ASSOCIATION INTERNATIONALE DE GÉODÉSIE

BUREAU
GRAVIMÉTRIQUE
INTERNATIONAL

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N° 80

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INFORMATIONS for CONTRIBUTORS

Contributors should follow as closely as possible the rules below :

Manuscripts should be typed (single spaced), 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).

NOTA : ***The publisher welcomes the manuscripts which have been prepared using WORD 6 for Macintosh and also accepts ASCII files on diskettes 3"5.***

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.

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. 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 O and zero, the letter l and the number one, kappa and k, mu and the letter u, nu and v, eta and n, also subscripts and superscripts should be clearly noted and easily distinguished. Unusual symbols should be avoided.

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 have 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.

Table. 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.

BUREAU GRAVIMÉTRIQUE INTERNATIONAL

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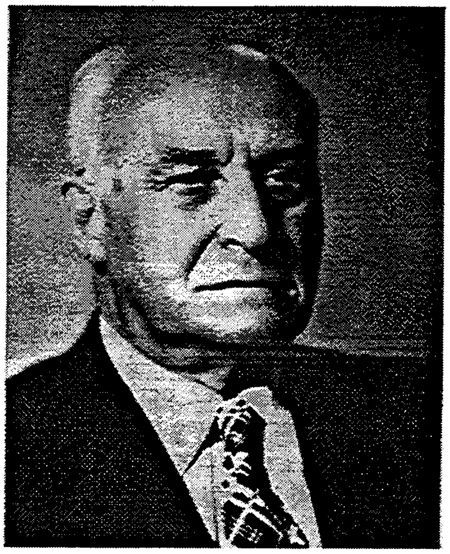
OBITUARY



We learnt with great sadness that Academician Professor Boulanger passed away on June 2, 1997. This is a great figure of geodesy who unfortunately disappears.

Professor Boulanger was known world-wide for having established fundamental gravity networks covering his whole country, and made numerous intercontinental gravity connections. He inspired for years the activities of the International Association of Geodesy (IAG), of IUGG, in absolute and relative gravity observations. He himself participated in several campaigns of measurements, of which some were regularly devoted to the intercomparison of absolute gravimeters. He initiated the establishment of the IAG Commission on Earth Tides, and of the Commission on Recent Crustal Movements of which he was Vice-President, then President (1971-1983).

He was President of IAG from 1971 to 1975 at which time he started to be involved in the activities of the International Gravity Bureau (BGI) : he chaired the Working Group on the World Gravity Maps of the International Gravity Commission, and was member of the BGI Directing Board until 1990.

Our community will miss him very much. We are sending our sincere condolences to his family and his friends.

G. Balmino

PART I

INTERNAL MATTERS

GENERAL INFORMATION

1. HOW TO OBTAIN THE BULLETIN
2. HOW TO REQUEST DATA
3. USUAL SERVICES B.G.I. CAN PROVIDE
4. PROVIDING DATA TO B.G.I.

1. HOW TO OBTAIN THE BULLETIN

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

The Bulletin contains general information 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, an issue contains the National Reports as presented at the International Gravity Commission meeting. 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 (79 have been issued as of December 31, 1996 but numbers 2,16, 18,19 are out of print).

- or subscribe for regularly receiving the two bulletins per year (the special issues. are obtained at additional cost).

Requests should be sent to:

Mrs. Nicole LESTIEU
CNES/BGI
18, Avenue Edouard Belin
31401 TOULOUSE CEDEX 4 - FRANCE

Bulletins are sent on an exchange basis (free of charge) to individuals, institutions which currently provide informations, data to the Bureau. For other cases, the price of each issue is 75 FF.

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

2.5.1. CD-Roms

The non confidential data, which have been validated by various procedures are available on two CD-ROMs.
The price of these is :

- *800 (Eight hundred) French francs for individual scientists, universities and research laboratories or groups working in geodesy or geophysics.*
- *3000 (Three thousand) French francs for all other users.*

Most essential quantities are given, in a compressed format. The package includes a user's guide and software to retrieve data according to the area, the source code, the country.

2.5.2. Data stored in the general data base

BGI is now using the ORACLE Data Base Management System. One implication is that data are stored in only one format (though different for land and marine data), and that archive files do not exist anymore.

There are two distinct formats for land or sea gravity data, respectively EOL and EOS.

EOL
LAND DATA FORMAT
RECORD DESCRIPTION
126 characters

Col.	1-8	B.G.I. source number	(8 char.)
	9-16	Latitude (unit : 0.00001 degree)	(8 char.)
	17-25	Longitude (unit : 0.00001 degree)	(9 char.)
	26-27	Accuracy of position	(2 char.)
		The site of the gravity measurements is defined in a circle of radius R	
		0 = no information	
		1 - R <= 5 Meters	
		2 = 5 < R <= 20 M (approximately 0'01)	
		3 = 20 < R <= 100 M	
		4 = 100 < R <= 200 M (approximately 0'1)	
		5 = 200 < R <= 500 M	
		6 = 500 < R <= 1000 M	
		7 = 1000 < R <= 2000 M (approximately 1')	
		8 = 2000 < R <= 5000 M	
		9 = 5000 M < R	
		10...	
	28-29	System of positioning	(2 char.)
		0 = no information	
		1 = topographical map	
		2 = trigonometric positioning	
		3 = satellite	
	30	Type of observation	(1 char.)
		1 = current observation of detail or other observations of a 3rd or 4th order network	
		2 = observation of a 2nd order national network	
		3 = observation of a 1st order national network	
		4 = observation being part of a nation calibration line	
		5 = coastal ordinary observation (Harbour, Bay, Sea-side...)	
		6 = harbour base station	
	31-38	Elevation of the station (unit : centimeter)	(8 char.)
	39-40	Elevation type	(2 char.)
		1 = Land	
		2 = Subsurface	
		3 = Lake surface (above sea level)	
		4 = Lake bottom (above sea level)	
		5 = Lake bottom (below sea level)	
		6 = Lake surface (above sea level with lake bottom below sea level)	
		7 = Lake surface (below sea level)	
		8 = Lake bottom (surface below sea level)	
		9 = Ice cap (bottom below sea level)	
		10 = Ice cap (bottom above sea level)	
		11 = Ice cap (no information about ice thickness)	
	41-42	Accuracy of elevation	(2 char.)
		0 = no information	
		1 = E <= 0.02 M	
		2 = .02 < E <= 0.1 M	
		3 = .1 < E <= 1	
		4 = 1 < E <= 2	
		5 = 2 < E <= 5	
		6 = 5 < E <= 10	
		7 = 10 < E <= 20	
		8 = 20 < E <= 50	
		9 = 50 < E <= 100	
		10 = E superior to 100 M	
	43-44	Determination of the elevation	(2 char.)
		0 = no information	
		1 = geometrical levelling (bench mark)	
		2 = barometrical levelling	
		3 = trigonometric levelling	
		4 = data obtained from topographical map	
		5 = data directly appreciated from the mean sea level	
		6 = data measured by the depression of the horizon	
		7 = satellite	
	45-52	Supplemental elevation (unit : centimeter)	(8 char.)
	53-61	**Observed gravity** (unit : microgal)	(9 char.)

62-67	**Free air anomaly** (0.01 mgal)	(6 char.)
68-73	**Bouguer anomaly** (0.01 mgal) Simple Bouguer anomaly with a mean density of 2.67. No terrain correction	(6 char.)
74-76	Estimation standard deviation free-air anomaly (0.1 mgal)	(3 char.)
77-79	Estimation standard deviation bouguer anomaly (0.1 mgal)	(3 char.)
80-85	**Terrain correction** (0.01 mgal) *computed according to the next mentioned radius & density*	(6 char.)
86-87	Information about terrain correction 0 = no topographic correction 1 = tc computed for a radius of 5 km (zone H) 2 = tc computed for a radius of 30 km (zone L) 3 = tc computed for a radius of 100 km (zone N) 4 = tc computed for a radius of 167 km (zone 02) 11 = tc computed from 1 km to 167 km 12 = tc computed from 2.3 km to 167 km 13 = tc computed from 5.2 km to 167 km 14 =tc (unknown radius) 15 = tc computed to zone M (58.8 km) 16 = tc computed to zone G (3.5 km) 17 = tc computed to zone K (18.8 km) 25 = tc computed to 48.6 km on a curved Earth 26 = tc computed to 64. km on a curved Earth	(2 char.)
88-91	Density used for terrain correction	(4 char.)
92-93	Accuracy of gravity 0 = no information 1 = E <= 0.01 mgal 2 = .01 < E <= 0.05 mgal 3 = .05 < E <= 0.1 mgal 4 = 0.1 < E <= 0.5 mgal 5 = 0.5 < E <= 1. mgal 6 = 1. < E <= 3. mgal 7 = 3. < E <= 5. mgal 8 = 5. < E <= 10 mgal 9 = 10. < E <= 15. mgal 10 = 15. < E <= 20. mgal 11 = 20. < E mgal	(2 char.)
94-99	Correction of observed gravity (unit : microgal)	(6 char.)
100-105	**Reference station** *This station is the base station (BGI number) to which the concerned station is referred*	(6 char.)

