we intend to pursue this study.

Conclusion

Our instrument and our analysis techniques have changed significantly since late 1985 when we first received JILA-2. Apart from changing a fair portion of the hardware, mechanical improvements such as a steadier tripod have made it more reliable in the field by eliminating instrument induced noise.

The importance of intercomparison between absolute gravimeters was made evident in March, 1988 when we had the opportunity to compare our results with simultaneous readings taken by the National Geodetic Survey (JILA-4) at our site near Ottawa. On that occasion, we improved on our gravity gradient correction technique when a 2 cm discrepancy showed up between our results. With 10 instruments at the BIPM, the potential for improvement is thus greatly enhanced.

We have documented here our technique for correcting the effects of inter-mode leakage in the laser, which we call the beat-mode correction. Although some lasers have been shown to give nearly identical gravity results in either laser modes, other lasers such as our own, have been shown to have discrepancies between the two modes of the order of 20 μGal. This effect should be removed from all instruments that show such large gravity differences for the two laser modes.

Ground noise not originating from the instrument will have to be studied in more detail. It would be unfortunate to learn that instrument discrepancies at the BIPM ICAG campaign are somehow due to different instrument response to a noisy environment.

With each ICAG campaign, techniques are compared and improved. We hope that such improvements will help further the real purpose of such efforts, namely more precise geophysical monitoring and understanding of our physical world.

Acknowledgments

We greatly appreciate the help and advise provided by Dr. G. Hanes of the National Research Council of Canada who performed the laser calibrations and laser leakage measurements. We wish to thank the staff at the BIPM for their warm welcome and for the opportunity to measure at their laboratories . This report is Geological Survey of Canada contribution ______________.

Table 1.

Contents of original JILA electronic racks

HP Universal Time Interval Counter (UTIC) SCALER COUNTER (4000 and 2000 scaler values) Rb 10 MHz oscillator High voltage power supply
Dropping chamber controller Super spring controller Vacuum ion pump Laser controller

Note: HP stands for Hewlett Packard

Table 2-A

Modifications to existing equipment and new equipment added to the original JILA-2 instrument

Electronic racks

HP300 computer with BASIC 5.0 language (comes with separate monitor)
HP 20 Mbytes hard disk drive with 3.5" floppy drive
HP tape cartridge (67 Mbytes) for recording individual fringes (HP9144A)
HP data acquisition controller for input and output
Air pressure sensor monitored through the data acquisition unit

Super spring

Internal restraint system used during transport
Electronic drift compensation circuit in the super spring controller board

Laser interferometer

New focusing optics for the avalanche photo-diode with X-Y mount for optimal output
Computer controlled laser mode switching
External and internal temperatures of laser monitored

Dropping chamber

Viton O-rings inserted in the brass pads of the dropping chamber legs
Additional braces to the legs
Clamping system of the mass strengthened for transport

Table 2-B

Electronic improvements	Additional external equipment
New SCALER COUNTER unit with separate circuits for fringe inputs and clock inputs so that cross-talk is minimized: +4 to +5 μGal change in the results.	HP signal analyser (HP3561A) with a L4 geophone (1 Hz and above)
Improved 50-pin connector for field ruggedness	100 MHz digital oscilloscope
Reduced scaler values to increase number of recorded fringes (1500 vs 4000 for fringe input, 300 vs 2000 for clock input)	Balzer turbo-pump for rapid high vacuum acquisition
	Auto-collimator to set the laser beam vertically to less than 5" of arc
	"X-Y" optical detector to adjust vertical alignment of the dropping chamber

Table 3
External parameters

Laser temperature (C°)
External temperature (C°)
Amplitude (V) and
Peak frequency (Hz) of ground noise
Super-spring position (mV)
Chamber vacuum (mV)
Atmospheric pressure (mbar)

Figure captions

Figure 1

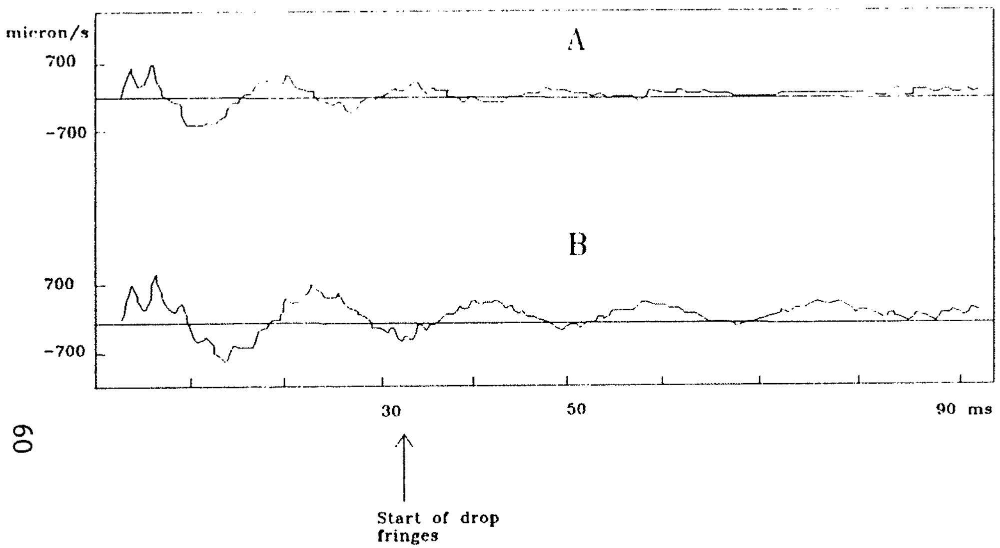
The plot shows the first 100 ms after a drop has been initiated where trace A represents the new set-up and where trace B, the best installation of the instrument after many trials.

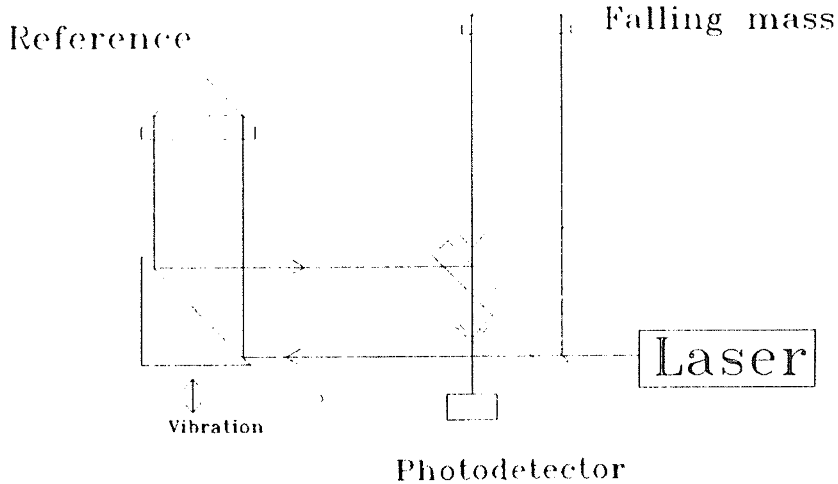
Figure 2

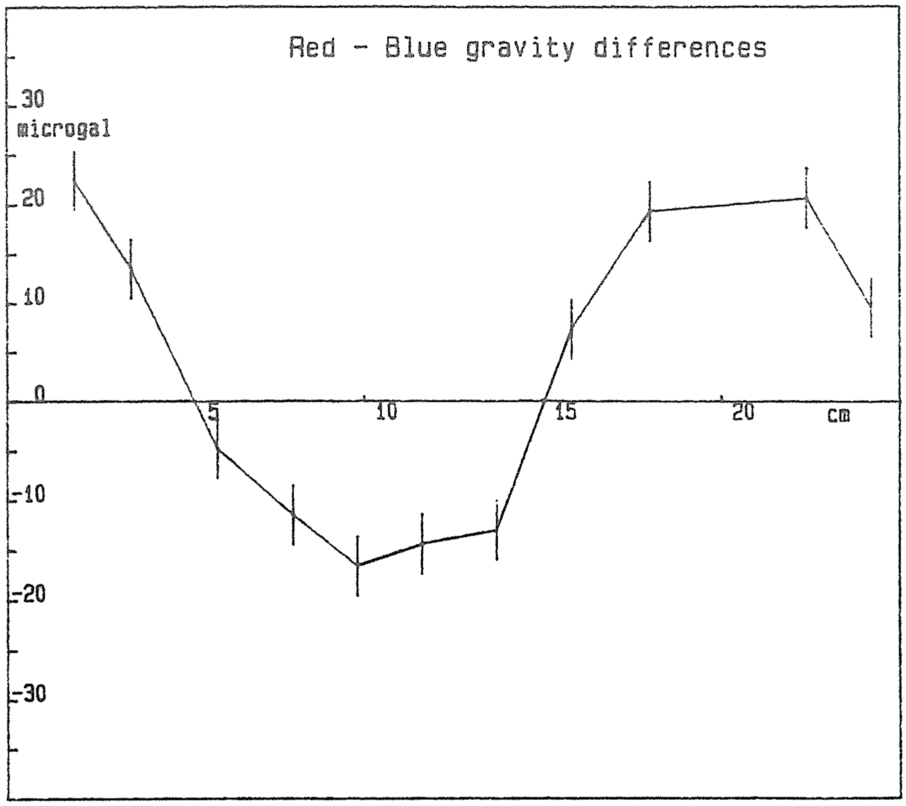
Simple representation of the interferometer under the falling mass and the corner-cube mirror of the super-spring. The mirror under the falling mass is a beam-splitter. The other mirror can vibrate vertically with respect to the beam-splitter and generate interference fringes.

Figure 3

Gravity difference between the red and the blue modes as a function of the chamber-interferometer base separation.


micron/s
700
-700
A
B
700
-700
30
50
90 ms
Start of drop fringes


Reference
Falling mass
Laser
Vibration
Photodetector


Red - Blue gravity differences
30
microgal
20
10
0
5
10
15
20
cm
-10
-20
-30

Absolute and Relative Gravity Measurements at Hannover and Potsdam in the Period 1988-1990

by

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Abstract

Repeated absolute and relative gravity measurements have been carried out in Hannover and Potsdam in this century. This paper concentrates upon observations in Potsdam, performed with the JILAG-3 absolute gravimeter of IfE in 1988 and 1990. Earlier observations with the USSR GABL-gravimeter in Potsdam, observations with JILAG-3 in Hannover and in Bad Harzburg, and relative ties between Potsdam, Hannover and Bad Harzburg are used for comparison purposes.

1. Introduction

At the end of the last century, F.R.HELMERT, the director of the Geodetic Institute Potsdam, initiated an absolute determination of the acceleration of gravity at his institute to get a reliable base value for the numerous relative gravity measurements which were accomplished already at that time at continents and oceans. This gravity value was determined using five reversible pendulums in the period 1898–1904 (KÜHNEN and FURTWÄNGLER 1906). In 1909, at the 16. General Conference of the Internationale Erdmessung at London, the Potsdam Gravity System was introduced and the result of the absolute gravity measurements at Potsdam, $9.81274 \pm 0.00003\ ms^{-2}$ was adopted as a world wide reference value (BORRASS 1911, RIECKMANN and GERMAN 1957, REICHENEDER 1959).

This system was used up to 1971 when it was replaced by the International Gravity Standardization Net 1971 (I.G.S.N.71, MORELLI et al. 1974). At that time about four to five millons of gravity points existed within the Potsdam Gravity System (BOULANGER 1980). Already in the 1920's it was suspected that a systematic error in the order of 100 μms^{-2} in the Potsdam gravity value might exist. Subsequent absolute gravity measurements performed with increasing accuracy at different places confirmed this supposition and finally led to a correction of $-140\ \mu ms^{-2}$ for the Potsdam gravity datum.

At the end of the 1960's, another absolute gravity value was determined at the Geodetic Institute Potsdam, since 1969 a part of the Zentralinstitut für Physik der Erde, by reversible pendulums (SCHÜLER et al. 1971). The result of $9.812601 \pm 0.000003\ ms^{-2}$ confirmed the above mentioned correction to the Potsdam gravity system.

In 1976, Prof. Boulanger, Moscow, and his group started a series of absolute gravity measurements using the USSR free-fall gravimeter GABL. Up to 1986 five gravity determinations were performed with the intention of a further improvement of the Potsdam gravity datum.

In January 1988 an absolute gravity determination was performed at Potsdam by Institut für Erdmessung, Universität Hannover, using the Faller-type gravimeter JILAG-3, followed by a second determination in January 1990. The Potsdam station was also tied to the IfE base station in Hannover in 1990, using four LaCoste-Romberg gravimeters. In Hannover altogether 21 absolute gravity determinations have been carried out between 1986 and 1990.

2. Station Descriptions

2.1 Hannover

Station Hannover 101 is located in the basement of a university building at Callinstraße 34, about 2 km north-west of the city center of Hannover. Its coordinates are:

$\varphi = 52.390°$, $\lambda = 9.714°$, $H = 53.46\ m$.

The station (see appendix 1) was established for technical investigations and maintainance of the absolute gravimeter JILAG-3, and it is one of 14 sites incorporated in the Gravimeter Calibration System Hannover. This system is in good agreement with the German Gravity Base Station Network (Deutsches Schweregrundnetz 1976), with respect to absolute level and scale.

From the examination of bore-holes in the close vicinity of the station, we found the uppermost layers down to 15 m below terrain level consisting of sand, gravelly and marly soil. The next few hundred to few thousand meters consist of sediments with increasing compactness. Since 1984, ground water table variations are permanently monitored at a gauge located about three meters beside the station. The variations are $\pm 0.5\ m$ around an average level of about 50 m (3.5 m beneath the station). Assuming an effective soil porosity of 25%, a gravity variation of $\pm 0.05\ \mu ms^{-2}$ would be expected. The attempt to correct for this effect did not show any improvement in the scatter of the gravity values.

Due to the central location in the city of Hannover, gravity measurements at the Hannover station are disturbed by high artificial microseismics.

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2.2 Potsdam

The station is situated on the top of a small hill, the Telegrafenberg, inside the main building (A17) of the Zentralinstitut für Physik der Erde, which was built in 1892 as the Geodetic Institute Potsdam. The uppermost layers of the ground are formed by different glacial stages and consist of sand and clay. They are underlain by sedimentary rocks up to a depth of about 2500 m and characterized by different salt structures and internal faults. The location of the absolute gravity sites inside the north-east basement of the building is described in appendix 2. The coordinates of point S14 are:

$\varphi = 52.381°$, $\lambda = 13.068°$, $H = 80.82\ m$.

The gravity differences to the base station 0 of the Potsdam Gravity System and to the reference station Potsdam A (MORELLI et al. 1974) amount to

$$g_{S14} - g_0 = 16.69\ \mu ms^{-2},$$

and

$$g_{S14} - g_A = 14.67\ \mu ms^{-2}$$

respectively.

The ground water table is found about 50 m beneath the station. The variations of the ground water table were observed in a well, situated in a distance of about 370 m from the absolute site. Between 1978 and 1990, the water level continuously rised up to more than one meter (Fig. 2.1). The corresponding gravity variations were estimated with the Bouguer plate model and an assumed porosity of 34% of the sandy soils derived from density measurements in different depths. These assumptions give a regression coefficient of 142 nms^{-2} per meter ground water table variation.