106-108 Apparatus used for the measurement of G (3 char.)

0.. no information
1.. pendulum apparatus before 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
34 = Boliden (Sweden)
4.. Metal spring gravimeters for ground measurements
41 = Frost
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
59 = SCINTREX CG2
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

109-111 **Country code (BGI)** (3 char.)

112 **Confidentiality** (1 char.)

0 = without restriction
.....1 = with authorization
2 = classified

113 **Validity** (1 char.)

0 = no validation
1 = good
2 = doubtful
3 = lapsed

114-120 Numbering of the station (original) (7 char.)

121-126 Sequence number (6 char.)

EOS
SEA DATA FORMAT
RECORD DESCRIPTION
146 characters

Col.		
1-8	**B.G.I.** source number	(8 char.)
9-16	**Latitude** (unit : 0.00001 degree)	(8 char.)
17-25	**Longitude** (unit : 0.00001 degree)	(9 char.)
26-27	Accuracy of position The site of the gravity measurements is defined in a circle of radius R 0 = no information 1 - R <= 5 Meters 2 = 5 < R <= 20 M (approximately 0'01) 3 = 20 < R <= 100 M 4 = 100 < R <= 200 M (approximately 0'1) 5 = 200 < R <= 500 M 6 = 500 < R <= 1000 M 7 = 1000 < R <= 2000 M (approximately 1') 8 = 2000 < R <= 5000 M 9 = 5000 M < R 10...	(2 char.)
28-29	System of positioning 0 = no information 1 = Decca 2 = visual observation 3 = radar 4 = loran A 5 = loran C 6 = omega or VLF 7 = satellite 8 = solar/stellar (with sextant)	(2 char.)
30	Type of observation 1 = individual observation at sea 2 = mean observation at sea obtained from a continuous recording	(1 char.)
31-38	**Elevation of the station** (unit : centimeter)	(8 char.)
39-40	Elevation type 1 = ocean surface 2 = ocean submerged 3 = ocean bottom	(2 char.)
41-42	Accuracy of elevation 0 = no information 1 = E <= 0.02 Meter 2 = .02 < E <= 0.1 M 3 = .1 < E <= 1 4 = 1 < E <= 2 5 = 2 < E <= 5 6 = 5 < E <= 10 7 = 10 < E <= 20 8 = 20 < E <= 50 9 = 50 < E <= 100 10 = E superior to 100 Meters	(2 char.)
43-44	Determination of the elevation 0 = no information 1 = depth obtained with a cable (meters) 2 = manometer depth 3 = corrected acoustic depth (corrected from Mathew's tables, 1939) 4 = acoustic depth without correction obtained with sound speed 1500 M/sec. (or 820 fathom/sec) 5 = acoustic depth obtained with sound speed 1463 M/sec (800 fathom/sec) 6 = depth interpolated on a magnetic record 7 = depth interpolated on a chart	(2 char.)
45-52	Supplemental elevation	(8 char.)
53-61	**Observed gravity** (unit : microgal)	(9 char.)
62-67	**Free air anomaly** (0.01 mgal)	(6 char.)
68-73	**Bouguer anomaly** (0.01 mgal) Simple Bouguer anomaly with a mean density of 2.67. No terrain correction	(6 char.)
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88-91	Density used for terrain correction	(4 char.)
92-93	Mathew's zone *when the depth is not corrected depth, this information is necessary. For example : zone 50* *for the Eastern Mediterranean Sea*	(2 char.)
94-95	Accuracy of gravity 0 = no information 1 = E <= 0.01 mgal 2 = .01 < E <= 0.05 mgal 3 = .05 < E <= 0.1 mgal 4 = 0.1 < E <= 0.5 mgal 5 = 0.5 < E <= 1. mgal 6 = 1. < E <= 3. mgal 7 = 3. < E <= 5. mgal 8 = 5. < E <= 10. mgal 9 = 10. < E <= 15. mgal 10 = 15 < E <= 20. mgal 11 = 20. < E mgal	(2 char.)
96-101	Correction of observed gravity (unit : microgal)	(6 char.)
102-110	Date of observation *in Julian day - 2 400 000 (unit : 1/10 000 of day)*	(9 char.)
111-113	Velocity of the ship (0.1 knot)	(3 char.)
114-118	Eötvös correction (0.1 mgal)	(5 char.)
119-121	**Country code (BGI)**	(3 char.)
122	**Confidentiality** 0 = without restriction 1 = with authorization 2 = classified	(1 char.)
123	**Validity** 0 = no validation 1 = good 2 = doubtful 3 = lapsed	(1 char.)
124-130	Numbering of the station (original)	(7 char.)
131-136	**Sequence number**	(6 char.)
137-139	**Leg number**	(3 char.)
140-145	**Reference station**	(6 char.)

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

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

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

where ϕ is the geographic latitude.

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

Formulas used in computing free-air and Bouguer anomalies

Symbols used :

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

Formulas :

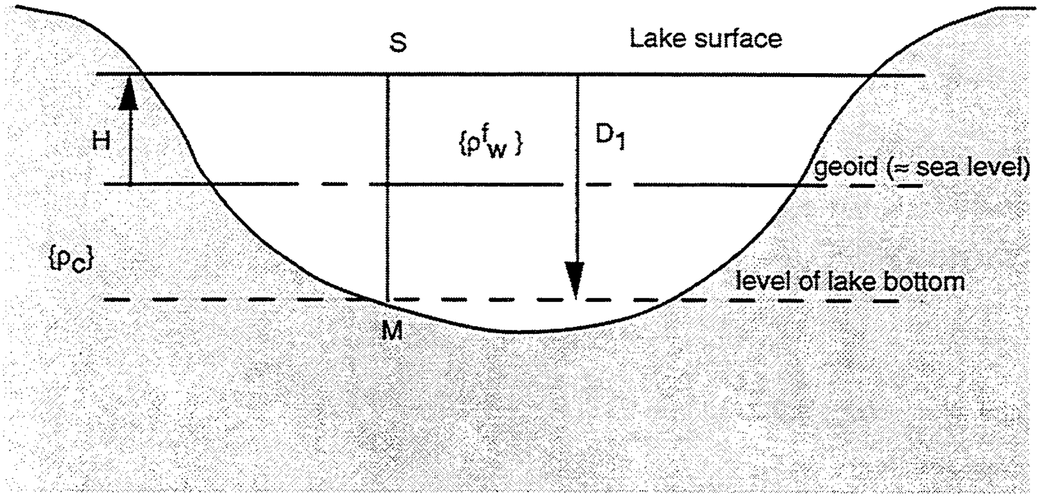
* *FA : The principle is to compare the gravity of the Earth at its surface with the normal gravity, which first requires in some cases to derive the surface value from the measured value. Then, and until now, FA is the difference between this Earth's gravity value reduced to the geoid and the normal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

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

---

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

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



$$g_S = g_M + 2\,k\,\rho_w^f\,D_1 - \Gamma D_1$$
$$\Rightarrow FA = g_S + \Gamma H - \gamma_o$$

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

$$\begin{aligned}\delta g_s &= g_s - k\,\rho_w^f\,D_1 + k\,\rho_c(D_1 - H)\\ &= g_s - k\,\rho_w^f\,[H + (D_1 - H)] + k\,\rho_c\,(D_1 - H)\\ &= g_s - k\,\rho_w^f\,H + k\,(\rho_c - \rho_w^f)(D_1 - H)\end{aligned}$$

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

The table below covers most frequent cases. It is an update of the list of formulas published before.

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 :

$$\begin{aligned}-k\,\rho_i H + k(\rho_c - \rho_i)(D_1 - H) &\equiv -k\,\rho_i(H - D_1 + D_1) - k(\rho_c - \rho_i)(H - D_1)\\ &\equiv -k\,\rho_i\,D_1 - k\,\rho_c(H - D_1)\end{aligned}$$

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	$FA = g + 2 k \rho_c D_2 + \Gamma (H - D_2) - \gamma_o$ $BO = FA - k \rho_c H$
3	Ocean Surface	$FA = g - \gamma_o$ $BO = FA + k (\rho_c - \rho_w^s) D_1$
4	Ocean submerged	$FA = g + (2 k \rho_w^s - \Gamma) D_2 - \gamma_o$ $BO = FA + k (\rho_c - \rho_w^s) D_1$
5	Ocean bottom	$FA = g + (2 k \rho_w^s - \Gamma) D_1 - \gamma_o$ $BO = FA + k (\rho_c - \rho_w^s) D_1$
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	$FA = g + 2 k \rho_w^f D_1 + \Gamma (H - D_1) - \gamma_o$ $BO = FA - k \rho_w^f D_1 - k \rho_c (H - D_1)$
8	Lake bottom, below sea level	$FA = g + 2 k \rho_w^f D_1 + \Gamma (H - D_1) - \gamma_o$ $BO = FA - k \rho_w^f H + k (\rho_c - \rho_w^f)(D_1 - H)$
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 ($H < o$)	$FA = g + (2 k \rho_w^f - \Gamma) D_1 + \Gamma H - \gamma_o$ $BO = FA - k \rho_c H + k (\rho_c - \rho_w^f) D_1$
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	$FA = g + \Gamma H - \gamma_o$ $BO = FA - k \rho_i D_1 - k \rho_c (H - D_1)$

All requests for data must be sent to :

Mr. Gilles BALMA
Bureau Gravimétrique International
18, Avenue E. Belin - 31401 Toulouse Cedex 4 - France
E-mail : Gilles.Balma@cnes.fr

In case of a request made by telephone, it should be followed by a confirmation letter, or fax. 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 as tarfiles on DAT cartridge (4 mm). for large amounts of data, or on diskette in the case of small files. The exact physical format will be indicated in each case. Also a FTP anonymous service is available on our computer center.

3. USUAL SERVICES BGI 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 on January 1, 1992 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 CD-Roms : see 2.5.1.
. on one of the following media :
** printout .... 2 F/100 lines*
** diskette........................ 25 F per diskette (minimum charge : 50 F-*
** magnetic tape .... 2 F per 100 records*
+ 100 F per DAT cartridge
(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°x20° 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 scale, 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 Δ xΔ' area : 10F/ΔΔ' per degree square.

. minimum charge : 150 F

. maximum area : 40°x40°

3.2. Charging Policy for Other Individuals or Private Companies

3.2.1. Digital Data Retrieval

. on CD-Roms : see 2.5.1.

. 1 F per measurement for non commercial use (guaranteed by signed agreement), 5 F per measurement in other cases (direct or indirect commercial use - e.g. in case of use for gridding and/or maps to be sold or distributed by the buyer in any project with commercial application). Minimum charge : 500 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 ihe polygon.

3.2.3. Data Screening

. 1 F per screened point for non commercial use (guaranteed by signed agreement), 5 F per screened point in other cases (cf. 3.2.1.).

. 500 F minimum charge

3.2.4. Gridding

Same as 3.1.4.

3.2.5. Contour Maps of Bouguer or Free-Air Anomalies

Same as 3.1.5.

3.2.6. Computation of Mean Gravity Anomalies

Same as 3.1.6.

3.3. Gravity Maps

The pricing policy is the same for all categories of users

3.3.1. Catalogue of all Gravity Maps

Printout : 200 F
DAT cartrdige (4 mm) 100 F

3.2.2. Maps

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

. Special maps :

Mean Altitude Maps

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

Maps of Gravity Anomalies

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

World Maps of Anomalies (with text)

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

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

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

Miscellaneous

CATALOGUE OF ALL GRAVITY MAPS

listing	200 FF
tape	300 FF

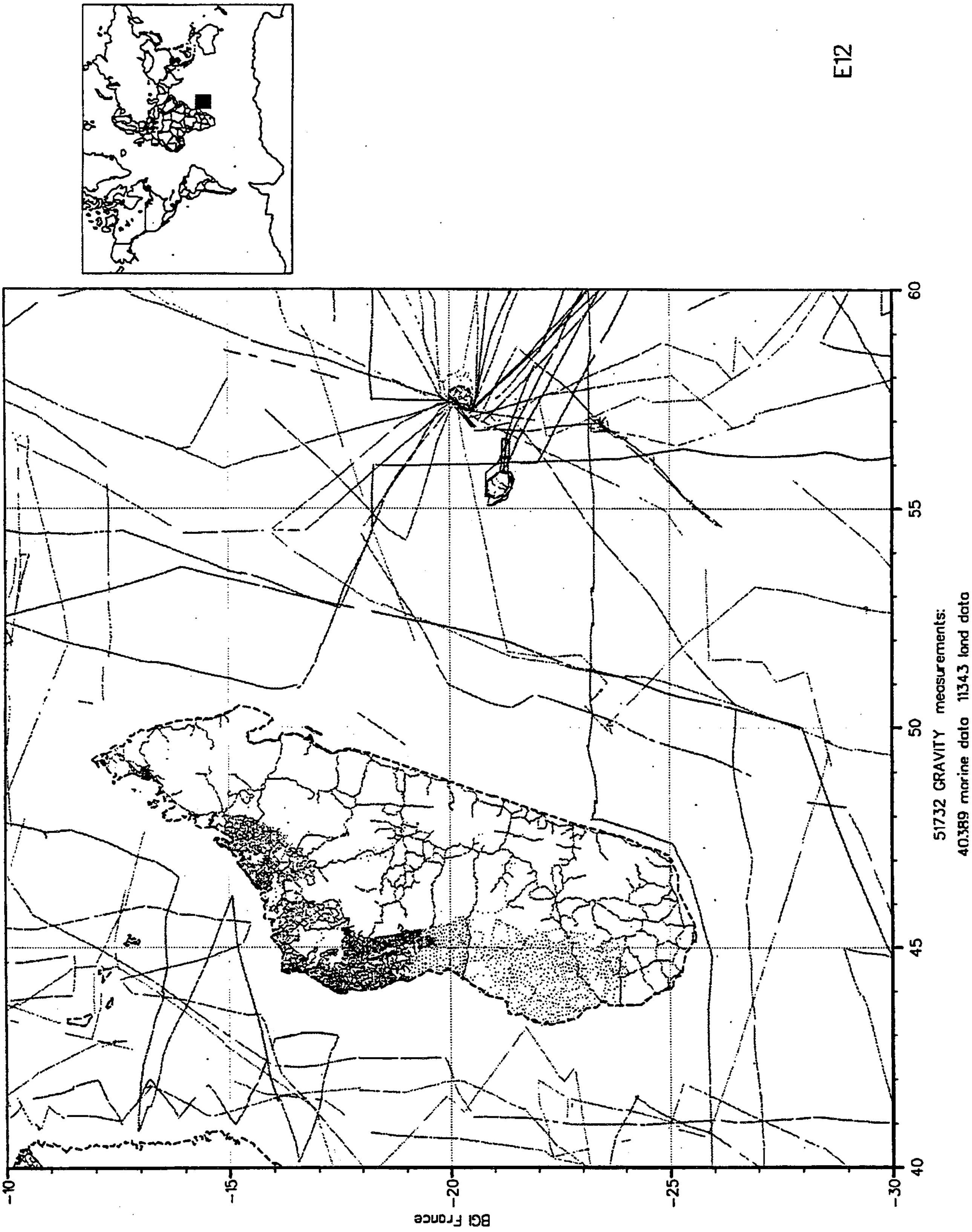
THE UNIFICATION OF THE GRAVITY NETS OF AFRICA

(Vol. 1 and 2) 1979 150 FF

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

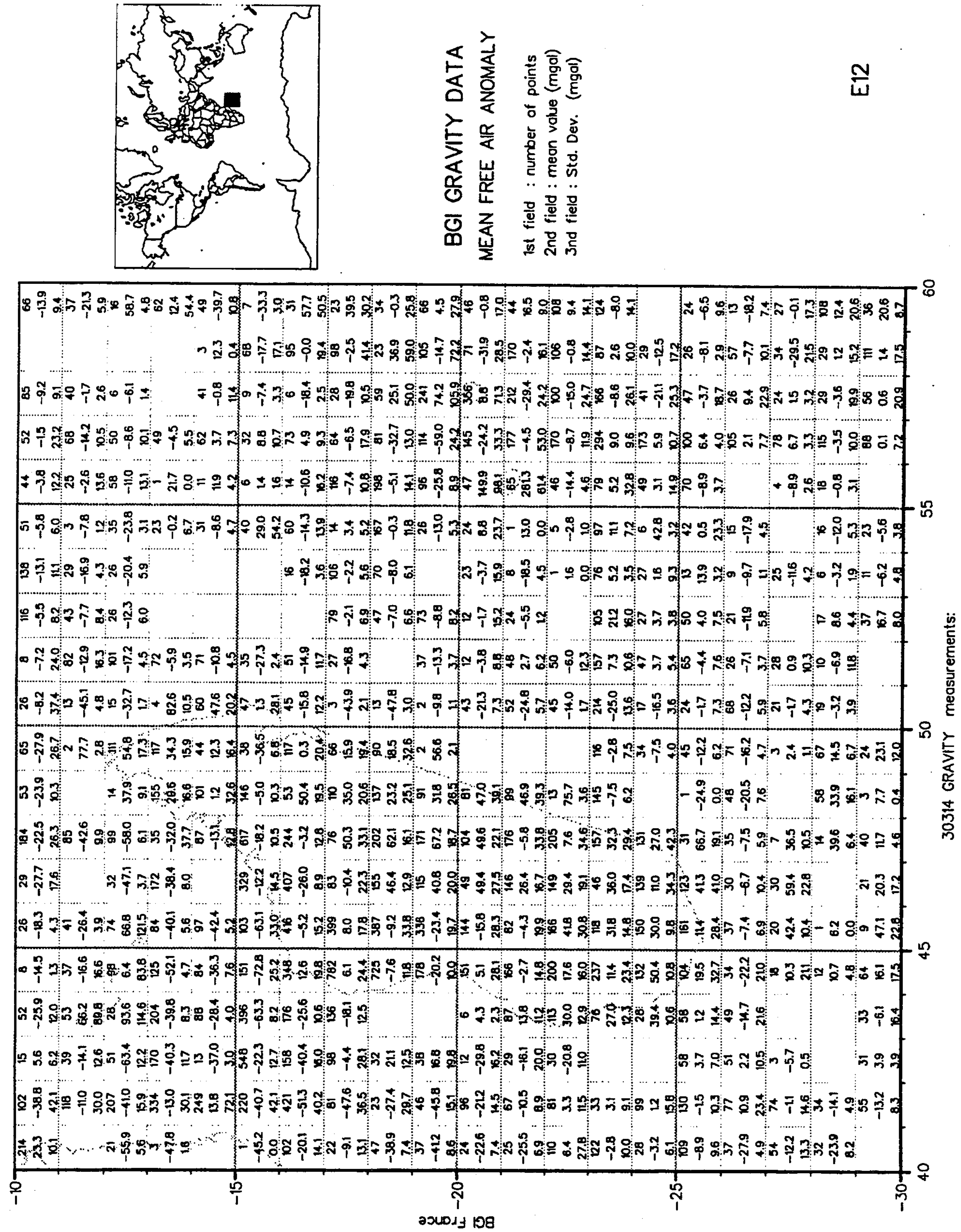
. Colour copy : price according to specifications of request.