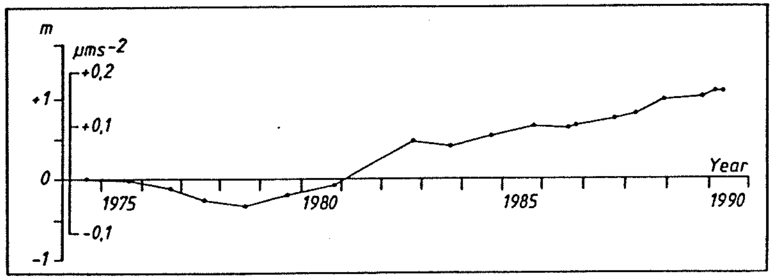

Fig. 2.1 Ground water table variation at Potsdam

The natural microseismic vertical movements at the station have periods between 4 and 7 seconds with amplitudes of 0.1 to 3 μm. The industrially caused microseismics show peaks at 0.2 and 0.025 to 0.029 seconds with amplitudes up to 0.5 μm.

3. Absolute Gravity Determinations

3.1 Measurements with JILAG-3 at Potsdam

In January 1988 and 1990 absolute gravity observations have been performed by IfE at station Potsdam using the gravimeter JILAG-3. A detailed technical description of the instrument is given by NIEBAUER (1987). Experiences of IfE are reported by TORGE et al. (1987) and TORGE et al. (1988). In 1988 the final result was computed from 4409 single experiments carried out in six runs, whereas in 1990 we used 3113 drops in ten runs. Between the runs, the leveling of the system was controlled and adjusted if necessary. The change in the procedure between 1988 and 1990 was made in order to get a more homogeneous data distribution with time. Off-leveling effects of the optical base could be reduced in this way, and systematic effects inherent in our on-line earth tide reduction routine are partly randomized. Although the number of drops per run was reduced, the precision of a run remained approximately the same. This is due to some technical improvements as the installation of a new scaler-counter and stabilization of the tripod carrying the dropping chamber. The accuracy of a gravity determination (mean value) with JILAG-3 is estimated to be at least $\pm 0.10\ \mu ms^{-2}$, including the uncertainties of the reductions. The results per run and the final values are given in tables 3.1 and 3.2. Fig. 3.1 gives the drop to drop scatter and the histograms.

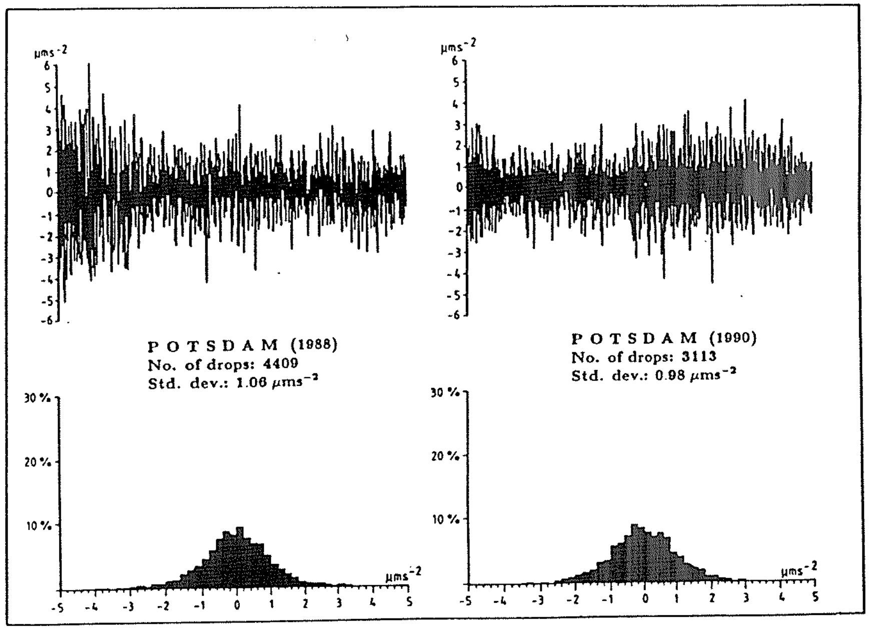

Fig. 3.1 Time sequences and histograms of absolute gravity measurements

Table 3.1: Results of absolute gravity observations in Potsdam 1988

Run	date	n	$g_{h=0.804\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	880108	488	9812614.595	1.834	9812616.70
2	880108	491	9812614.485	1.418	9812616.58
3	880108	491	9812614.727	0.798	9812616.83
4	880109	980	9812614.597	0.939	9812616.70
5	880109	980	9812614.681	0.783	9812616.78
6	880110	979	9812614.582	0.782	9812616.68
		4409		Mean:	9812616.71
					$s = \pm 0.086$
					$\bar{s} = \pm 0.035$

Table 3.2: Results of absolute gravity observations in Potsdam 1990

Run	date	n	$g_{h=0.839\ m}$ $[\mu ms^{-2}]$	s_{drop} $[\mu ms^{-2}]$	g_{floor} $[\mu ms^{-2}]$
1	900114	279	9812614.401	1.153	9812616.59
2	900114	276	9812614.392	0.714	9812616.58
3	900114	268	9812614.327	0.753	9812616.52
4	900114	289	9812614.434	0.782	9812616.62
5	900114	285	9812614.380	0.743	9812616.57
6	900115	265	9812614.305	1.156	9812616.50
7	900115	290	9812614.475	1.260	9812616.67
8	900115	290	9812614.482	1.107	9812616.67
9	900115	291	9812614.424	1.075	9812616.62
10	900115	580	9812614.484	0.891	9812616.68
		3113		Mean:	9812616.60
					$s = \pm 0.063$
					$\bar{s} = \pm 0.020$

n: number of drops,
g_h: gravity in the reference height,
s_{drop}: standard deviation per drop,
g_{floor}: gravity value at floor level, reduced with observed gravity differences (see chapter 3.3),
s, $\bar{s}$: standard deviation of one run resp. of the mean value, calculated from the differences of the runs.

3.2 Absolute Gravity Observations at Hannover and Bad Harzburg

In the Federal Republic of Germany a number of absolute gravity measurements have been performed with JILAG-3 since 1986, establishing 28 stations until 1990. The stations Hannover 101 and Bad Harzburg (former pendulum station S1) are of interest here, since they have been tied to Potsdam by relative measurements (see chapter 4). For Hannover there exists a series of 21 determinations performed between March 1986 and June 1990. The number of drops varied between a few hundreds and a few thousands. The mean value for the whole period is 9812633.30 μms^{-2}. The long-term accuracy achieved with JILAG-3 may be estimated from the r.m.s. scatter of repeated measurements. In Hannover it is ± 0.07 μms^{-2} for one determination, calculated from the values obtained between 1986 and 1990. Two of the determinations (one in Dec. 1987 and one in Feb. 1990) approximately coincide with the observations at Potsdam. Together with the relative measurements between Hannover and Potsdam (chapter 4) they will be compared with the Potsdam results in chapter 5.

In Bad Harzburg absolute gravity measurements were carried out in April 1986 and in May 1987. The mean gravity value is 9811655.06 μms^{-2}. It can be compared with the Potsdam results by a relative tie performed already in 1964 (chapter 5).

3.3 Reductions Applied to the JILAG-3 Measurements in Potsdam

Light travel time

Light travel time is based on a velocity value of $c = 299792458\ ms^{-1}$. The effect of the finite travel time on the time measurement is corrected by adding the term z_i/c to the observed time values (z_i = actual position of the dropped object with respect to the first observed position) before further data processing. The amount of the correction varied for the Potsdam measurements between -0.12 and -0.14 μms^{-2} depending on the scaled fringes beeing used.

Earth tides

Earth tide reductions are applied on-line for each drop and are controlled by post-processing using the Cartwright-Tayler-Edden development with 505 waves. Local parameters for Potsdam were provided by ZIPE (Tab. 3.3). Up to now (9/1990) no significant discrepancies were found between the two computations, provided that the observations were spread over a time span of at least two days.
The constant part of the tidal gravity effect is removed from the observations using the amplitude factor 1.000 and phase lag zero. The corresponding response of the earth is included by:

$$\delta g_{MOSO} = -0.0483 + 0.1573 \sin^2 \psi - 0.0159 \sin^4 \psi \quad [\mu ms^{-2}],$$

ψ is the geocentric latitude.

Table 3.3: Local earth tide parameters for Potsdam

Wave group		Amplitude factor	Phase
001	001	1.0000	0.00
002	128	1.1640	0.00
129	193	1.1503	−0.24
194	219	1.1522	0.02
220	241	1.1408	0.05
242	251	1.1519	0.33
252	254	0.6012	89.60
255	274	1.1398	0.16
275	296	1.1607	−0.38
297	333	1.1585	0.29
334	374	1.1605	1.94
375	398	1.1764	1.93
399	424	1.1845	1.21
425	441	1.1495	0.67
442	450	1.1878	0.40
451	488	1.1824	0.17
489	505	1.0272	−0.10

Air pressure

Gravity changes due to air pressure changes (direct gravitation of air masses and indirect effect via deformation of the solid earth) are reduced by

$$\delta g_{air} = 0.30 \cdot 10^{-2} (p_a - p_n) \quad [\mu m s^{-2}],$$

p_a is the actual air pressure in hPa. At the JILAG-3 gravity determinations p_a is measured with an electronic sensor before the start of every run.
p_n is the normal air pressure. It is is computed according to DIN 5450:

$$p_n = 1013.25 \cdot \left(1 - 0.0065 \frac{H}{288.15}\right)^{5.2559} \quad [hPa],$$

H is the station elevation in meter.
The mean reduction in Potsdam amounted to:
$+0.043\ \mu m s^{-2}$ in 1/1988 and to $+0.027\ \mu m s^{-2}$ in 1/1990.

Polar motion

The change of the position of the earth's body relative to its spin axis causes a gravity change. Referenced to CIO, the gravity reduction used is:

$$\delta g_{Pol} = 1.164 \cdot 10^6 \omega^2 a\, 2 \sin\phi \cos\phi\, (y \sin\lambda - x \cos\lambda) \quad [\mu m s^{-2}],$$

x, y: pole coordinates in the IERS system in radian,
ω : $7292115 \cdot 10^{-11}$ $[rad\, s^{-1}]$ (angular velocity),
a : 6378136 $[m]$ (semimajor axis of the reference ellipsoid),
ϕ, λ: geographical station coordinates, longitude positive east of Greenwich.

For real time evaluation an appropriate prediction for the pole coordinates is employed.
The mean reduction values for Potsdam are:
$+0.014\ \mu m s^{-2}$ for 1/1988 and $+0.044\ \mu m s^{-2}$ for 1/1990.

Reduction to ground level

The gravity difference between the reference height of JILAG-3 and ground level has been measured directly using two LaCoste-Romberg gravimeters. Measuring the difference ten times with each of the gravimeters results in an accuracy of this reduction of $0.02\ \mu m s^{-2}$.
The mean reduction values are:
$+2.100\ \mu m s^{-2}$ for 1988 and $+2.191\ \mu m s^{-2}$ for 1990.

3.4 Results of Earlier Absolute Measurements

In Table 3.4 the results of the absolute gravity determinations performed at Potsdam since the beginning of this century are listed.

Table 3.4: Results of absolute measurements at Potsdam referred to site S141

Epoch	Observers	Instrument	g_{S141} 9812610.00 + ... $\mu m s^{-2}$	δg_{GW} $\mu m s^{-2}$
1898–1904	KÜHNEN and FURTWÄNGLER	reversible pendulums	146.69 ± 30.00	
1968-69	SCHÜLER et al.	"	7.69 ± 3.00	
1976.54	ARNAUTOV et al.	GABL	6.79 ± 0.17	0.00
1978.74	"	"	6.55 ± 0.16	0.03
1980.70	"	"	6.83 ± 0.08	−0.01
1983.86	"	"	7.17 ± 0.11	−0.08
1986.33	"	"	7.01 ± 0.07	−0.12
1988.02	WENZEL, SCHNÜLL	JILAG-3	6.71 ± 0.10	−0.14
1990.04	TIMMEN, SCHNÜLL	"	6.60 ± 0.10	−0.18

δg_{GW}: ground water reduction (not applied to the gravity values)

The GABL- and JILAG-3 results listed in Tab. 3.4 have been reduced to the same models for tidal variation, polar motion, air pressure and ground water table variation. This has been done by transforming the GABL-data to the JILAG-3 system.
In the GABL data the stationary tides are included by:

$$(M0S0)_{Potsdam} \cdot 1.164 = 0.266 \cdot 1.164 = 0.310\ \mu m s^{-2}.$$

The JILAG-3 data contain only the response of the Earth to the stationary tidal forces:

$$(M0S0)_{Potsdam} \cdot (1.164 - 1) = 0.044 \ \mu ms^{-2}.$$

Thus an additional tidal correction of $-0.266 \ \mu ms^{-2}$ had to be added to the GABL data.

The following air pressure reduction was applied to the GABL data:

$$(\delta g_{air})_{GABL} = 0.406 \cdot 10^{-2}(p - 1013) \ \mu ms^{-2},$$

p is the air pressure observed at a neighbouring meteorological station. We have $p = p_a - 2$ hPa, where p_a is the actual air pressure at the gravity site.

The JILAG-3 results are reduced by

$$(\delta g_{air})_{JILAG-3} = 0.3 \cdot 10^{-2} \cdot (p_a - 1003.6) \ \mu ms^{-2}.$$

The difference

$$(\delta g_{air})_{JILAG-3} - (\delta g_{air})_{GABL} = -0.106 \cdot 10^{-2} \cdot (p_a - 1047.26) \ \mu ms^{-2}$$

had to be added to the GABL results (Table 3.5).

Table 3.5: Corrections with respect to air pressure reductions for GABL measurements at Potsdam

Epoch	Mean air pressure p_a hPa	Correction μms^{-2}
1976.54	1006	+0.04
1978.74	1001	+0.05
1980.70	1000	+0.05
1983.86	1018	+0.03
1986.33	1018	+0.03

The polar motion reductions for the two gravimeters do not significantly differ from each other. Reductions to a normal ground water level were not applied as they did not give any improvements. The reductions calculated with the Bouguer plate model explained in chapter 2.2 are given in the last column of Tab. 3.4.

The reduction of the GABL observations to the surface of pillar S14 was realized by using gravity gradient measurements and model calculations from the distribution of masses around the absolute site (ELSTNER et al. 1986). The discrepancies between the results of the relative gravity measurements and the corresponding model calculation did not exceed 0.01 to 0.02 μms^{-2}.