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



Map 1. Example of data coverage plot

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



4. PROVIDING DATA TO B.G.I.

4.1. Essential Quantities and Information for Gravity Data Submission

1. Position of the site :

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

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

---

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

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

. Isostatic gravity

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

. Description of geological setting of each site

4.3. Formats

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

The contributor may use the EOL and/or EOS formats as described above, or 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 magnetifc tapes are used, contributors are kindly asked to use 1600 bpi, unlabelled tapes (if possible), with no password, and formatted records of possibly fixed length and a fixed blocksize, too. Tapes are returned whenever specified, as soon as they are copied

PART II

Contributing Papers

Results of Absolute Gravity Measurements at the Geodetic Observatory Pecny

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From October 1978 to September 1996 eight absolute gravity measurements were carried out at the absolute gravity station at the Geodetic Observatory Pecny by the following agencies:

Institut fiziki Zemli (Institute of Physics of the Earth), Moscow (1978, 1983, 1986),
Bundesamt für Eich- und Vermessungswesen (Federal Office for Metrology and Surveying), Vienna 1992),
Defense Mapping Agency, U.S.A. (1993),
Institut für Angewandte Geodäsie (Institute of Applied Geodesy), Frankfurt am Main (1995),
Politechnika Warszawska (Warsaw University of Technology), Warsaw (1995, 1996).

The results were partially published in (Simon, 1993) and (Simon, 1994).

Here we present in Table 1 a summary of results of all measurements. They are corrected in the same way after (Boedecker, 1988) for the influence of the air pressure, polar motion and of the earth and ocean tides. For tidal corrections the parameters of the tidal waves were used as determined from the long term tidal observations at the observatory which ensure the accuracy of these corrections on the level of about 10 nm s^{-2} . However, in (Simon, 1995) it is shown that when using an appropriate routine of the absolute measurements, the accuracy of the tidal wave parameters is not decisive. In correspondence with the recommendation of the IAG only the direct effect of celestial bodies was included into the corrections with the constant part of the tides whereas the influence of the constant tidal deformation of the Earth was preserved in the measured value.

The gravity values given in Table 1 are reduced down to the top of the observing pier. The vertical gravity gradients used for the reductions are given in the column 4 of Table 1. We intend to make a detailed survey of the vertical structure of the gravity field above the absolute site Pecny. Then it will be possible to improve the reductions of the measurements performed in different effective heights of the instrument.

Starting with the year 1992 the heights of the underground water level are given in column 5 of the table. These heights were measured in an unused lying well located at about 50 m distance from the absolute site.

The gravity values for the gravimeters JILAG-6, FG5 No. 107 and FG5 No. 101 are corrected for systematic errors of the interferometer electronics (Marson et al, 1995). At the beginning the results seemed to indicate possible gravity changes but since 1992 the changes have been within the limits of 160 nm s^{-2}.

At the other Czech absolute site Polom (50.35° N, 16.32° E, 738 m), where the measurements were performed by the group of the Defense Mapping Agency in 1993, the resulting gravity value, corrected for the systematic error of the electronics, is $g = 9.\ 80\ 921\ 1633\ ms^{-2}$.

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Boedecker, G. (1988): International Absolute Gravity Basestation Network (IAGBN). Absolute Observations Data Processing Standards and Station Documentation. Bulletin B.G.I. No. 63, 51-57.

Marson, I. et al. (1995): Fourth International Comparison of Absolute Gravimeters. Metrologia No. 32, 137-144.

Simon, Z. (1993): Absolute gravity Measurements at the Geodetic Observatory Pecny in the Period 1978-1992. Research Institute of Geodesy, Topography and Cartography, Zdiby.

Simon, Z. - Olejnik, S. - Dusatko, D. (1994): Absolute Gravity Measurements in the Czech Republic in 1993. Proceedings of Research Works 1994, Vol. 40, No. 13. Research Institute of Geodesy, Topography and Cartography, Zdiby.

Simon, Z. (1995): Elimination of Tidal Influences on Absolute Gravity Measurements. Bulletin Marées Terrestres No. 121, 9066-9069.

Table 1. Results of absolute gravity measurements at the station Pecny
Coordinates of the absolute point 49.92° N, 14.78° E, 534.84 m

Date	Instrument Observer	g [m s^{-2}]	Vertical gradient used [nm s^{-2}/m]	Ground water level height [m]
1	2	3	4	5
78 10 04 78 10 08	GABL Arnautov	9.80 933 2571	3216	
83 11 18 83 11 20	GABL Arnautov	9.80 933 2993	3216	
86 05 06	GABL Arnautov	9.80 933 3055	3216	
92 02 10 92 02 12	JILAG-6 Ruess	9.80 933 2648	3216	521.13
93 09 11 93 09 13	FG5 No. 107 Friederich	9.80 933 2698	3216	519.03
95 04 20 95 04 22	FG5 No. 101 Falk	9.80 933 2703	3186	522.88
95 09 26 95 09 27	ZZG Zabek	9.80 933 2619	3210	522.79
96 10 03 96 10 04	ZZG Zabek	9.80 933 2545	3210	523.41

Absolute Gravity Value Measured at Syowa Station, Antarctica

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Abstract: In 1987, Japanese Antarctic Station "Syowa" was selected as one of the 36 subset (A) stations of the International Absolute Gravity Basestation Network (IAGBN) by International Association of Geodesy (IAG). National Institute of Polar Research (NIPR) established a gravity hut at Syowa Station and absolute gravity measurements started in the 1991-92 austral summer season. The first measurement was done by the 33rd Japanese Antarctic Research Expedition (JARE-33) members from the Geographical Survey Institute (GSI) employing a GA60 gravimeter (BIPM-JAEGER/GSI) in January 1992. In the following season, JARE-34 carried out the second measurements using two gravimeters. The third measurement was made by JARE-36 of GSI members using FG5 absolute gravimeter (#104/GSI) in January-February 1995. To discuss the four absolute gravity values obtained at Syowa Station, NIPR organized a workshop on January 1996 and it was concluded at the workshop that the absolute gravity value at Syowa Station is as follows:

g = 982524.327 mgal, S.D. = 0.015 mgal, φ = 69°00'27.035" S,
λ = 39°35'06.372" E, h = 21.492 m.

1. Introduction

The establishment of the International Absolute Gravity Basestation Network (IAGBN) was recommended at the 19th General Assembly of the International Association of Geodesy (IAG) held at Vancouver, Canada in 1987 (Torge *et al.,* 1987). The IAGBN was planned to consist of 36 subset (A) stations. Japanese Antarctic Station "Syowa" in Lützow Holm Bay, East Antarctica was selected as one of the IAGBN stations, together with the other station "McMurdo" in the Antarctic. According to the recommendation by IAG, the Japanese Antarctic Research Expedition (JARE) made the measurement program under the direction of the Geodetic Society of Japan (GSJ). An ad'hoc Working Group (WG) was set up with Dr. I. Nakagawa, the president of GSJ, National Institute of Polar Research (NIPR), the Geographical Survey Institute (GSI) and National Astronomical Observatory Mizusawa (NAOM) for proceeding with the measurements at Syowa Station.