4. Relative Measurements Between Potsdam and Hannover resp. Bad Harzburg

4.1 The gravity difference between Potsdam and Hannover

In connection with transportation of JILAG-3 from Hannover to Potsdam and back in January 1990 and at a separate campaign in March 1990, the gravity difference between the stations Hannover 101 and Potsdam S141 has been observed 32 times using the LaCoste-Romberg gravimeters D-14, G-79, G-298, and G-709 of IfE, employing the IfE electrostatic feedback system (SRW-system) of these gravimeters. These SRW-systems have been calibrated in the Gravimeter Calibration System Hannover. As the gravity difference is less than 20 μms^{-2}, no systematic errors from calibration are expected. Under the given transportation conditions, the accuracy of a single tie should be about 0.2 μms^{-2}, which results in an accuracy of 0.05 μms^{-2} for the mean value of the gravity difference. The mean values for the difference g_{H101}-g_{PS141} for the four instruments involved are:

D-14F:	$-16.53 \pm 0.10 \ \mu ms^{-2}$
G-79F:	$-16.45 \pm 0.10 \ \mu ms^{-2}$
G-298F:	$-16.63 \pm 0.10 \ \mu ms^{-2}$
G-709F:	$-16.42 \pm 0.10 \ \mu ms^{-2}$
Mean:	$-16.51 \pm 0.05 \ \mu ms^{-2}$.

4.2 The gravity difference between Potsdam and Bad Harzburg

Already in February 1964, the gravity difference between Potsdam and Bad Harzburg was determined by a joint project of the Geodetic Institute of the University of Hannover and the Geodetic Institute Potsdam (GROSSMANN and PESCHEL 1964) using five Askania gravimeters. By these measurements the stations Potsdam S2 situated at the NW-corner of the main building A17 and Bad Harzburg S1 (pendulum station, Ev. Gemeindehaus) were connected. The result (mean value) is:

$$g_{BHS1} - g_{PS2} = -951.5 \pm 0.2 \quad \mu ms^{-2}.$$

The scale factor for this difference has been derived from the former European Calibration Line between Oslo and Rome, which was adjusted within the former European Calibration System (GROSSMANN 1963). For conversion to I.G.S.N.71 we find a calibration factor correction of $+3 \cdot 10^{-4}$. The scale corrected difference thus becomes:

$$g_{BHS1} - g_{PS2} = -951.8 \pm 0.2 \quad \mu ms^{-2}.$$

Taking into account the eccentricity

$$g_{PS2} - g_{PS141} = -9.58 \pm 0.05 \quad \mu ms^{-2}$$

we obtain

$$g_{BHS1} - g_{PS141} = -961.38 \pm 0.21 \quad \mu ms^{-2}.$$

5. Comparisons

Comparing the absolute gravity values obtained at Potsdam between 1976 and 1990 (Table 3.4), we find discrepancies up to 0.62 μms^{-2} (r.m.s. $\pm$22 μms^{-2}) between the independent determinations. Considering the small standard deviations, there is an indication for systematic changes of the gravity value. The scatter with time for Potsdam is given in Fig. 5.1 and for Hannover in Fig. 5.2. In Hannover the scatter is less, and seems to be random.

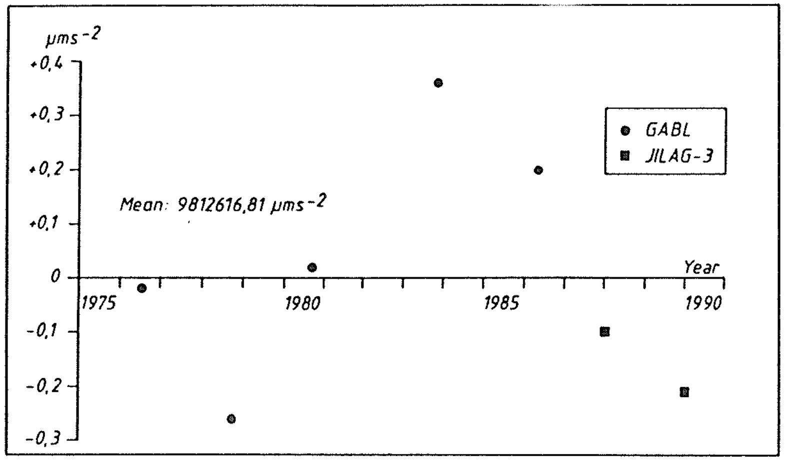

Fig. 5.1 Scatter with time at Potsdam

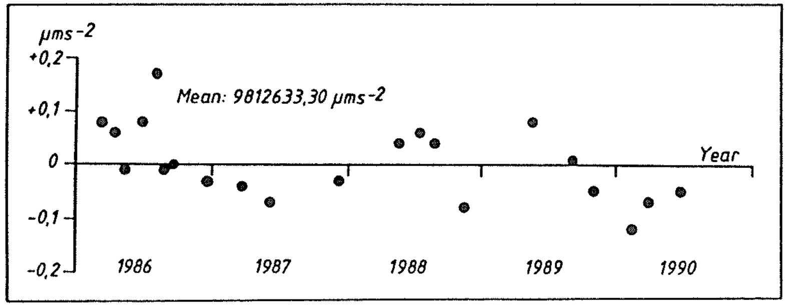

Fig. 5.2 Scatter with time at Hannover

The simple mean of all absolute gravity values determined at Potsdam by free fall instruments is 9812616.81 μms^{-2}. A check of this value is possible by transferring the mean value of station Hannover 101 with the relative tie of 1990:

$$g_{PS141} = g_{H101} + \Delta g_{(H101-PS141)} = 9812633.30 - 16.51 = 9812616.79\ \mu ms^{-2}.$$

The discrepancy is only 0.02 μms^{-2}. The simple mean value of the five determinations with the GABL-gravimeter is 9812616.88 μms^{-2} (0.07 μms^{-2} above the total mean), while the mean value obtained with JILAG-3 is 9812616.66 μms^{-2} (0.15 μms^{-2} below the total mean).
In order to check the reliability of the JILAG-3 measurements in Potsdam, we compare the gravity difference Hannover–Potsdam obtained with JILAG-3 at nearly the same epoch and the result of relative observations using four LaCoste-Romberg gravimeters in 1990 (chapter 3.2). For $g_{H101} - g_{PS141}$ we have:

JILAG-3	1988	$-16.56\ \mu ms^{-2}$,
JILAG-3	1990	$-16.58\ \mu ms^{-2}$,
LCR	1990	$-16.51\ \mu ms^{-2}$.

The small discrepancies are well within the estimated error of the individual determinations and show that any time variations between 1988 and 1990 should be below 0.05 μms^{-2}.

For the 1964 relative tie Bad Harzburg–Potsdam (chapter 4.2), and the JILAG-3 difference (chapter 3.2) we have:

JILAG-3 (1986/90):	$+961.60\ \mu ms^{-2}$,
Askania grav. (1964):	$+961.38\ \mu ms^{-2}$.

Again the discrepancy is well within the error estimates.

6. Conclusions

We draw the following conclusions:

- The JILAG-3 observations performed 1988 and 1990 in Potsdam agree well within the estimated accuracies of $\pm 0.10 \mu ms^{-2}$. The relative ties to the JILAG-3 stations in Hannover and Bad Harzburg confirm this statement, indicating a relative accuracy Hannover–Potsdam of better than 0.05 μms^{-2}.
- The JILAG-3 results in Potsdam deviate significantly ($> 2\ \sigma$-level) from the GABL-results, which between 1976 and 1986 show a remarkable variation.
- Further investigations of the instruments, and future measurements at Potsdam, Hannover, and other stations should be carried out to find out the reason (instrumental, local or regional variations with time) for this phenomenon. An attempt to interprete the time variation as a periodic signal has been made by ARNAUTOV et al. (1990).
- The JILAG-3 results do not show any significant gravity variation with time, neither for Potsdam between 1988 and 1990, nor for Hannover between 1986 and 1990.
- The absolute gravity baseline Hannover–Potsdam can be used as a reference for future geodynamic investigations by gravimetric methods, in the German coastal regions.

Acknowledgements

The 1988 measurements were performed by *Dr.-Ing. habil. H.-G. Wenzel* and *Dipl.-Ing. M. Schnüll. Cand. geod. S. Sander* and *Dipl.-Ing. M. Schnüll* participated in the 1990 campaign in addition to the IfE authors. The project was partly supported by *Deutsche Forschungsgemeinschaft*. For their continuous efforts and the absolute gravity measurements at Potsdam the ZIPE author is deeply indebted to *Prof. Ju. D. Boulanger*, Moscow, and his coworkers. The valuable support given by *Dr. H.-J. Dittfeld* during the JILAG-3 measurements at Potsdam and the help of *Ing. W. Altmann* in the relative measurements is gratefully acknowledged.

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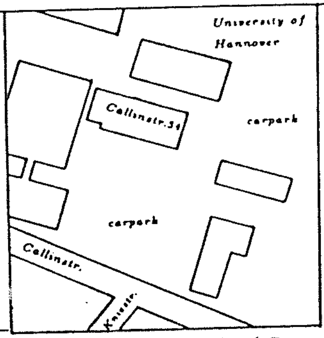
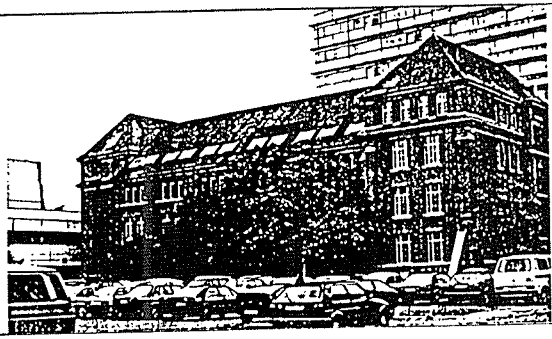
Appendix 1

Absolute Gravity Station

Station Location: Hannover	Country: Federal Republic of Germany		
$\varphi =$ 52.390°N	$\lambda =$ 9.714° E	H = 53.5 m	g = 9.812 633 30 ms^{-2}

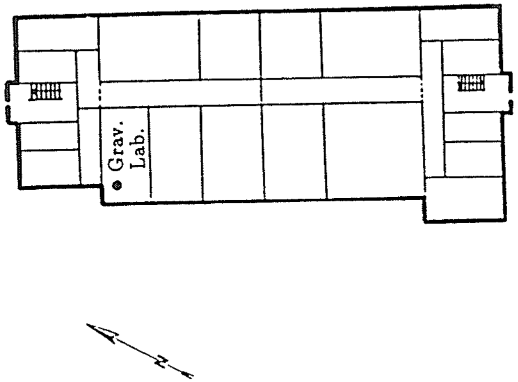


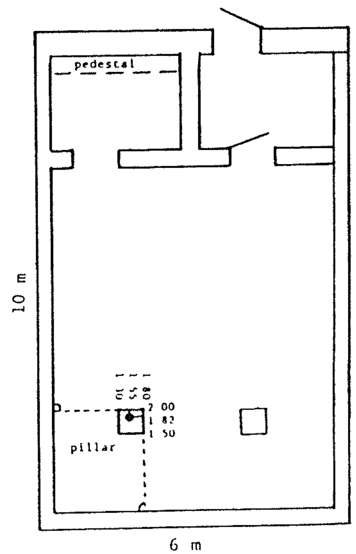


Remarks / Station Identity / Contact

The station is in the northern part of Hannover and belongs to the Institut für Erdmessung, University of Hannover. Observations are made in the basement of a four storey building on a concrete pillar.
The address is: Callinstr. 34, 3000 Hannover 1, FRG

Detailed Sketch (North? Station Marker?) / Photograph



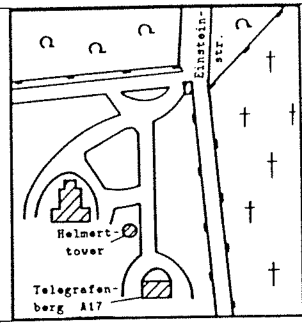


Date / Author September 1990, L. Timmen

Appendix 2

Absolute Gravity Station

Station Location: Potsdam	Country: Federal Republic of Germany		
$\varphi =$ 52.381° N	$\lambda =$ 13.068° E	H = 80.82 m	g = 9.812617 ms^{-2}

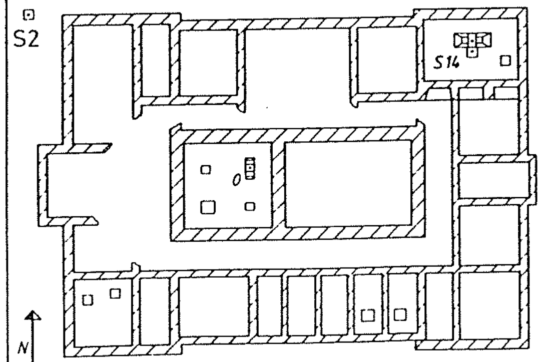


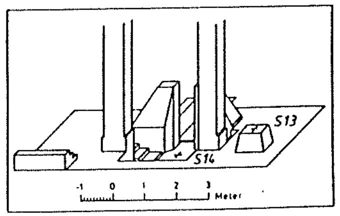
Remarks / Station Identity / Contact

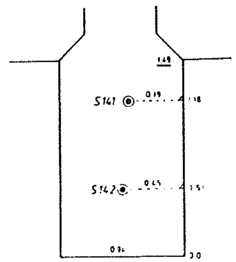
The station is in the north-east basement of building Telegrafenberg A17. Observations with JILAG-3 were performed at S142 and have been transfered to S141.

Contact: Dr. Claus Elstner
Zentralinstitut für Physik der Erde
Telegrafenberg A17
1561 Potsdam

Detailed Sketch (North? Station Marker?) / Photograph







Date / Author October 1990 / R.H. Röder, Cl. Elstner

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Gravimetric Works on the Soviet Lomonosov Site

L. Vitushkin

On the Lomonosov site of the D. I. Mendeleyev Research Institute of Metrology an underground observatory in the tunnel positioned horizontally (H = 45 m, 1 = 150 m) has been constructed giving rise to a number of metrological laboratories and a base station of the international absolute gravity system. Up to now, two supports have been erected and bench marks for the precision relevelling microcircuit made along with the length of the tunnel and at the corners of the gravimetric supports. Initial levelling for the supports was carried out by the Estonian hydrogeological party. Relative connections between the supports and with the ground gravimetric network were performed at the Institute of Geophysics (the USSR Academy of Sciences) by means of the Type "SODIN" and GAG-3 gravimeters (R.B. Rukavishnikov, M.B. Shteiman, T.E. Demyanova) concurrently with the vertical gradient measurements (R.B. Rukavishnikov, M.B. Shteiman).

The age-old ground gravimetric network of satellite stations comprises two lines passing through Lomonosov - Shepelevo's doubler of the Kronstadt foot gauge and Lomonosov - Kronstadt. Reference observations with the help of the Type GAG-3 gravimeters were done by the Institute of Geophysics (T.E. Demyanova). A gravimetric communication of Lomonosov - Pulkovo (the USSR Academy of Sciences Astronomical Observatory) is contemplated. The gravimetric stations in Lomonosov, Kronstadt and Shepelevo are made coincident with deep drill hole bench mark stations (Yu.D. Boulanger, B.I. Bogdanov, L.A. Savitsky, S.D. Yashchuk). The ground network of gravimetric stations is made coincident with the primary levelling line passing through Kronstadt - Gorskaya - Leningrad - Pulkovo - Lomonosov - Shepelevo. The first relevelling is presently under way (Production Association "North-Western Aerogeodesy" of the CSGC of the USSR). The Lomonosov drill hole bench mark station comprises four bench marks made in the crystal substructure (230.7 m) and in the sedimentary rock (31.5, 120.9 and 182.8 m deep). A hydrological hole for observation is functioning in the area of Martyshkino. In addition to the stations mentioned above, the D.I. Mendeleyev Research Institute of Metrology has a gravimetric station in Leningrad conducting measurements of absolute (the Type GABL gravimeter) and relative gravity.

Using the underground observatory as the base, future plans provide for the development of an absolute gravimeter, an absolute gradiometer and a long-base strain recorder as well as for seismic survey and studies on variations in physical fields. Observations of the gravity tidal variations are also contemplated.

Up to now, an adequate basis has been created for precision studies in physics and metrology. Comprehensive studies conducted in weakly seismic areas can be of particular interest in complex with the investigations made in active seismic areas to solve a number of problems of Earthquake prediction. The underground observatory works are coordinated within the scope of comprehensive studies made at the Leningrad geodynamic circuit.

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Dissimilarity of the Gravity Field on and above Postaments.

As known value of the vertical gradient of the gravity is theoreticaly 308.6 mkGal/m, while horizontal along the meridian is approximately equal 0.1 mkGal/m and along the parallel is about 0.

However it isn't suffisbent to know only normal values of gravity gradients if one deals with solution of the «chamber gravimetry» problems.

Theoretical calculations taking into account sizes and shape of the postament for gravity measurements indicate that the real gravity field essentially differs from the normal one. It is especially important in absolute gravity determinations and in measurements of small gravity differences (1 — 3 mkGal) done by high-precision relative gravity meters. It's quite possible to solve su[illegible] [illegible]blems now [1, 3, 4, 5].

[illegible] determination of the real gravity distribution on and above postaments in the Ljodovo laboratory measurements of horizo[illegible] and vertical small gravity differences have been carried out using high-precision quartz astatic gravity meters W.Sodin (models 420 P and 410 G). The estimated r.m.s. error of the mean value of the single difference is 0.6 — 1.0 mkGal.

Then vertical and horizontal gradients were calculated for two postaments (A and B) setted in the same room about 3 m apart from each other. The postament A of 7.0 x 1.0 m is on the floor level, the postament B of 1.5 x 1.0 m is 1 m high above the floor level.

Vertical gradients were obtained for the central point of each postament by measuring small gravity differences on several heights up to 100 — 140 cm with intervals of 20 cm. On the sureface of the postament A the vertical gradient in the center is 285 mkGal/m but increases with height. On heihgt of 120 cm it becomes 315 mkGal/m (with r.m.s. error of 0.6 mkGal). Its mean value as measured on the postament B is 340 mkGal/m and doesn't depend upon the height in range of r.m.s. error of 1.0 mkGal (fig.1) [2, 3]. When analogous measurements were made in Tbilisi the value of the vertical gradient notably decreases with height.

Hence every measured point has its own value the vertical gradient and its dissimilarity with height.

The vertical gradients on the postament B were determined in its geometrical centre as well as in 8 points evenly arranged all over the sureface of the postament (fig.3) [2, 3]. Equivalent accurate measurements were repeated on 4 levels above the postament each 20 cm higher. As a result of forty times repeated measurements we have constructed the spatial picture of the gravity distribution above the postament B.

The horizontal anomalies on the surface of the postament B are negative compared with the central point and its values are: -12, -15 and even -17 mkGal (fig.3). Hence the horizontal gradient averages 30 — 35 mkGal/m (!) [3].

On the surface of the postament A small gravity differences measurements tied the centre with 15 points were made. The distribution of gravity on the postament A substantially differs from this one on the postament B and is far from results of theoretical calculations, though all 15 anomalies are also negative in regard to the centre.

It's absolutely obvious that the distribution of the gravity is influenced by not only the shape and mass of the postament, but of the room configuration and of the masses arrangement around.

The next example is the second comparison of absolute gravity meters being carried out in 1985 in the Sevre. Gravity meters were arranged on 7 postaments, having been placed in different points of building:some of them in the room on the ground floor, others on the basement. It was highly important to perform the right reducing of all comparing measurements to one on the postament A. For this reason were carried out measurements with relative gravity meters. Morover, r.m.s. error of the single gravity difference as well as single absolute measurement was less then 1 mkGal.

Although working heights of absolute gravity meters ranged from 830 to 1120 mm, it was taken one mean value of vertical gradient for one mean height 215 mm. As well it was ignored the factor that vertical gradients on various points of the gravity net essentially differ from each other and from caculated mean value. Vertical gradients on postaments setted in the room on ground floor (A, A3) equal 325 and 310 mkGal/m, while its values on postaments A4, A5, A6 and A7 were arranged on the basement varies from 255 to 273 mkGal/m. It was quite natural, that results received with disregarding pointed obove factors differ from each other from 10 - 15 to 40 mkGal. We calculated vertical gradients for working heights of each gravity instrument, took into consideration its arrangement on the surface of the postament and after reducing of all measurements to one point A we obtained results disperse no more then 6 mkGal. Consequently it's urgent to study carefully the unevenness of the gravity distribution on and obove every posyament befor carrying out high accuracy measurements.

All discribed obove becomes especially important when ties measurements are conducting by large group of gravity instruments of different models as it periodically taking place in Sevre.

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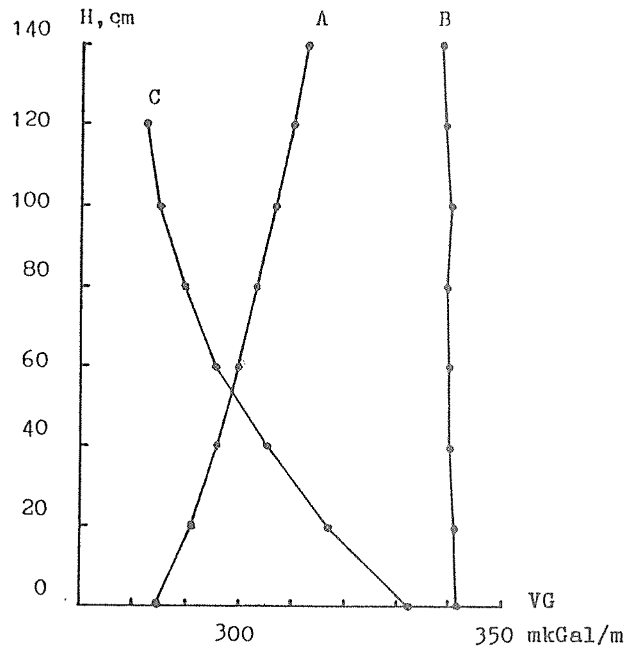

Fig.1 . Vertikal gradient's values on different heights from postament sureface: A- point Liodovo, postament A; B- point Liodovo, postament B; C- point Tbilisi. H- height,cm; VG - vertical gradient in mkGal/m

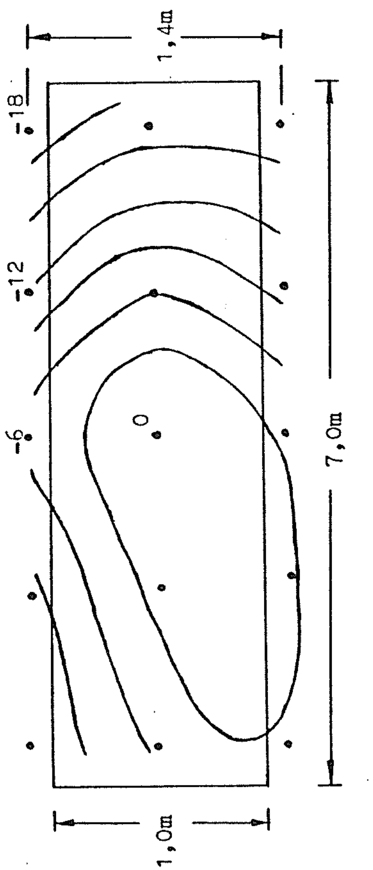

Fig.2 Values of the horizontal gradient near the sureface of postament A,point Liodovo.

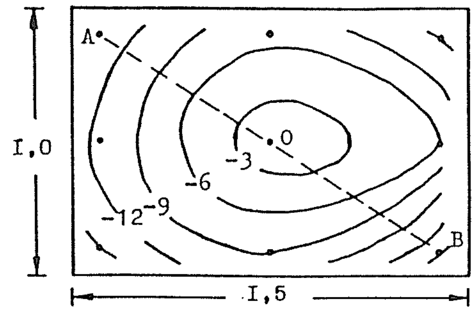

Fig.3 Values of the horizontal gradient near the sureface of postament B,point Liodovo.

On the Calibration table of La Coste-Romberg gravimeters.

G. Strang van Hees
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To convert gravimeter readings into milligal values one has to interpolate in the calibration table provided with the La Coste- Romberg gravitymeter. This is a source of making errors, and can difficult be incorporated in a computer program. The following method is much easier and gives less chance of making errors. The idea is to work with a fixed calibration factor and to give a small correction to the reading of the gravimeter.

Suppose:

- r = reading of the gravimeter.
- v = milligal value corresponding to r.
- f = calibration factor corresponding to r.
- r_o = fixed reading value.
- v_o = milligal value corresponding to r_o.
- f_o = fixed calibration factor.
- c = correction to r.

Corresponding values of r_i and v_i are taken from the table. c_i can be computed with the following formula.

$$v_i - v_o = f_o(r_i + c_i) - f_o(r_o + c_o) \qquad (1)$$

r_o and f_o are chosen, in principle arbitrary, however the corrections c_i become small if r_o and f_o are chosen as mean values of the survey area.
c_o can also be chosen freely and is set to zero. So c_i becomes:

$$\boxed{c_i = \frac{(v_i - v_o)}{f_o} - (r_i - r_o)} \qquad (2)$$

For round values of r_i, c_i can be computed. For other values of r_i, c_i can be interpolated. As c_i is a very small value the interpolation is very easy. Gravity differences can now be computed with:

$$g_i - g_k = v_i - v_k = f_o((r_i + c_i) - (r_k + c_k)) \qquad (3)$$

This means that the readings should be corrected with c_i and in the adjustment program one can work with a fixed calibration factor f_o.

The corrections c_i can also be computed from the interpolation factors f_i which are also tabulated. This is even preferable above (2), because the values v_i in the table are rounded to 0.01 milligal. To get c_i in microgal, v_i should also be in microgal.

From the table follows:

$$v_{i+1} - v_i = f_i(r_{i+1} - r_i).$$

Summation over several intervals with Δr = 100 gravimeter units:

$$v_i - v_j = \Delta r \,.\, \sum_{k=j}^{i-1} f_k \,, \qquad \text{if } r_i > r_j \qquad (4)$$

over n intervals is:

$$r_i - r_j = n.\ \Delta r = \frac{\Delta r}{f_o} \sum_{1}^{n} f_o \qquad (5)$$

Inserting (4) and (5) into (2) gives:

$$c_i = \frac{\Delta r}{f_o} \,.\, \sum_{k=o}^{i-1} (f_k - f_o) \,, \qquad \text{if } r_i > r_o \qquad (6)$$

The correction values for $r_i < r_o$ are obtained in a similar way:

$$c_i = -\frac{\Delta r}{f_o} \sum_{k=i}^{-1} (f_k - f_o) \,, \qquad \text{if } r_i < r_o \qquad (7)$$

As the calibration factors f_k are tabulated corresponding to a microgal precision, formulas (6) and (7) are more accurate then (2).

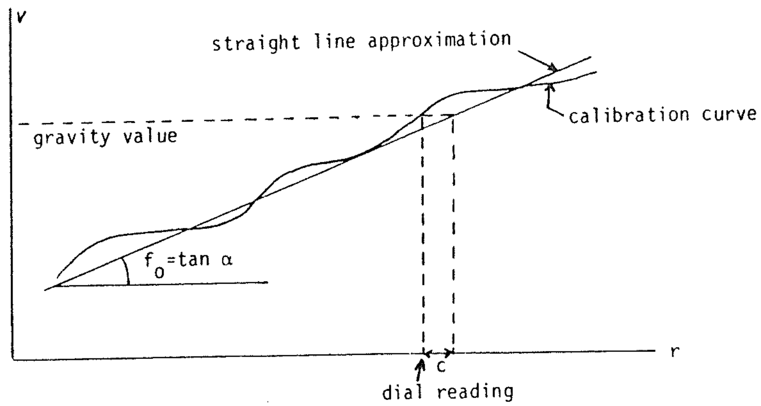
Example

$r_o = 4600$ $f_o = 1.02121$

r	v	f	c microgal
3800	3847.46	1.02134	-104
3900	3976.59	1.02135	- 91
4000	4078.73	1.02136	- 77
4100	4180.86	1.02136	- 63
4200	4283.00	1.02136	- 48
4300	4385.13	1.02136	- 34
4400	4487.27	1.02133	- 19
4500	4589.40	1.02128	- 7
4600	4691.53	1.02121	0
4700	4793.65	1.02112	0
4800	4895.76	1.02102	- 9
4900	4997.87	1.02090	- 27
5000	5099.96	1.02076	- 58
5100	5202.03	1.02061	-102

If the survey area is not very large, the correction c can also be approximated by a third degree polynomial. This function can be used in a computer program for automatic correction.

Graphical illustration



Horizontal: dial reading.

Vertical : gravity value in mgal.

The calibration curve is approximated by a straight line, which can be chosen as the tangent to the calibration curve in the survey area.

The correction c is the horizontal distance between the calibration curve and the straight line.

If c is added to the dial reading, the straight line can be used as calibration curve. This means that one can use a fixed calibration factor, being the slope of the straight line.

Part III

CONTRIBUTING PAPERS

Absolute Gravity Observation Documentation Standards
(1991)

G. Boedecker, Chairman BGI-WG2 'World Gravity Standards'

1. Introduction

Working Group 2 (WG2) 'World Gravity Standards' of the International Gravity Commission (IGC) has published - after site selection criteria for stations of the International Absolute Gravity Basestation Network (IAGBN) - at last "Absolute Observations Data Processing Standards & Station Documentation" in the Bulletin d'Information (no. 63 as of December 1988) of the Bureau Gravimetrique International (BGI). In continuation of this standardization, in the sequel some guidelines for absolute observations documentation are published as working stardards to be applied for observations in the IAGBN. These are recommended for use in all absolute observations employing modern free-rise-and-fall or free-fall instruments.

2. Basic Considerations

There has been an increasing number of absolute observations in the past few years and it appears necessary to make sure also by adequate observations documentation, e.g. for the BGI data holdings, that optimum use can be made of these observations also for later re-analysis and for correlation with any other type of relevant data.

- Absolute observations to be published should be made **homogeneous** in form and **comparable**.

- Data **exchange** should be facilitated.

- The procedures leading from the very original observations to the published g-value should be made more **transparent** and should be published more **completely**.

- If in future new standards are introduced, it should be possible to **re-evaluate** the original processing at least in the more significant parts.