The first measurements were made by the 33rd Japanese Antarctic Research Expedition (JARE-33) members from GSI in January 1992 at a new gravity hut of Syowa Station which had been constructed in 1991 (Fujiwara et al., 1993). The details of the hut were reported by Nakagawa *et al.* (1994). The second measurements were made by NAOM members of JARE-34 from December 1992 to February 1993 using two different absolute gravimeters (Hanada and Tsubokawa, 1994, Tsubokawa and Hanada, 1994). The processes and details of the measurements were already reported by Nakagawa *et al.* (1994).

In January-February 1995, the third measurements were accomplished by GSI members of JARE-36 (Yamamoto, 1996). In all, four sets of absolute gravity measurements were carried out at Syowa Station, and four different absolute gravity values were obtained.

On 22 January 1996, a workshop on the absolute gravity measurements at Syowa Station, Antarctica was held at NIPR to discuss the absolute gravity values obtained by the scientists of NIPR, GSI, NAOM, Kyoto University and Earthquake Research Institute, the University of Tokyo. Based on its discussion, at the workshop, it was concluded that the absolute gravity value obtained by the third measurement among four sets of gravity measurements at Syowa Station should be used until the succeeding measurement is made.

2. Contributors to measurements and data processing

The GSI has carried out geodetic and topographic survey in the Japanese Antarctic Research Activities. These activities include the gravity measurements at Syowa Station. A number of people were involved for making gravity measurements in and around Syowa Station. Personnel contributing to the absolute gravity measurements are as follows:

GA60:	S. Fujiwara, K. Watanabe, T. Akiyama and M. Kaizu (GSI), and Y. Fukuda (Ocean Research Institute, the University of Tokyo, Present: Kyoto University).
NAOM#2:	T. Tsubokawa and H. Hanada (NAOM).
AGRVP:	H. Hanada and T. Tsubokawa (NAOM).
FG5:	H. Yamamoto, H. Nitta and M. Murakami (GSI).
Miscellaneous:	K. Shibuya, M. Kanao (NIPR), and M. Ishihara (GSI).

Prof. K. Yokoyama of NAOM organized to carry out gravity measurements by NAOM #2 and AGRVP at Syowa Station in Japan.

Results of the absolute gravity measurements at Syowa Station are given in Table 1.

3. The absolute gravity value at Syowa Station

The third measurement at Syowa Station was made by the JARE-36 members of the GSI from 20 January to 11 February 1995 (Yamamoto, 1996). A total of 45,386 drops were made. Although a major hardware failure occurred in a part of mechanical compensation mechanism, relatively large amount of highly accurate measurement data was obtained. In addition to the absolute gravity value itself, systematic temporal gravity change with a peak to peak amplitude of about 10 μgal was detected. This small gravity change was estimated to be an elastic deformation response caused by oceanic tide. The detection of the small signal indicates the improvement in measurement of absolute gravimetry with the FG5. The estimated precision in microgal level for the determined absolute gravity value is supported by the fact that the FG5 is sensitive to detect the small signal.

At the workshop organized by NIPR in January 1996, it was concluded that the absolute gravity value by the FG5 gravimeter (#104) be adopted as the value at Syowa Station instead of the value by the GA60 gravimeter which was reported by Nakagawa *et al.* (1994). The main reason to adopt the value by the FG5 gravimeter (#104) is the high reliability of the FG5 gravimeters and is already a consensus choice of international gravimetric community in addition to large amount of significant data. After processing the measurement data according to the "Absolute Observations Data Processing Standards" by Boedecker (1992), the absolute gravity value at the IAGBN Syowa Station are as follows:

$g = 982524.327 \pm 0.004$ mgal
SD of a single measurement: 0.015 mgal
$\varphi = 69°00'27.035''$ S
$\lambda = 39°35'06.372''$ E
$h = 21.492$ m

The followings are the specification of the gravimeter and process of data corrections.

Type: FG5 Absolute Gravimeter #104 / GSI 1994.08
Rubidium atomic clock: FRK-L (Efratom Division of Ball Aerospace Engineering)
Light source: ISL- 1 He-Ne Laser (Winters Electro-Optics, Inc.)
Absorption line / wave length: d line / peak 632.9911774 nm
Laser modulate frequency: 1178.8784 Hz
Test falling object: Reverse corner cube reflection
Drift rate: None
Measurement by falling mode,
1) Light travel time correction was based on c = 299792458 m/s

2) Earth tide correction was applied to each measurement value from each drop using build-in processing software with the instrument. The correction was confirmed to be the same as that of the GA60 by JARE-33. The correction of + 7.7 μgal is necessary for the gravity value obtained by the software adopting the constant δ-factor of 1.164 for the constant component. The value of + 7.7 μgal was taken as correction as constant component of earth tide does not include Honkasalo correction.

3) Correction for polar motion was made following the IAGBN standards (Boedecker, 1992). The daily values of EOP parameter by IERS were used.

4) Atmospheric pressure variation correction was made by exactly following IAGBN standards.

5) In order to reduce the measured gravity values to height of the station marker, vertical gravity gradient along plumb line was measured using LaCoste & Romberg gravimeters.

6) A correction was made to compensate an off-set caused by the frequency dependence of the old type photo detector of the FGS gravimeter, and this correction value is -13.7 μgal.

The above procedures of the measurement data analysis is consistent with the IAGBN standards by Boedecker (1992). Additional comments are provided below for the correction 2) and 6) listed above respectively.

a) Corrections due to the photo detector

Niebauer *et al.* (1995) pointed out that a correction is necessary for the gravity value measured by the FGS gravimeter which uses an older version of photo detector. The correction depends on the fringe intensity. The correction is possible by using a chart given in the article by Niebauer *et al.*. The fringe intensity was 110 mV in the measurement at Syowa Station and the correction for this intensity needs -13.7 μgal in the chart.

b) Honkasalo correction

Tide correction procedure in the IAGBN is to use the constant δ-factor of 1.0 (Boedecker, 1992). This means that Honkasalo correction is not included in the IAGBN procedures. As the gravity value at Syowa Station obtained by the FGS gravimeter was corrected with the δ-factor of 1.16, a new correction of +7.7 μgal was to be made. Honkasalo term was removed by this correction.

Table 1: Results of absolute gravity measurements at Syowa Station, Antarctica

Period	**Instrument**	**Number of measurements**	**Gravity value (mGal)**
January 1992	GA60	834	982524.254 ± 0.030
Dec. 1992 -Jan. 1993	NAOM#2	276	982524.152 ± 0.040
"	AGRVP	43	982524.113 ± 0.040
Jan.-Feb. 1995	FG5 (#104)	45,386	982524.327 ± 0.015

Acknowledgement

The authors express their sincere thanks to attendance of the workshop for their valuable discussion. The authors thanks extend to Dr. I. Nakagawa, Emeritus Professor of Kyoto University and the former President of GSJ for his efforts and leadership in establishing the absolute gravity station at Syowa Station. Without his efforts, the IAGBN Syowa Station could not have established.

The authors extend thanks to Ms. M. Minegishi of NIPR for preparing this manuscript.

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The National Gravimetric Network of Uruguay

0. Introduction and Summary

A systematic survey of the Republica Oriental del Uruguay started in 1962, with a first international connection to Buenos Aires, transferring the absolute gravity datum from the Argentinian fundamental station to Montevideo. The Servicio Geografico Militar de Uruguay (SGM) then established a fundamental gravity network along the main roads between 1967 and 1968 including 924 stations. This relative type network consists of 25 loops, connected to the reference station in Montevideo. Densification surveys were mainly performed from 1984 to 1986 and increased the number of gravity stations to 2376 (average station distance 5 to 10 km). In addition, new international relative ties to Brazil and Argentina were performed in 1987, 1989 and 1993, relating the gravity network to the International Gravity Standardization Net 1971 (IGSN71), and the Latin American Gravity Standardization Network 1977 (LAGSN77). As part of the IFE Absolute Gravity Program "South America" 1989-1991 (IFE: Institut für Erdmessung, University of Hannover, Germany), three absolute gravity stations were established in Uruguay in 1989 and 1991, and connected to the fundamental gravity network, as well as the IFE absolute station Buenos Aires. From these recent references to the international gravity standard (IGSN71 as well as absolute gravity standard provided by absolute gravimeters), and from an analysis of the network calculation procedures applied previously it was decided to perform a new calculation of the network, using all available absolute and relative data, and employing homogeneous and most advanced evaluation, reduction and adjustment procedures. SGM and IFE agreed to jointly carry out this task, the results of this cooperation project are presented here. The paper describes the absolute and relative gravity meters involved in the establishment of the network, the surveys performed, the evaluation and reduction of the data as well as the adjustment method and the quality of the results. The main features of the new National Gravimetric Network of Uruguay may be summarized as follows:

- The absolute gravity datum is now accurate to ± 0.05 μms^{-2}. . . ± 0.10 μms^{-2},

- the network scale is provided with an accuracy of $\pm 3.10^{-5}$, and a calibration line (0.0037 m/s^2) realizes this standard,

- the average accuracy (st.deviation) of the stations is ± 0.3 μms^{-2} and varies between ± 0.1 and ± 0.6 μms^{-2} depending on observations involved,

- the IGSN71 absolute standard in Uruguay is changed by - 0.5 μms^{-2}, while the scale factor changed at the order of 1.10^{-3}, which demonstrates the high quality of IGSN71 but also the improvement by absolute gravimetry. The gravity standard (IGSN71, LAGSN77) of Brazil and Argentina also differs between - 0.5 and -1.0 μms^{-2}.

1. Absolute Gravimetry

1.1 The JILAG-3 absolute gravimeter system

The JILAG-3 absolute gravimeter of IFE (Institut für Erdmessung, University of Hannover, Germany) was employed at the South America Absolute Gravity Program in combination with relative-type LaCoste-Romberg gravimeters. The *JILAG-3 gravimeter is* a transportable free-fall apparatus, developed by Prof. J.E. Faller and coworkers at the Joint Institute for Laboratory Astrophysics (JILA), Boulder, Col., U.S.A. (Faller et al. 1983). It is operated by IFE since 1986, and has since been used for more than 130 absolute gravity determinations worldwide. As the instrument as well as the measurement and evaluation method employed at IFE is well documented (Torge et al. 1987, Torge 1991), we here only summarize the main features.

The instrument (Fig. 1) includes a Michelson interferometer with a frequency stabilized laser for positioning of the dropped object (one corner cube reflector of the interferometer), and an atomic frequency standard for timing. It is operated under high vacuum (10^{-4} Pa), and microseismic noise on the reference reflector is strongly absorbed by a "superspring", with an electronically generated Eigen-period of 30 to 40 sec. 200 evenly distributed time/distance measurements are carried out over the falling distance of 0.25 m, and adjusted on-line to a fitting parabola thus giving one g-value for the reference height (about 0.8 m). Generally, 1500 drops are performed per station, distributed over 1 to 2 days, and the drop number is increased at a higher noise level. From the analysis of the JILAG-3 results obtained during 6 years, the average *precision* (standard deviation of the mean value per station) has been found at the order of 0.01 μms^{-2} at "stable" stations. Long-term *accuracy* includes errors of laser calibration, residual microseismic and floor recoil effects, and "gravitational noise" from not sufficiently modelled effects of earth tides, air pressure changes and (on sediments) soil moisture and ground water variations, and is estimated to ± 0.07 μms^{-2} on the average (Torge 1991).

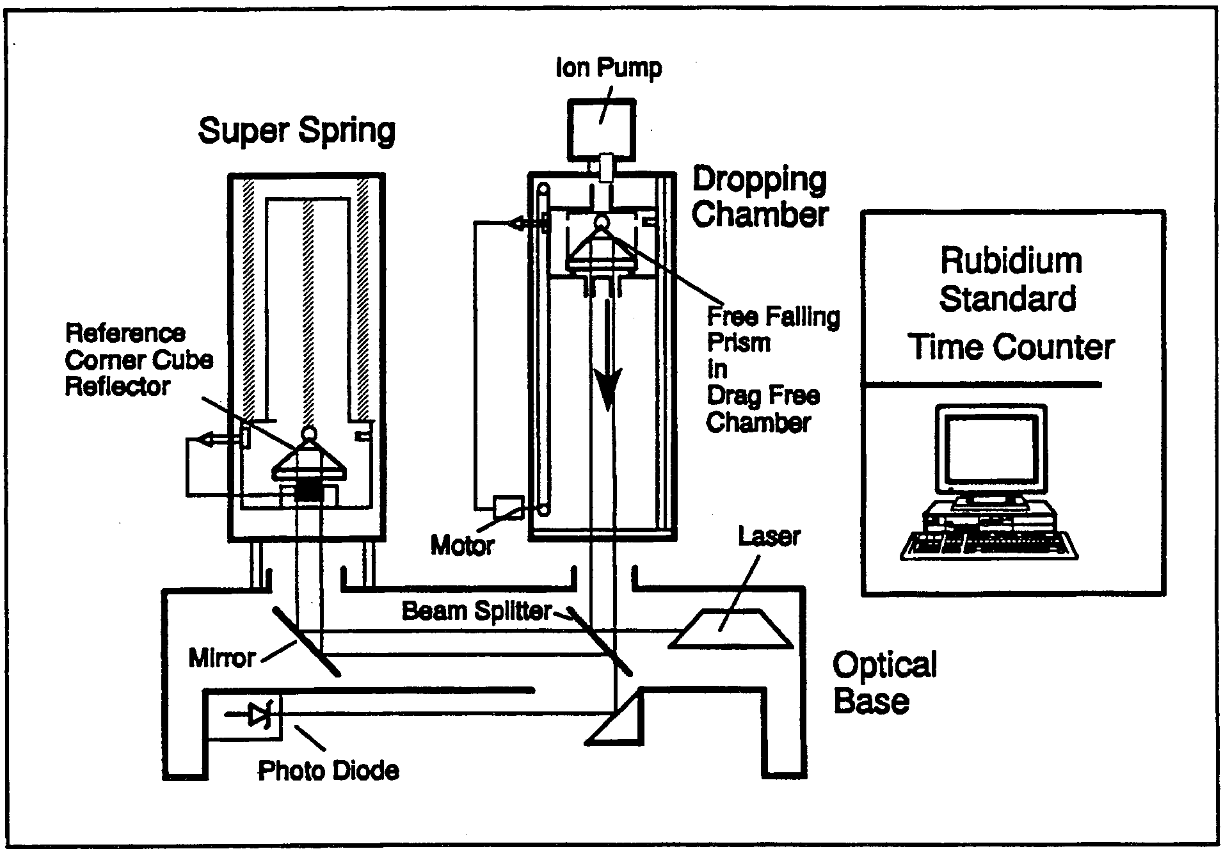

Fig. 1: Schematic of JILAG-3 absolute gravimeter

Relative gravity measurements have to be included into the absolute gravimetry projects, in order to transfer the absolute value from the reference height to a ground marker, to connect the absolute station to existing gravity networks, and to establish local eccenter stations for relative control of the station stability with time. At IFE, two LaCoste-Romberg (LCR) gravimeters are used for the relative ties, both of them equipped with the SRW electronic feedback system (Röder et al. 1988). By repeated measurements (e.g. 10 times for the vertical transfer of gravity) gravity differences < 100 μms^{-2} can be determined then with an accuracy of ± 0.02 to ± 0.03 μms^{-2}.

1.2 Absolute gravity measurements in Uruguay

Through the *IFE Absolute Gravity Program "South America" 1988-1991* (Torge et al. 1994) an absolute gravity control system was established, consisting of 22 absolute gravity stations, and covering large parts of South America. In Uruguay the regional and local selection of the stations was handled by the SGM (Servicio Geografico Militar, Montevideo, Uruguay), following the criteria given by the IFE gravimetry group, and taking local aspects of logistics and microseismic into account. The IFE JILAG-3 absolute gravimeter system has been employed, together with the LCR gravimeters G298 and G709 (IFE), and G013 and G703 (SGM). 1500 to 3000 drops have been performed per station according to local microseismic. The absolute stations Rivera and Toledo were established in March 1989. In December 1991, the station Paysandu was added, and Toledo was reoccupied. The standard deviation for one drop varied between ± 0.5 and ± 1.5 μms^{-2}, the standard deviation of the adjusted gravity values is between ± 0.01 and ± 0.06 μms^{-2}. To improve the absolute gravity datum definition in Uruguay, the station in Toledo was connected to the absolute point in Buenos Aires (occupied by JILAG-3 in 1989, stand.dev. ± 0.04 μms^{-2}, and 1991, ± 0.05 $\mu m/s^2$).

The field work with JILAG-3 and LCR gravimeters was performed by Dipl.-Ing. D. BEENING (IFE, 1989), Cap. J. MELCONIAN (SGM, 1989), Dr.-Ing. R. H. RÖDER (IFE, - 1989/1991), Dipl.-Ing. S. SANDER (IFE, 1991) and Maj. W. SUBIZA (SGM, 1991).

1.3 Data processing

1.3.1 Observation equation

During one free-fall experiment with JILAG-3, 200 time and distance measurements are performed. The equation of motion for a single time/distance data pair is given by

$$z_i = z_0 + v_0\, t_i + \frac{1}{2}(g_0 + z_0\,\gamma)\, t_i^2 + \frac{1}{6} v_0\,\gamma\, t_i^3 + \frac{1}{24} g_0 \gamma\, t_i^4, \qquad i = 1, 2, 3...200. \tag{1.1}$$

z_i is the measurement position at time t_i. The integration constants z_0 and v_0 are the position and the velocity of the falling body at $t = 0$. Introducing the vertical gravity gradient γ, the gravity value g_0 refers to the starting position of the test mass $z = 0$ (point of release). For the gradient γ, the value $\Delta g/\Delta H_{(1m)}$, as defined by relative gravity measurements between the ground marker and the point at 1 m height, is used. By a least squares adjustment of one free-fall experiment, the unknowns g_0, z_0 and v_0 are derived.