- The reading of an absolute gravity meter may depend on - besides the gravity acting - also on the **current state of the instrument** including the physical construction, adjustment, calibration and software, the **current state of the environment** as air pressure etc. and the **current state of the station**. Therefore the most significant parameters of these have to be referenced or recorded along with the gravity value observed.

- As gravity at a location may change, also the instrument, the environment and the station may change with time. Therefore the **history** of these has to be recorded as far as it may be relevant for the observations.

3. The Data

Starting from the above considerations, each absolute gravity observation report prepared as the result of the work of one party at one station at one epoch (usually taking a few days) should consist of two parts:

- a header section that contains all the data that may change from year to year but remain unchanged during the days when an observation tåkes place.
- An observation section containing the observations.

3.1 Header Section

3.1.1 Station Subsection

- Country
- Station name: Number and/or name of town or habitat
- Identity: Number or name for identical station used by others
- Description: Reference to station documentation or description included on present state; photograph and sketch are helpful
- History: Reference to relevant information on earlier states of the station
- Coordinates: Latitude and longitude to 0.0001 deg., altitude to 0.001 m inc. height reference
- Gravity: The current final g-value observed for the station to $1*10^{-9}$ ms^{-2} for A (0.80 m height above ground marker), B (definition height of the instrument) and C (ground marker).
- Vertical gravity gradient: Reference to publication or own observed value
- Eccentricities: Gravity differences to eccentres
- General remarks

Comments:

. Identity: Two stations can only be regarded as identical if they coincide to the millimetre

. History: As one could learn from the fate of many IGSN71 stations which made necessary various revisions and updates, it is important to keep track of the changes of the station, e.g. construction modifications in the near vicinity, changes of the floor covering, changes of seismic noise etc.

. Vertical gravity gradient: Reference to publication or details of the determination such as type of instruments etc.

. Eccentricities: If the/an instrument could not observe in the plumbline through the station marker, details should be given as to the relative gravity ties etc.

3.1.2 Instrument Subsection

- Type/status
- Reference to publication or details on type of frequency standard, type of light source, absorbtion line/wave length, material/weight of falling object, drift rates

Comments:

. Type/status: As e.g. in the case of software and also as is done in a similar way when a relative gravity meter is modified, one has to define different states in the ongoing development and modifications of an absolute meter, by a suffix to the name, e.g. JILAG-6.4 or JILAG 6.1988. The details for an instrument so defined should either be given by referencing another publication or in the observation report itself.

3.1.3 Environment Subsection

- General situation: Remarks on humidity, groundwater, power supply, floor-gravimeter response etc.

3.2 Observation Section

3.2.1 Reference Subsection

- Reference to the standards used for the corrections applied, models applied, such as earth tide model, oceanic tides model

3.2.2 Observation Subsection

For each drop (minimum data set):

- Time: Year, month, day, H:min:sec (UTC)
- Original observation to 1 * 10^{-9} ms^{-2} (also for corrections)
- Height of definition point above marker
- Correction for light travel time
- Correction for earth tides
- Correction for oceanic tides
- Correction for earth rotation changes (polar motion with x_P, y_P)
- Correction for atmospheric masses
- Other corrections, to be explained in reference subsection
- For whole data set: Histogramm with 1 * 10^{-7} ms^{-2} slots

The Use of Optimal Estimation for Gross-error Detection in Databases of Spatially Correlated Data.

by

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Abstract: When establishing and updating a data base it is necessary to identify - and possibly correct - gross errors. For large numerical data bases, semi-automatic methods, which identify suspected gross errors, are used, followed by a more detailed analysis of the individual values.

For data, which are associated with a spatial position (location), it is very often so that data are spatially correlated. The distance plays the role time does in time series, while the directional dependence often is small or may be disregarded.

This may be used to detect gross errors, using tools developed for optimal estimation in stohastic processes. A new item to be loaded into the data base is first predicted from the data associated with the e.g. the 10 closest points stored in the data base. Here methods like optimal linear prediction (sometimes denoted least squares collocation or Kriging) makes it possible also to estimate the error of prediction. A comparison of the difference between the observed and the predicted value with the error estimate, may then be used to identify a possible gross error.

The success of this procedure depends on whether the statistical properties are homogeneous for the geographical area being considered. If this is not the case, the data must be preprocessed, removing trends and the physical factors causing the inhomogeneity. This has been used for the detection of gross errors in gravity field related data, which in the paper is used as an example to illustrate the method.

Presented CODATA (12th Int. Conf., Columbus, July 1990).

1. Introduction

When establishing a (scientific) data base it is important to eliminate or at least flag gross errors. The size of many modern data bases now makes it virtually impossible to check and correct a suspected error. A remeasurement of quantities obtained e.g. by a satellite 10 years ago will in most cases be impossible due to the costs involved.

Data bases seems to obey the same law as computer programs: there is always an error left. Unfortunately, many data sets, in the Earth sciences at least, seems to contain up to 1 % erroneous data, see e.g. Tscherning (1990), Remmer (1984). Despite these errors, excellent scientific results are generally obtained because one single data entity is not used alone, but together with other entities. A simple example is from surveying, where one always will try to observe all three angles in a triangle, even if two are sufficient when determining the shape of the triangle. The data bases will therefore contain redundent data, even if this generally is one of the characteristics used to describe a file system which is not a data base. An important requirement for data bases in many fields of earth sciences is therefore that the data contained are redundant. This is then used when applying least-squares procedures for the determination of associated parameters like the positions of the vertices of a triangle. Even if data are not as clearly redundant as in the case of the triangle, data may be strongly correlated, simply because they are associated with points spatially close to each other. The gravity in two points a few meters apart will be only slightly different, because the attracting masses, as seen from the points, will be nearly identical.

This spatial correlation may be used to detect gross-errors, in the same manner as it is done for time series. If a value differs more than usual from its neighbouring values, it may be a gross-error.

For time series, the similarity of two values $x(t_1)$, $x(t_2)$ is expressed through the auto-covariance function, $C(t)$, which for stationary time series is a function of time difference (t_1-t_2) only. For spatially distributed data, the correlation may be expressed through a covariance function generally only dependent on the distance and the altitude of two points. We will explain this in section 2.

When a covariance function is given, we may qualitatively express what we mean by stating that a value differ more than usual from other values. This is expressed by a comparison of the observed value with the value obtained by optimal prediction (interpolating or extrapolation) from the neighbouring values. In section 3 we give the necessary algorithms.

The method is routinely used to detect gross errors in data bases containing gravity field related data, and in section 4 two examples illustrate this.

2. Covariance function for spatially distributed data

We will in the following discuss spatially distributed data. These data may also vary as a function of time, but we will here keep the time fixed.

For such data the (horizontal) distance plays (or as we shall see may be forced to play) the role time difference does for a time series. The directional (azimuthal) dependence is often small or may be removed, but (as with gravity data) the altitude does play a role, which should not be disregarded.

For a time series, we generally have many repetitions of the same phenomena. This has been used to justify the description of the signal as a stohastic process or random function. For repeated occurrences the covariance may be computed in the usual manner as the mean value of products of observations, observed at the same time by two observers. If only one observer is "active", the products are formed for observations, observed with a constant time difference. The time series is supposed to be stationary.

For spatially distributed data, especially data observed on or outside the surface of the Earth, we have no possibility to have repeated occurrences. We only have one Earth! But as with time-series, repetitions may be introduced artificially. The Earth(or a planet) rotated around its center, is regarded as a new Earth. (It may be enough to rotate around a certain axis, but we will not discuss this here). Data located in the same altitude may therefore be used when estimating the covariance, as a function of the (spherical) distance between pairs of points where observations have taken place.

The estimation of the covariance C, as a function of distance d, is in practice simply done by grouping pairs of data in classes according to distance intervals, and then forming the mean of the products of the pairs,

$$C(d_k) = \left(\sum_{i=1}^{n} x(P_i)\, x(Q_i)\right)/n. \qquad (1)$$

Here P_i and Q_i are points with distance d_i,

$$d_k - \tfrac{1}{2}v \le d_i < d_k + \tfrac{1}{2}v,$$

where v is the magnitude of the interval within which the products are sampled, and d_k the k'th interval midpoints. We have in eq (1) supposed that the mean value has been subtracted.

An example of a gravity autocovariance function is given in Figure 1, computed using data in a local areas (Ohio). Note that the function has both positive and negative values.

The applied procedure is statistically correct, if we may regard the physical phenomena as an isotropic random function (see e.g. Sanso (1986)). But even if it is not correct, we are able to evaluate numerically eq. (1) and obtain a sample of values $C(d_k)$, k = 1, ... m. If data are distributed globally, the covariance function may be expressed as the sum of a Legendre series,

$$C(d) = \sum_{i=1}^{\infty} \sigma_i \, P_i(\cos d) \qquad (2)$$

where d is the distance in radians, P_i are the Legendre-polynomials and σ_i are positive constants called degree-variances. The σ_i express the variation per spherical harmonic degree of the observed quantity. These quantities will not be known, but their values may be expressed as simple functions of the degree. For gravity values simple exponential "rules" have been found, see e.g.Kaula (1959), Rapp (1990). Some of these rules makes it possible to express C(d) by a closed formula. If data are given only in a limited area, a Fourier analysis may be used to obtain the coefficients of the Fourier series. The square of the coefficients (the power-spectrum) are then the coefficients in the planar auto-covariance function similar to eq. (2).

3. Gross-error detection for spatially distributed data

Simple statistical tools, such as the formation of a histogram, are extremely useful when trying to detect gross-errors. Here it may be useful to first low-pass filter the data (trend removal), and then inspect the histogram of the filtered data. For globally distributed data, a spherical harmonic analysis, will produce a function representing the global trend. For regional or local data, the first coefficients in a Fourier expansion or a low degree polynomial in plane coordinates (x, y) will represent the trend.

The filtered data may then be contoured, and gross-errors may then show up as "chimneys" or volcanos on a contour map, see Fig. 2. However, a contour map may show several chimneys, and it may be very difficult to judge which are important, and which are "normal".

Here the method of optimal linear prediction (Krigning, least-squares collocation) has been used with success, as will be described in the next section. The idea is to interpolate or extrapolate (predict) an observed value from neighbouring values, and then compare the predicted and the observed value. If the difference is larger than for example 3 times the error of the prediction, then the observative is flagged as a suspected gross-error.

Let us denote the observation to be analyzed by y, and the surrounding observations by x_i, i = 1, ..., n. Then linear prediction determines an estimate $\tilde{y}$ by

$$\tilde{y} = \sum_{i=1}^{n} a_i \ x_i , \qquad (3)$$

where a_i are unknown constants. We may decide to determine $\tilde{y}$ so the mean square error is as small as possible, where the mean is take over all point configurations, which may be created on a sphere by rotations of the observations points Q, P_i, i = 1,..., n associated with y_{obs}, x_i, i = 1, ..., n, respectively. Then it is easily shown (Moritz, 1980) that

$$\{a_i\} = \{C_{Qi}\}^T \ \{\bar{C}_{ij}\}^{-1}$$
$$\bar{C}_{ij} = C_{ij} + D_{ij} \qquad (4)$$

where C_{Qi} is the covariance between y and x_i, C_{ij} is the covariance of the observations and D_{ij} the covariance of the observation error associated with x_i and x_j. The mean square error of $\tilde{y}$ will be

$$\sigma^2(y-\tilde{y}) = C_o - \{C_{Qi}\}^T \ \bar{C}^{-1} \ \{C_{Qj}\}, \qquad (5)$$

where C_o is the variance of y. If this quantity and the observation error of $\tilde{y}$, σ_y are both χ^2 - distributed, then

$$\sigma^2(y_{obs}-\tilde{y}) = \sigma_y^2 + \sigma^2(y-\tilde{y}) \qquad (6)$$

If the actual difference

$$|y_{obs}-\tilde{y}| > k \cdot \sigma(y_{obs}-\tilde{y}) \qquad (7)$$

then we may decide to regard y as a possible gross-error.

The success of this procedure depends on the statistical homogenity of the data. A good (and actual example) is the situation where data consist of two subsets each associated with a separate unknown linear parameter: Satellite observations, from two different time periods from the same area, affected by different satellite orbit errors, may form two such sets. The above described linear estimation method may be extended to take account of this. Also data do not need to be of the same type, as long as a cross-covariance function is also known, see Moritz (1980).

Other inhomogenieties may have physical causes, such as varying geology or topography. These physical causes may be taken into account (removed), see Forsberg (1986).

The above described procedure is not without pitfalls. A gross-error may "contaminate" neighbouring values. So an iterative procedure is recommended, where the largest suspected gross-errors are removed, and the prediction is repeated for smaller suspected errors.

4. Gross-error detection in gravity field data

A data base with global gravity coverage is managed by Bureau Gravimetrique International (BGI) in Toulouse, France. Here several million data are stored. Data originate from both scientific and commercial sources, and date 100 years back. Many national institutions also administrate gravity data bases.

Gravity is the modules of the gradient of the gravity potential. The Mean sea-level coinsides with a surface where the potential is constant called the geoid. The height of this surface above a reference ellipsoide, plus height variations due to tides, currents etc. may be observed by measuring the distance from a satellite to the sea surface by a radar altimeter. Such data has been collected by several satellites at a rate of 1 per second, and new satellites will be launched in the comming years (ERS-1, Topex-Poseidon). So, huge gravity field data sets are and will be collected, which are spatially correlated. But the data contain many errors, which must be eliminated or flagged. At BGI, optimal linear prediction is used to mark suspected gross-errors on a CRT (see Fig. 2), which is used to display a contour map of the data. Interactively the suspected errors may be removed, and if smooth contour lines occur after the removal, then the observation is flagged as an error. An experienced analyst can validate 5000-7000 points per day under optimal conditions, (BGI, 1989, p. 110).

The method is also used when analyzing gravity and satellite radar altimeter data, see Tscherning (1990). Here the possibility of also removing biases were used.

The method of least-squares collocation is not restricted to be used with only one datatype. The combined use of altimeter an gravity data improved the power of the method, so that 0.3% further gross errors were detected in addition to the 0.7% error detected using the altimeter data alone.

5. Conclusion

Spatially distributed data are often spatially correlated. A covariance function which primarily is a function of distance may be estimated, by forming mean values of products of data having the same spherical distance. Using optimal linear prediction, the values may be computed from neighbouring values, and compared with the observed value, thereby indicating an error if the difference is larger than a factor k times the prediction error.

The use of the method requires that the observations are "homogenized", by low-pass filterning, and removal of an-isotropies, if possible. It has been used with success for gravity field data, but it should be possible to use the method for many other types of spatial data.

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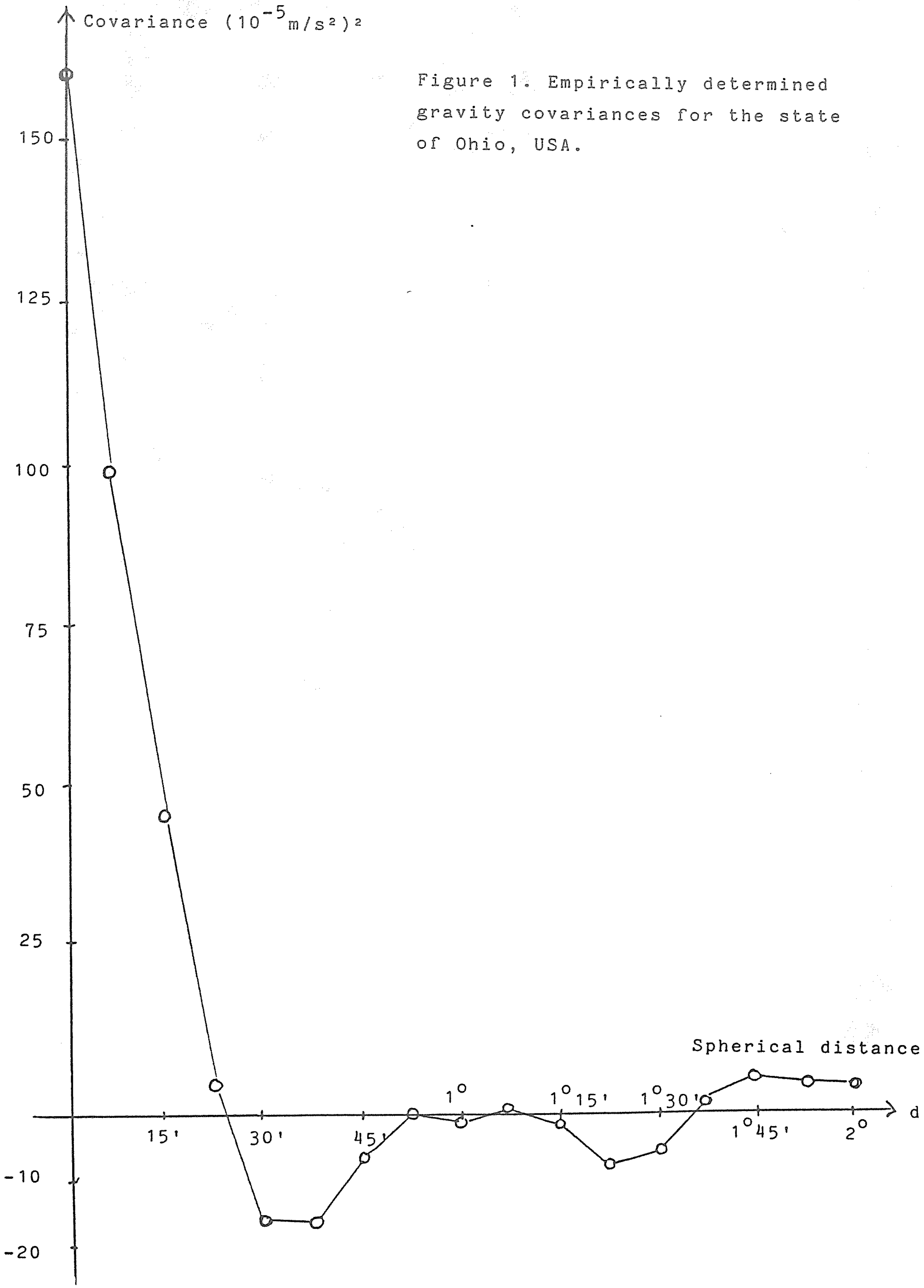

Figure 1. Empirically determined gravity covariances for the state of Ohio, USA.

Figure 2: Gravity map with six measurements predicted as suspected grosserrors using collocation (From BGI, 1989, p. 120).

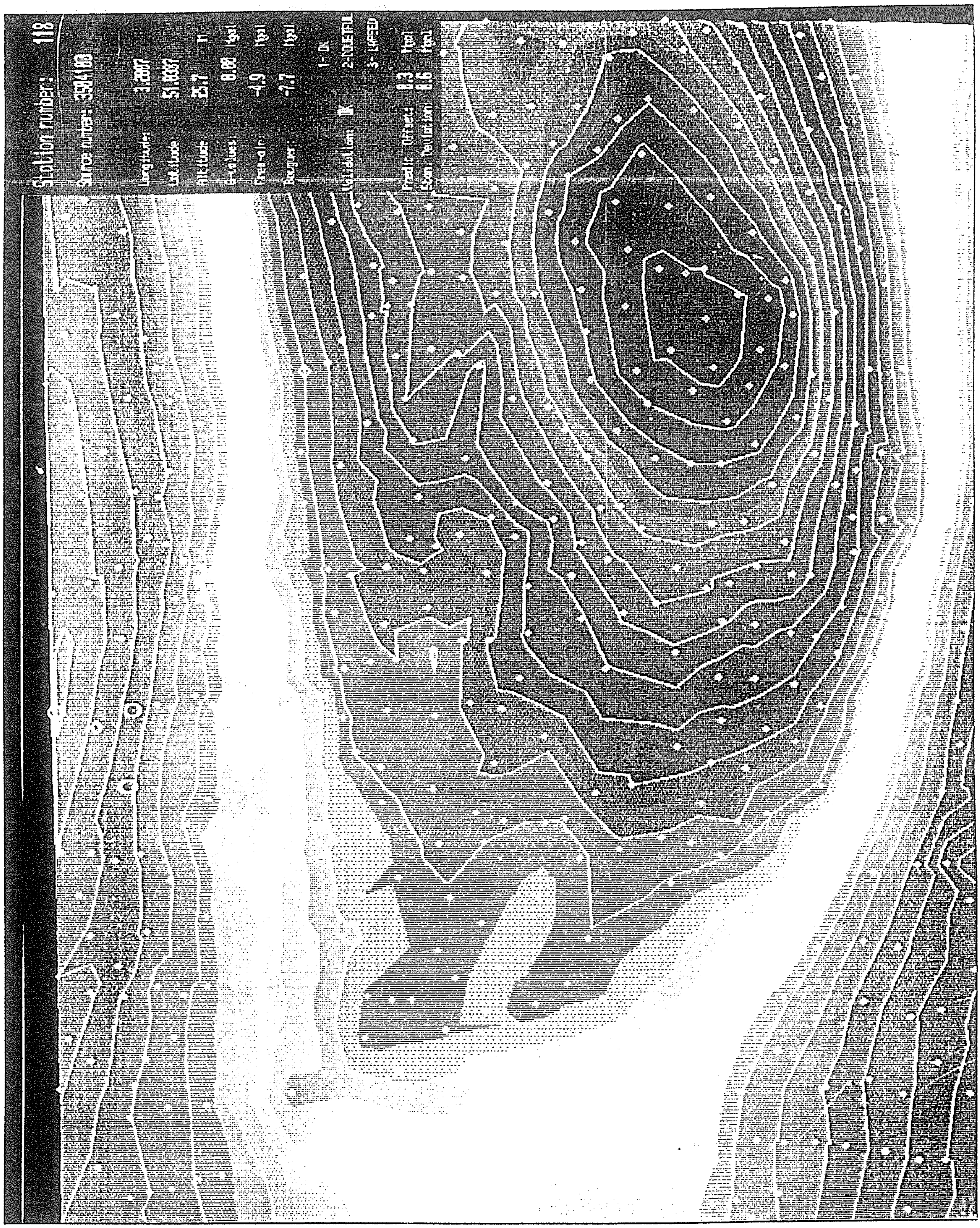

Figure 3: Gravity map, same as Figure 2, but with two largest errors removed (From BGI, 1989, p. 121).

RECENT CRUSTAL MOVEMENTS ON ICELAND AND THE ACCOMPANYING DENSITY CHANGES IN THE INTERIOR

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Abstract

Recent crustal movements give rise to changes of the heights, of the gravity values, and of the gravity potential. The vertical derivative of this changing potential is expressed in terms of the changes of the height and of the gravity. This vertical derivative depends on the density changes which accompany the recent crustal movements. These density changes consist of two parts : The first part is a surface layer of the real density and of a width which is equal to the height changes. Thus, the first part has beforehand given parameters. The second part are the density changes in the interior of the Earth.

Along these lines, it is possible to find a signal function for these density changes in the interior. These density changes can be found in terms of this signal function by the gravity methods of the geophysical prospecting.

1. Introduction

In many test-areas and along many test-lines, the changes of the heights and of the gravity values caused by recent crustal movements are detected by levellings and by gravity measurements. As to the geophysical interpretation of these measurements, it is intended here to develop a comprehensive and satisfactory theory. Till now the height changes are discussed separately. In other cases, the gravity changes are discussed separately accounting for the reduction on account of the height changes (applying the free-air gradient or the free-air gradient supplemented by the effect of the Bouguer plate). Then, the reduced or the non-reduced gravity values are divided through the height changes, and finally the thus obtained quotient is computed. But in the literature, there is no satisfactory quantitative discussion about the value of this quotient which is influenced by the accompanying density changes in the interior of the Earth. The latter question is the subject to be treated here.

2. Theoretical foundations

Along the surface of the Earth σ, the perturbation potential T depends on the free-air gravity anomalies Δg_T by the following expression, Arnold (1986), (1987b) (1989 a,b) :

$$T = \frac{1}{4\pi R} \int\int_V [\, \Delta g_T + C + C_1(M) \,] \, S(\psi) ds + \{\Omega^{*}(M)\} \tag{1}$$

the braces denote that the harmonics of zero and first degree are split off. In (1), we have :

$$\begin{aligned} \Omega^{*}(M) = \; & M\frac{H_P}{R} + \frac{1}{4\pi R}\int\int_V \left[4\pi f \rho_o H_Q \frac{H_Q}{R} - \frac{2BH_Q}{R^2} \right] S(\psi) ds \\ & + \frac{1}{2\pi}\int\int_V \Delta g_M \frac{3Z}{2R}\frac{1}{e_o} ds + \frac{1}{2\pi}\int\int_V \frac{M}{R}\frac{Z}{R}\frac{1}{e_o} ds \\ & - \frac{1}{8\pi R^2}\int\int_V \frac{\partial M}{R\,\partial\psi} Z \left[\frac{\cos\frac{\psi}{2}}{\left(\sin\frac{\psi}{2}\right)^2} + 2\frac{dS(\psi)}{d\psi} \right] ds \end{aligned} \tag{2}$$

V denominates the globe with the radius R. H_p, resp. H_Q, is the height of the test point P, resp. of the moving integration point Q. f is the gravitational constant, ρ_o is the standard density (ρ_o = 2,67 g.cm^{-3}). S (ψ) is the Stokes function, ψ the spherical distance. We have :

$$Z = H_Q - H_P \tag{3}$$

$$e_o = 2R \sin\frac{\Psi}{2} \tag{4}$$

$$M = B - T \tag{5}$$

$$\Delta g_M = -\frac{\partial M}{\partial r} - \frac{2}{r}M \tag{6}$$

B is the potential of the mountain masses (of standard density ρ_o) situated above the surface of the globe V. C is the plane terrain reduction of the gravity ; $C_1(M)$ has the form, ARNOLD (1989 a,b),

$$C_1(M) \cong -Z\frac{1}{2\pi}\int\int_V \frac{(\Delta g^*)_Y - (\Delta g^*)_Q}{(e_\infty)^3} ds \tag{7}$$

Δg^* is the Bouguer anomaly as described by HEISKANEN and MORITZ (1967). The relation (1) is valid as long as the test point P is not situated in high mountains, ARNOLD (1989 a).

By the recent crustal movements happening during the time Φ between the epoch values t_1 and t_2, the T value changes by :

$$D = T_2 - T_1 \tag{8}$$

$$D = \frac{1}{4\pi R}\int\int_V [(\Delta g_T)_2 - (\Delta g_T)_1] S(\psi) ds \tag{9}$$

The other terms in the expression for T, (1), (i.e. : C, $C_1(M)$, $\Omega^*(M)$) do not change by essential values during the time Φ.

The free-air anomaly is obtained from the gravity g at the surface point Q and from the standard gravity γ at the telluroid point perpendicular below Q. Thus, with self-explanatory notations :

$$(\Delta g_T)_1 = (g_1)_\sigma - (\gamma_1)_\tau \tag{10}$$

$$(\Delta g_2)_2 = (g_2)_\sigma - (\gamma_2)_\tau \tag{11}$$

$$(\Delta g_T)_2 = (\Delta g_T)_1 = \delta g - \frac{\partial \gamma}{\partial h}\delta h \tag{12}$$

$$\delta g = g_2 - g_1 = (g_2)_\sigma - (g_1)_\sigma \tag{13}$$

$$\delta h = (h_n)_2 - (h_n)_1 \tag{14}$$

where h_n is the normal height.

The developments from (9) through (14) give :

$$D = \frac{1}{4\pi R}\int\int_V \left[\delta g + \frac{2G}{R}\delta h\right] S(\psi) ds \tag{15}$$

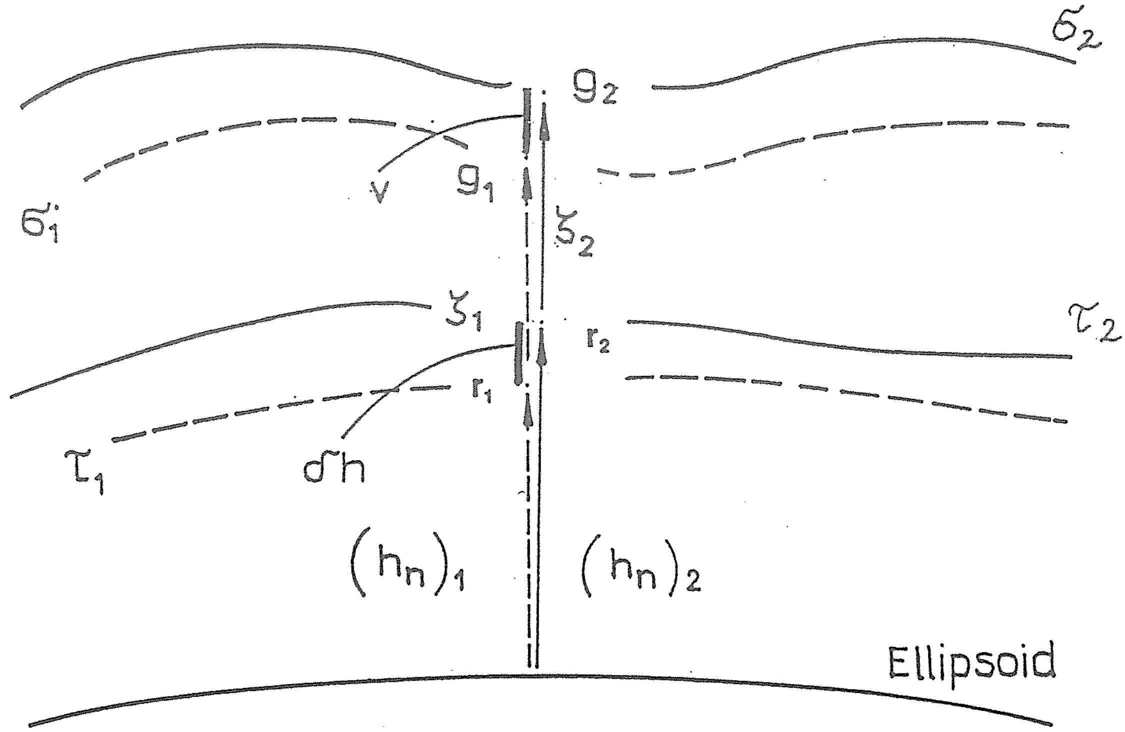

Fig. 1 : The shifts of the telluroid τ and of the Earth's surface σ ; the changes of the normal gravity γ, of the observed gravity g, and of the normal heights h_n. The elapsed time is between epochs t_1 and t_2.