1.3.2 Reductions

In order to consider the *finite light travel time* (c = 299792458 ms^{-1}) during the interferometric measurement procedure, the single time observations t_i are corrected by adding the term z_i/c before further data processing. The resulting t_i values are introduced in (1.1). The amount of the correction is in the order of 0.13 μms^{-2}.

For the gravimetric *earth tide* reduction an expanded series development was used, with a tidal amplitude factor of 1.164 and a zero phase shift (till 1989) for the long and short partial tides. For the time-constant M0S0 term the amplitude factor 1.000 and phase lead 0.000° was used according to IAG standards (Rapp 1983). Since 1990, IFE uses the CTE (Cartwright-Tayler-Edden) series development (505 waves) (Cartwright and Tayler 1971, Cartwright and Edden 1973) and the data base of the International Earth Tide Center (Melchior et al. 1984), to apply a refined tidal model with observed parameters. The earth tide parameters used at the evaluation of the 1991 results, are given in Tab. 1.

According to the IAG Resolution No. 9, 1983, the gravity variations due to *air pressure changes* (direct effect of air mass attraction and indirect effect via deformation of the solid earth) are reduced by

$$\Delta g_{air} = 0.30.10^{-2}(p_a - p_n)_{[hPa]}\left[\mu ms^{-2}\right]. \tag{1.2}$$

p_a is the actual air pressure, which is measured by an electronic sensor during the gravity determinations with JILAG-3. p_n is the normal air pressure defined by DIN5450:

$$p_n = 1013.25\left(\frac{1 - 0.0065\, H_{[m]}}{288.15}\right)^{5.2559} [hPa]. \tag{1.3}$$

Tab. 1: Earth tide parameters for Paysandu and Toledo (used at the data processing of the 1991 results)

wave group	wave number from	wave number to	amplitude factor [ ]	phase [ ]
M0S0	1	1	1.000	0.00
Mf	2	128	1.164	0.00
01	129	241	1.182	-0.29
K1	242	333	1.149	-0.04
N2	334	398	1.163	0.26
M2	399	441	1.172	0.59
S2	442	488	1.144	0.08
M3	489	505	1.100	0.00

H is the station evaluation above sea level.
The change of the position of the earth body relative to its spin axis *(polar motion)* causes a gravity change. Referenced to the Conventional International Origin (CIO), the applied gravity reduction is:

$$\Delta g_{pol} = -\delta\,\omega^2\,a\sin(2\varphi)(x\cos\lambda - y\sin\lambda) \qquad (1.4)$$

with the amplitude factor δ = 1.16, the earth angular velocity (reference ellipsoid GRS80) $\omega = 7.292115.10^{-5}$ rad s^{-1}, the semimajor axis (GRS80) a = 6378137 m, the geographical station coordinates (GRS80) φ, λ and the pole coordinates x, y [rad] in the IERS (International Earth Rotation Service) system. The IERS provides daily pole coordinates. The applied reductions for Uruguay varied between 0.01 and 0.10 μms^{-2}.
The measured absolute gravity value has to be transferred from the JILAG-3 reference height (~ 0.8 to ~ 0.9 m) to a ground marker. The reduction to *ground level is* calculated by:

$$\Delta g_{ground} = -\frac{\Delta g}{\Delta H_{1m}} . H_{ref}, \qquad (1.5)$$

with $\Delta g / \Delta H_{(1\,m)}$ as defined by relative gravity measurements, c.f. chapter 1.3.1.
All reduction terms have to be added to the measured g value.

1.3.3 Station gravity results

The adjustment of JILAG-3 measurements according to (1.1) results in a g value for each individual free-fall experiment (drop). The measurement procedure is organized in such a way, that 300 drops (1 run) are automatically performed in about 70 minutes. A run is divided into 10 sets (30 drops, Δt = 12 s) with a break of 1 minute between each set. When one run is finished, the instrument is re-aligned and the adjustment of the electronics is checked. To derive a reliable station gravity result, usually 5 runs (1500 drops) are performed. At stations with high microseismic effects the number of runs is increased up to 3000.
During one run the earth tides change the gravity up to an amount of 0.5 μms^{-2}. Therefore, the earth tide reduction is applied to each drop. The station gravity result is calculated in the following way:

a) after each set:
calculation of the set result (arithmetical mean of the earth tide reduced drop results)

$$g_{set} = \frac{\sum_{i=1}^{nd} g_i}{nd}, \quad nd: drops\ per\ set \quad , \qquad (1.6)$$

with the standard deviation of a single drop and of the set mean

$$s_{drop} = \sqrt{\frac{\sum_{i=1}^{nd}(g_{set} - g_i)^2}{nd-1}}, \quad s_{set} = \frac{s_{drop}}{\sqrt{nd}}; \qquad (1.7)$$

b) after each run :
calculation of the run result

$$g_{run} = \frac{\sum_{j=1}^{ns} g_{set,j}}{ns}, \quad ns: sets\ per\ run \quad , \tag{1.8}$$

with its standard deviation

$$s_{run} = \sqrt{\frac{\sum_{j=1}^{ns}\left(g_{run} - g_{set,j}\right)^2}{ns(ns-1)}} \; ; \tag{1.9}$$

the air pressure and the polar motion reduction values have to be added to the run results ;

c) having finished all measurements on a station:
calculation of the station result (arithmetical mean of the air pressure and polar motion reduced run results)

$$g_{station} = \frac{\sum_{l=1}^{nr} g_{run,l}}{nr}, \quad nr: runs\ per\ station \quad , \tag{1.10}$$

and its standard deviation

$$s_{mean} = \sqrt{\frac{\sum_{l=1}^{nr}\left(g_{station} - g_{run,l}\right)^2}{nr(nr-1)}} \; ; \tag{1.11}$$

After applying the height reduction (1.5) to $g_{station}$ the resulting gravity value at floor level $g_{station,\, h\, =\, 0.000\, m}$ is the reference for subsequent relative gravity measurements (connections to national networks etc...).

2. Relative Gravimetry

2.1 The LaCoste & Romberg relative gravimeter system

The LaCoste & Romberg relative gravity meter is based on the concept of the "zero length spring" suspension of a mass, developed by Lucien LaCoste in 1932. After some improvements, the G model (standing for "Geodetic") was built in 1959, with a worldwide range of 0.07 ms^{-2} (Torge 1989). The screw and system levers are calibrated by the manufacturer, who delivers a third order calibration function for the readings. In order to adjust these relative values to absolute ones, a scale factor for each gravimeter must be obtained. This is carried out by measuring over a set of stations with known gravity values (calibration lines, absolute measurements, global or regional gravity adjustments). A final difference gravity value is reached when the relative value from the readings is multiplied by this scale factor.

The final accuracy is between ± 0.1 to ± 0.5 μms^{-2} taking into account careful field survey methods in order to eliminate additional error sources. The zero reading position has also some temporal variations due to zero drift and transportation drift. The zero drift is caused by the aging of the spring and is about less than 5 to 10 μms^{-2} per month (LCR 1992). Another important source of errors arises from the transport conditions of the meter. An easy and stable way of transportation will avoid shocks and vibrations that could affect the measuring system and cause tares.

Based on similar concepts is the Worden Gravimeter, from Texas Instruments, USA. The main difference to the LCR gravimeter is the quartz system used here, with larger drift behaviour. This kind of gravimeter was used also in the first attempts to establish a gravimetric datum for Uruguay.

2.2 Relative gravity measurements in Uruguay

2.2.1 Early gravity determinations

The first gravimetric determination well documented, was performed in February 18, 1932 by Prof. Vening Meinesz. He used a three-pendulum apparatus with photographic recording developed by himself on board of a Dutch submarine, and obtained at the bottom of the Montevideo Bay a gravity value of 9.79760 ms^{-2}. In the 1950s, Prof. N.C. Harding from Wisconsin University, USA established a gravity station in the Carrasco Airport (Areopuerto de Carrasco) near Montevideo city, within the frame of a regional geological study, with a station value 9.797467 ms^{-2}.

A 600 km submarine profile was set up between July 31 and August 4, 1962 with the "North American UW-2R" gravimeter, operated from an Argentinian navy ship by the Facultad de Ingenieria, University of Buenos Aires, Argentina. During this survey, Buenos Aires harbour, Cabo San Antonio/Argentina and Montevideo harbour/Uruguay were connected, thus establishing another gravity station in Uruguay.