The relation (15) and the fundamental equation of physical geodesy (6) lead to :

$$-\frac{\partial D}{\partial r}-\frac{2}{r}D=\delta g+\frac{2G}{R}\delta h \tag{16}$$

where G is the global mean value of the gravity.

In the mass-free exterior of the body of the Earth, the potential D has the following series development in spatial spherical harmonics :

$$D=\sum_{n=2}^{\infty}\frac{1}{r^{n+1}}\sum_{m=o}^{n}P_{nm}(\phi)\,[d_{1,nm}\cos m\lambda+d_{2,nm}\sin m\lambda] \tag{17}$$

$P_{nm}(\phi)$ are the spherical harmonics, $d_{1,nm}$ and $d_{2,nm}$ are the Stokes constants, and r, ϕ, λ are the spatial polar coordinates.

The series development (17) is uniformly convergent in the exterior of the Earth body, ARNOLD (1978) (1986) (1987 a,b). Abbreviating (17), we can write :

$$D=\sum_{n=2}^{\infty}\frac{1}{r^{n+1}}Y_n(\phi,\lambda) \tag{18}$$

The above series for D contains the generic term :

$$\Gamma=\frac{1}{r^{n+1}}Y_n(\phi,\lambda) \tag{19}$$

Thus, the series for $\frac{\partial D}{\partial r}$ has the following corresponding term :

$$\frac{\partial\Gamma}{\partial r}=-(n+1)\frac{1}{r^{n+2}}Y_n(\phi,\lambda) \tag{20}$$

The individual areas where the recent crustal movements happen will have a horizontal extent of not more than about 1000 km x 1000 km. Consequently, it is allowed to assume the inequality :

$$n>20 \tag{21}$$

Thus, combining (19), (20), (21),

$$|\frac{\partial\Gamma}{\partial r}|\gg|\frac{2}{r}\Gamma| \tag{22}$$

Further, from (18) :

$$\left|\frac{\partial D}{\partial r}\right| \gg \left|\frac{2}{r}D\right| \tag{23}$$

Hence, introducing the downward derivative of D,

$$-\frac{\partial D}{\partial r}=\frac{\partial D}{\partial \nu} \tag{24}$$

$$\frac{\partial D}{\partial \nu}=\delta g+\frac{2G}{R}\delta h \tag{25}$$

δg and δh are quantities given by measurements : by (25), they determine the derivative of D taken vertically downwards.

In view of the further intentions, it is convenient to divide the potential D into 2 parts :

The potential D_b of a surface layer and the potential D_g of the density changes ρ in the interior.

Thus,

$$D=D_b+D_g \tag{26}$$

with :

$$D_b=f\int\int_\sigma \rho\frac{1}{e}\nu d\sigma \tag{27}$$

$$D_g=f\int\int\int_V \delta\rho\frac{1}{e}dV \tag{28}$$

ρ is the real density along the Earth's surface, e is the straight distance, ν is the vertical shift of the Earth's surface (Fig. 1), and V is the volume of the body of the Earth.

The derivation of (27) in the direction of ν leads to (29) using the jump relation for this derivation, KELLOGG (1929) :

$$\frac{\partial D_b}{\partial \nu}=2\pi f\rho\nu+\frac{1}{2R}D_b \tag{29}$$

and with (23) :

$$\frac{\partial D_b}{\partial \nu}\cong 2\pi f\rho\nu\cong 2\pi f\rho\delta h \tag{30}$$

The relations (25), (26) and (30) give :

$$\frac{\partial}{\partial \nu}D_g=\frac{\partial}{\partial \nu}D-\frac{\partial}{\partial \nu}D_b=\delta g+\left(\frac{2G}{R}-2\pi f\rho\right)\delta h \tag{31}$$

Approximating ρ by the standard density $\rho_o = 2.67$ g cm^{-3}, (31) turns to :

$$\frac{\partial}{\partial \nu}D_g=\delta g+0.1967\ \delta h \tag{32}$$

(The gravity in mgal, the heights in meters).

$\frac{\partial}{\partial \nu}D_g$ is a signal function for the density changes in the interior.

3. The Density Changes Along the Main Profile of 100 km Length

The main profile on Iceland crosses the rift zone and has a length of about 100 km. In 1975 and in 1980, along this profile, precise measurements of the heights and of the gravity were carried out. The levellings have a standard deviation of ± 1.5 mm/km. The gravity values are measured within ± 6 µgal by relative gravity meters. Thus, the changes of the heights and of the gravity values are found precisely. The reference point of the levellings lies at an undisturbed coastal place, (a height change by 1 cm reflects in the gravity by 2 µgal). A comprehensive review of these measurements can be found in : Zeitschrift f. Vermessungswesen 114 (1989), Tectonophysics 71 (1981), J. of Geophysics 47 (1980). By (32), the δg values and the δh values measured along this main profile allow to compute the signal function $\frac{\partial}{\partial \nu}D_g$ along this profile, KANNGIESER (1982), TORGE (1989).

Considering the shape of the signal function in Fig. 2, it is obvious that the mean level of these values is lower between 1975 and 1980, by an amount of - 9 μgal ; this number has a standard deviation of about ± 1.3 μgal (the averaging is over 150 values of the signal function).

Thus, the subsidence of the level of the signal function is significant ; it cannot be explained only by a change of the gravity at the reference point.

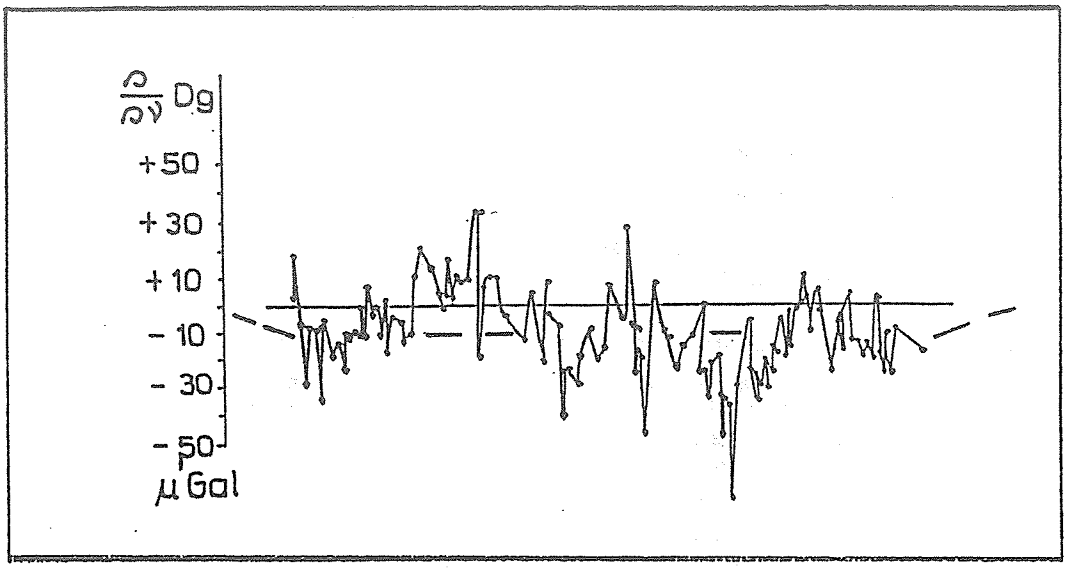

Fig. 2 : The shape of the signal function $\frac{\partial}{\partial v}D_g$ along the 100 km profile.

As to the interpretation of this subsidence, the methods of gravimetrical prospection come now into the fore. The potential D_g can be expressed in terms of mass changes δm in the interior of the Earth :

$$D_g(P_K) = f \sum_{i=1}^{N} \delta m_i \frac{1}{e(P_K, K_i)} \tag{33}$$

e is here the distance between the test point P_k and the place K_i of the point mass δm_i. The following 4 lines are self-explanatory :

$$\frac{\partial}{\partial v} D_g P_K = f \sum_{i=1}^{N} \delta m_i (Z_K - \overline{Z}_i) \frac{1}{e^3(P_K, K_i)} \tag{34}$$

$$p = Aq \tag{35}$$

$$q = A^{-1} p \tag{36}$$

with :$q = \{\delta m_i\}$ and $\rho = \left\{ \left(\frac{\partial}{\partial v} D_g \right)_{P_K} \right\}$ (37)

Z_k is the vertical coordinate of P_K, $\overline{Z}_i$ that of the point K_i.

Returning back to the interpretation of the values of $\frac{\partial}{\partial v}D_g$ shown by Fig. 2, a Bouguer plate of 7 km width takes the place of the δm ; values of (33), (7 km is the width of the lithosphere in Iceland). A lowering of the $\frac{\partial}{\partial v}D_g$ values by an amount of - 9 μgal is equivalent to a decrease of the density of this Bouguer-layer of $\delta\rho = 3.4\ 10^{-5}$ g cm^{-3}.

In this context, the dynamic of the spreading movement of the lithosphere in the area of Iceland is of interest. A diminution of the density of the masses in the lithosphere plate by - 3.4 . 10^{-5} g cm^{-3} can have its cause in a horizontal extension of this plate. This extension has to happen in the direction of the main profile of 100 km length, i.e. the direction perpendicular to the rifts.

There are two opinions about this driving mechanism. They are described by JACOBY et al. (1980) : "What is the driving mechanism of the rifting event ? Is magma squeezed in gravitationally (buoyantly) pushing the sides into compression or is regional tension from plate divergence released in fissures tearing open and making space for the magma ? The regional deformation of the area can be interpreted either way."

Our gravimetric investigations about the signal function $\frac{\partial}{\partial v}D_g$ yield a diminution of the density along the profile. Thus, the evaluation of our signal function is in favour of a long-distance extension of the lithosphere plate. Thus, our signal function is able to discriminate between the different geophysical models.

In this context, it is of interest that the extension of the main profile of 100 km was determined by terrestrial geodetic distance measurements, MOLLER (1989) : "... whole the test area having an east-west range of about 110 km has merely an extension of not more than 2 m...".

This quantity leads to a density change by about $\delta\rho = -2.10^{-5}$ g cm^{-3}. But the values of the density change are in a relative good agreement, (the value obtained gravimetrically by $\frac{\partial}{\partial v}D_g$, and the value obtained by terrestrial geodetic measurements).

In the above investigations about the lowering down of the signal function $\frac{\partial}{\partial v}D_g$ along the 100 km profile, the reference points for the heights and for the gravity had to be stable. The stability of the heights can be controlled within some millimeters by water-gauge observations in a satisfactory way. The stability of the gravity level can be checked by absolute gravity measurements, a precision of about ± 1 μgal is announced to come, being satisfactory in our applications.

4. The Density Changes Within the Test Area of 10 km x 14 km Size

Now, we consider a test area with an extension of 10 km x 14 km. The eastern and the southern part of it covers the hot spots of the Kraflar caldera and of the Namafjall area. In the pronounced uplift phase of 1978, the changes of the heights δh and that of the gravity δg were determined precisely by measurements. The first measurement campaign was in January 1978 and the final one was in June 1978. During this time some seismic events and eruptions occured in this area. These δg and δh values allow to compute the signal function $\frac{\partial}{\partial v}D_g$ by formula (32). Fig. 3 shows the shape of our signal function within the 10 km x 14 km test area, FALK (1988), KANNGIESER (1985).

The signal function of Fig. 3 has a smoothed shape because a smoothing operator was applied. In the areas of the hot spots, the signal function $\frac{\partial}{\partial v}D_g$ has two minima of about - 20 μgal. In the north-western part, the test area has a maximum of about ± 20 μgal. From Fig. 3, two profiles are plotted. Fig. 4 and Fig. 5 show the shape of the signal function along these two profiles.

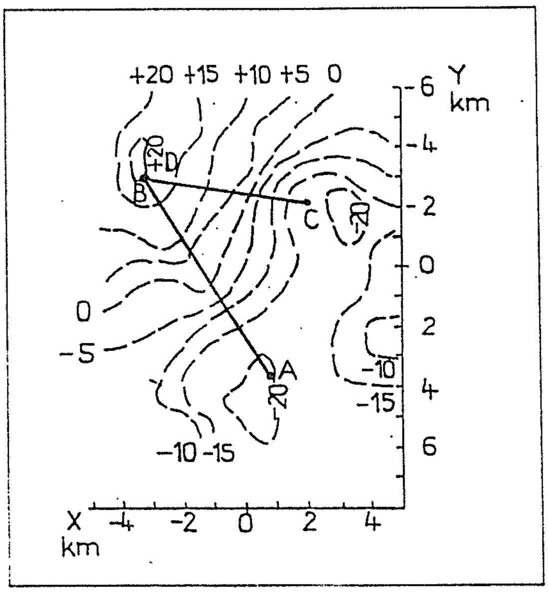

Fig. 3 : The shape of the signal function within the 10 km x 14 km test area.

The shape of the signal function along these two profiles was approximated by straight lines, applying the method of least squares.

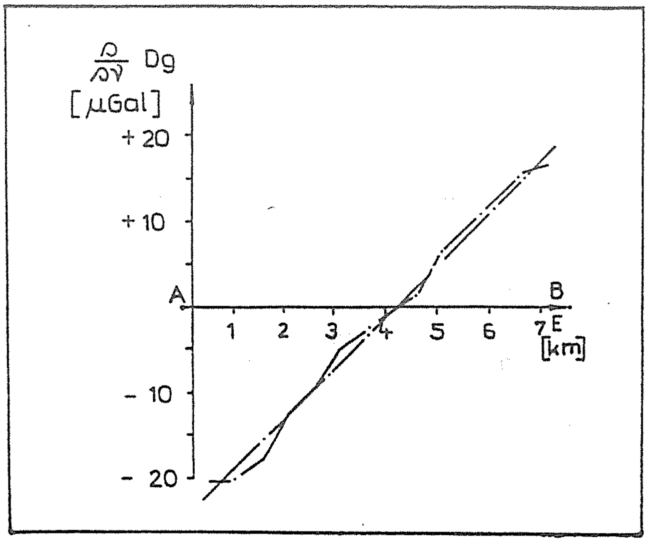

Fig. 4 : The profile A-B

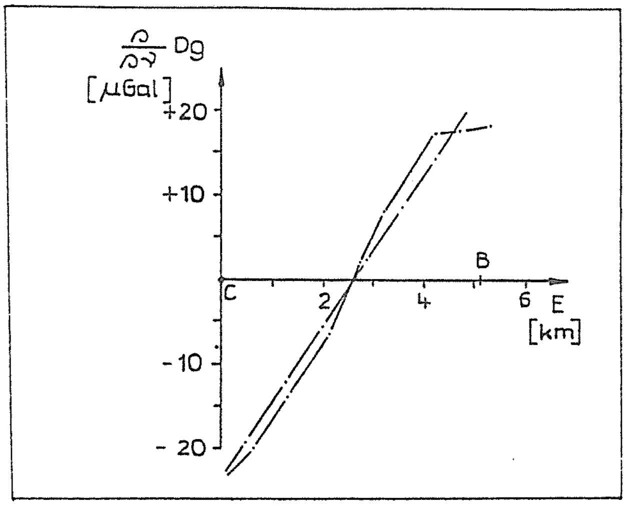

Fig. 5 : The profile C-D

The parameters of these 2 straight lines and the associated standard deviations are as follows, expressing the signal function in µgal :

. Profile A-B :

$$\frac{\partial}{\partial v} D_g = (+5.8 \pm 0.1) E_{km} - (24 \pm 0.6) \tag{38}$$

. Profile C-B :

$$\frac{\partial}{\partial v} D_g = (+9.1 \pm 0.6) E_{km} - (23 \pm 1.8) \tag{39}$$

Thus, the coefficients of these lines are significantly determined. Consequently, the structures of the signal function shown in Fig. 3 are clearly significant, proving that certain density changes in the interior have to exist.

A depression of the signal function with a minimum value of about - 20 μgal can be explained by certain density changes in the interior, along the lines of the methods of the gravimetrical prospection, (34) through (37). For instance, a spherical mass of radius $v = 1$ km, of density contrast $\delta\rho = -0.006$ g cm^{-3}, and with center at a depth of 3 km will cause a depression of the signal function having a horizontal extent of about 4 km and a minimum value of about - 20 μgal, as in Fig. 3. This absolute density change means a relative density change by - 0.006/2.67, being equal to - 2 . 10^{-3}; this corresponds to a horizontal stretch of the upper layers of the Earth by about 4 m over a distance of 2 km. Stretches of such an amount are determined by terrestrial geodetic distance measurements in this rift area, indeed, MOLLER (1989) : "... the great extension quantities in the rift zone amounting up to 4 m..." (This is valid for the period 1977-1980).

5. The Relationship between δg and δh

Several authors finish the discussion of the measured δg and δh values by quoting the relation between δg and δh. For instance, Hagiwara found for the Izu-peninsula, WENZEL (1989) :

$$\frac{\delta g}{\delta h} = -0.3\ mgal\ m^{-1} \tag{40}$$

leading to the following quantity for our signal function, (32) :

$$\frac{\partial}{\partial v} D = -0.1\ \delta h \tag{41}$$

For Iceland, we have according to TORGE (1989) :

$$-0.43\ mgal\ m^{-1} < \frac{\delta g}{\delta h} < -0.12\ mgal\ m^{-1} \tag{42}$$

hence, for the lower limit of (42) :

$$\frac{\partial}{\partial v} D = -0.23\ \delta h \tag{43}$$

and for the upper bound of (42) :

$$\frac{\partial}{\partial v} D = +0.08\ \delta h \tag{44}$$

As an extreme value, TORGE found :

$$\frac{\delta g}{\delta h} = +1.3\ mgal\ m^{-1} \tag{45}$$

thus,

$$\frac{\partial}{\partial v} D_g = +1.50\ \delta h \tag{46}$$

For $\delta h = 1$ m, the relation (46) leads to :

$$\frac{\partial}{\partial v} D_g = 1.5\ mgal \tag{47}$$

Such a value of our signal function can be interpreted by the gravitational effect of a sphere of 1 km radius, having a homogeneous density of 0.45 g cm^{-3}, with its center at a depth of 3 km. In this case, we have possibly an inflow of magma into an empty or into a widening chamber.

Consequently, the evaluation of the δg and δh values should not stop after the first step which leads to the values of $\delta g : \delta h$, only. A second step should follow computing the signal function (31) (32) which allows to calculate plausible values for the density changes in the interior.

6. The Mass Conservation Law

Finally, a discussion of the mass conservation law is of importance. In this context, this law has the following form, in introducing tolerable approximations, HEISKANEN and MORITZ (1967), KELLOGG (1929) :

$$\delta M = \frac{1}{4\pi f} \int\int_V \frac{\partial}{\partial v} D\, ds = 0 \qquad (48)$$

Of course, the mass change δM during the time period Φ has to be equal to zero.

Relations (25) and (48) lead to :

$$\int\int_V \left[\delta g + \frac{2G}{R} \delta h \right] ds = 0 \qquad (49)$$

relating the global integral over δg and that over δh,

$$\int\int_V \delta g\, ds = -\frac{2G}{R} \int\int_V \delta h\, ds \qquad (50)$$

This is a constraint always to be satisfied when considering a recent crustal movement phenomenon.

The coefficient - $2G/R$ is the free-air gradient being equal to - 0.3 mgal m^{-1}.

For instance, applying the above developments about the mass conservation law on the Fennoscandian land uplift, we have for this area, by empirical means, WENZEL (1989) :

$$\frac{\delta g}{\delta h} = -0.19\ mgal\ m^{-1} \qquad (51)$$

(32) and (51) give :

$$\frac{\partial}{\partial v} D = 0 \qquad (52)$$

(51) shows that there are no density changes in the interior observing (51). Thus, the Fennoscandian uplift has no vertical compensation of the mass changes, but a horizontal one, necessarily. Consequently :

$$\delta M = \int\int_V \delta h\, ds = 0 \qquad (53)$$

that is the central uplift area ($\delta h > 0$) has to be surrounded by a belt of subsidence.

7. Results

In a refinement of the geodynamic model discussed here, the first step should be to replace the standard density ρ_o of the surface layer by the real density on the surface of the Earth. The current method, which stops the discussion of the gravity and height changes by quoting the relation $\delta g : \delta h$ only, is not an optimal one. The information content of the measurements is not exhausted fully, leaving the reasoning halfway.

In any case, it is better to add a second step, in computing the signal function (31), (32) in terms of the δg and δh values and determining plausible quantities for the density changes in the interior. This second step should not be missed. The estimation of the density changes should then be interpreted in close collaboration with geophysicists and geologists.

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Earthquakes

Earthquake Damage - General

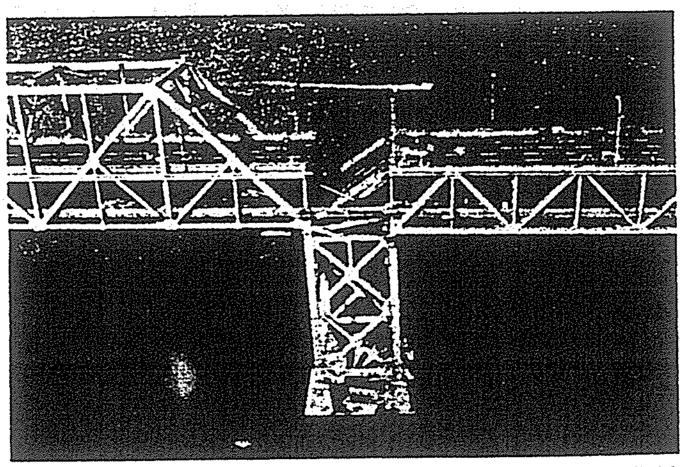
Illustrates several kinds of effects caused by 11 earthquakes in seven countries and four states in the United States. Pictures show strike-slip and thrust faulting, surface ruptures, landslides, fissuring, slumping and sand boils, as well as structural damage. This set is designed to give an overview and summary of earthquake effects. (Color; **647-A11-001**)

NEW Earthquake Damage, the Armenian Soviet Socialist Republic, December 1988

Includes spectacular damage photographs taken in and around the devastated cities of Spitak and Leninakan where 25,000 deaths occurred. Illustrates the structural types that were vulnerable to failure. This set graphically shows that inadequate building construction combined with shaking from a moderate earthquake can result in high death tolls and tremendous economic loss. (Color; **647-A11-011**)

Earthquake Damage to Transportation Systems

Depicts earthquake damage to streets, highways, bridges, overpasses, and railroads caused by 12 earthquakes in Guatemala, Japan, Mexico, Armenia, and five states in the United States. Views of structural damage to the San Francisco-Oakland Bay Bridge and the Nimitz Freeway (I-880) resulting from the October 1989 earthquake are included. (B&W/Color; **647-A11-004**)

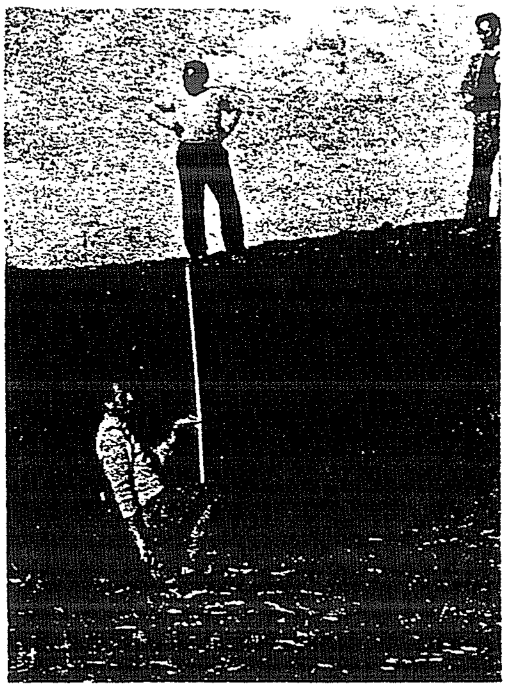


Damaged section of the San Francisco-Oakland Bay Bridge, California, October 17, 1989.

National Geophysical Data Center

Earthquake Damage to Schools

Nine destructive earthquakes that occurred in the United States and eight earthquakes that occurred in foreign countries from 1886 to 1988 are depicted. The set graphically illustrates the potential danger major earthquakes pose to school structures. The photograph taken in 1886 of the damage at Charleston College, Charleston, South Carolina, is of special interest since it is an illustration of earthquake damage possible on the east coast of the United States. (B&W/Color; **647-A11-005**)



Fault scarp from October, 1980 earthquake in Algeria.

NEW ### *Faults*

Includes a schematic and illustrations showing normal, reverse, and strike-slip faults and related features. The faults are located in Alabama, California, Idaho, Montana, Nevada, Oregon, and Wyoming in the United States and in Algeria, Guatemala, and Iceland. The set includes an aerial view and other views of the famous San Andreas fault in California. (Color; **647-A11-010**)

Earthquake Damage, San Francisco, California, April 18, 1906

Includes a panoramic view of San Francisco in flames a few hours after the earthquake, dramatic damage scenes from the area, and other unique photographs. (B&W; **647-A11-002**)

Earthquake Damage, Great Alaska Earthquake, March 1964

Shows geologic changes; damage to structures, transportation systems, and utilities; and tsunami damage. Features the effects of four major landslides in Anchorage including the dramatic Fourth Avenue and Turnagain Heights landslides. (Color; **647-A11-007**)

Earthquake Damage, Mexico City, Mexico, September 1985

Shows different types of damaged buildings and major kinds of structural failure including collapse of the top, middle, and bottom floors and total building failure. The effect of the subsoils on the earth shaking and building damage is emphasized. (Color; **647-A11-003**)

Earthquake Damage, Southern California, 1979-1989

Shows earthquake damage from the following events: Imperial Valley, 1979; Westmorland, 1981; Palm Springs, 1986; and Whittier, 1987. Partially and totally collapsed buildings caused by the Whittier Narrows earthquake are shown. (Color; **647-A11-008**)

NEW ### *Earthquake Damage, Central California, 1980-1984*

Shows earthquake damage from the following events: Livermore, 1980; Coalinga, 1983; and Morgan Hill, 1984. Several totally and partially collapsed buildings in the downtown area of Coalinga are shown. (Color; **647-A11-009**)

NEW ### *Earthquake Damage, Loma Prieta, October 1989, Set I - Loma Prieta vicinity*

Includes damage in Boulder Creek, Aptos, Los Gatos, San Jose, Santa Cruz, Scott's Valley, and Watsonville. The slides depicting earth cracks and structural damage to homes in the Santa Cruz mountains are especially dramatic. (Color; **647-A11-012**)

NEW ***Earthquake Damage, Loma Prieta, October 1989, Set II - San Francisco and Oakland***

Highlights the spectacular damage in the Marina area of San Francisco. The set also includes photographs of the damaged building in the area south of Market Street where five deaths occurred, the now famous damage to the San Francisco-Oakland Bay Bridge, and the Cypress Section of the Nimitz Freeway (I-880) where 41 deaths occurred. (Color; **647-A11-013**)

Tsunamis

Tsunamis - General

Depicts advancing waves, harbor damage, and structural damage from seven tsunami events which have occurred since 1946 in the Pacific region. The set includes dramatic before-and-after views of Scotch Cap Lighthouse in the Aleutian Islands that was completely washed away by a wave of more than 30 meters! A somewhat out-of-focus, but nevertheless unique photograph of a man about to be inundated by a huge wave that destroyed the Hilo, Hawaii, waterfront is also included. (B&W/Color; **648-A11-001**)

Landslides

Landslides

Depicts diverse types of landslides and mass wasting. Photos were taken at various locations in the United States, Canada, Australia, Peru, and Switzerland. Of particular interest are views of the famous 1903 rock slide at Frank, Alberta, Canada, that covered the town of Frank in less than two minutes, and the 1970 earthquake-induced rock- and snowslide that buried the towns of Yungay and Ramrahirca in Peru. (Color; **647-A11-006**)

Volcanoes

Volcanic Rocks and Features

Illustrates eruption products and features resulting from volcanism in Australia, the Canary islands, New Zealand, Scotland, and the United States. Pictures are examples of lava types, ash, cinders, bombs, necks, dikes, and sills. Aerial views of Devils Tower, Wyoming, and Ship Rock, New Mexico, landmark volcanic neck remnants, and Diamond Head, famous tuff cone on the Island of Oahu, are of special interest. (Color; **739-A11-002**)

Volcanoes in Eruption, Set I

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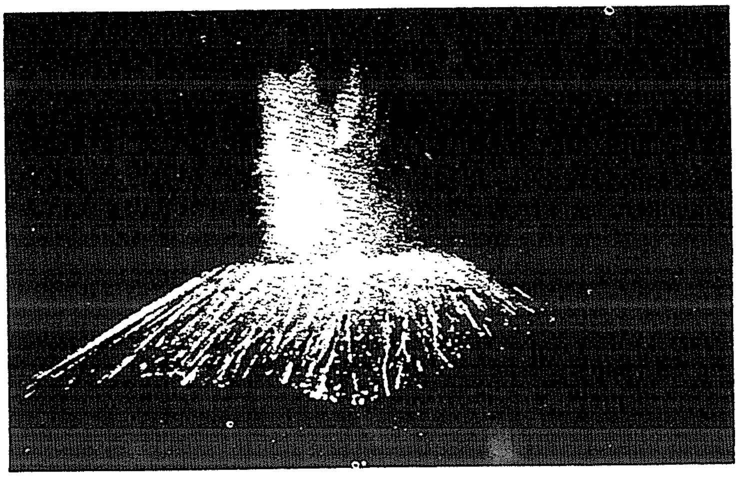

Night view of 1944 eruption of Paricutin in Mexico.

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