2.2.2 Gravity datum

In order to establish a gravity datum for Uruguay, both Buenos Aires and Montevideo Universities carried out a gravimetric connection between the airports Ezeiza/Buenos Aires and Carrasco/Montevideo. Three Worden gravimeters (No. 51, 488 and 497) were used on two days delivering three ties per day. Additional ties were set up between airports and harbours on each side, thus allowing a loop closure, and including the above mentioned submarine profile. The loop misclosure was 1.7 μms^{-2} and the gravity value for the fundamental station in Uruguay was transferred from the Argentinian fundamental station as follows:

Estacion Aeropuerto Carrasco (Subsuelo):
Latitude South: - 34°50'18", Longitude West: - 56°01'18", Altitude (MSL): 12.13 m.
Gravity value: 979 7474.7 μms^{-2}.

In 1967, the SGM of Uruguay, in charge of the determination of the gravity field in the country, started a national gravity survey in order to cover the entire country with gravity stations. The survey program included a new tie to the Miguelete absolute station in Buenos Aires, the division of the country into 25 polygons following the First Order Levelling Net (Fundamental Gravimetric Network) and a further densification within the polygons, in order to finally reach an average station distance less than 10 km.

The LCR gravimeter No. G061 was lent by the InterAmerican Geodetic Service (IAGS), and several preparatory steps were taken. This included the determination of the scale factor for LCR-G061, by observation of 6 Argentinian gravity stations including Miguelete, and connecting also Ezeiza station. Two gravimetric ties were performed between Buenos Aires harbour and Colonia station in Uruguay by ship (45 minutes transportation time), employing LCR-G061 and the thermostatised Worden gravity meter no. 488. Colonia then was connected with Aeropuerto Carrasco by LCR-G061 following a first order levelling line along the national route No.1. A step method was employed, establishing a station every 5 km, and taking three readings (one minute time each) per station with a maximum difference of 3 units being allowed. After applying the scale factor, and the earth tide reduction the combination of these measurements gave a loop misclosure of 2 μms^{-2}, and it was decided to keep the previous gravity value adopted for the fundamental station at Aeropuerto Carrasco.

2.2.3 The Fundamental Gravimetric Network

The Fundamental Gravimetric Network was established between June, 1967 and May, 1968. The network consists of 45 lines arranged in 25 polygons with 35 nodal points (intersection of two or more lines) or terminal stations. The station distance along the lines is between 3 and 5 km. The profile method was employed to measure the lines, and a maximum discrepancy of 0.5 μms^{-2} was accepted at the re-occupation of the stations. Altogether 924 stations were observed, along 4,590 line km, the travelled distances being about 15,000 km. In addition 12 nodal points were connected by air ties for control of the gravity difference (Fig. 2).

Data evaluation included the calculation of the raw station gravity values, the adjustment of the lines, and a least squares method adjustment of the network, giving the final gravity value for each station. Free Air and Bouguer anomalies were calculated, using the 1930 international normal gravity formula. A publication describing the Fundamental Gravimetric Network results (stations, grid references, gravity values and anomalies) and a 1/1,000,000 scale map of the anomalies (50 μms^{-2} contour interval) was issued in 1973, for public information (SGM 1970).

2.2.4 Network densification

In 1984, the gravity field operations were taken up again. The LCR gravimeter G013 was lent by the IAGS, and a new value (g= 9.7973255 ms^{-2}) was adopted for the gravity datum station Carrasco, taking

into account the bias of about 150 μms^{-2} of the Potsdam Gravity System. The scale factor was determined on 7 stations located in south-north direction, using the previously calculated gravity differences. In addition a new computer program for Longman's earth tide reduction was introduced.
About 1,300 new gravity stations were planned in order to densify the 25 polygons of the Fundamental Net. They were measured by the profile method with at least a 30% of the stations reoccupied. The reading procedure remained the same as in the Fundamental Network. The station distances vary between 3 and 8 km. As far as possible the stations were related to the levelling net. For positioning and heighting of the stations not related to the levelling net, a special survey team was set up. Maps of scale 1/50,000 and aerial photos scale 1/10,000 and 1 /20,000 were used to give plane coordinate, but in most cases a vertical profile had to be measured in order to get the station altitude. In 1986 LCR gravimeter G703 was added to the survey, which allowed to finish the densification in January 1988. It should be mentioned that strong efforts were made to also cover difficult regions (hardly accessible and flooded areas). The statistics of the densification survey reads as follows:

- 1328 new stations established,
- 308 days of field surveys,
- 4.3 stations surveyed per day,
- 8 . . 9 km average station distance.

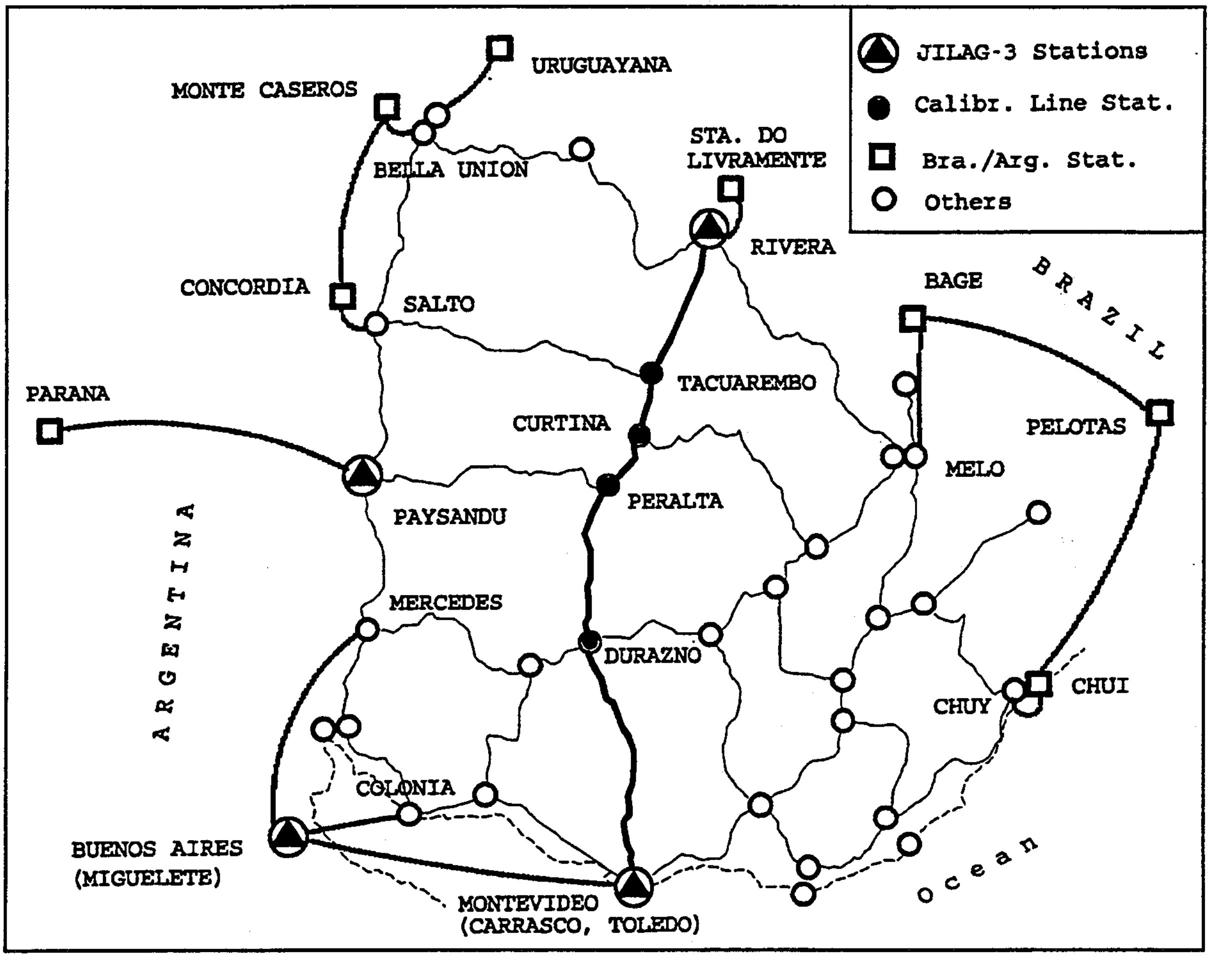

Fig. 2: Main gravity ties (along traffic connections) in the Uruguayan national network with links to Argentina and Brazil

Data processing was based on a set of PC programs (GravSys) from the Ottawa Gravity Data Center, Canada. The calculation delivered the gravity values and the reductions as well as Free Air and Bouguer anomalies, using now the 1980 normal gravity formula (GRS80). A National Gravimetric Data Centre was established, which now contains all the information about the gravity net: description, station number, altitude, gravity value, anomalies and short station descriptions. This information is available for scientific or technical research programs, and for public demands.

2.2.5 International relative gravimetric ties 1987/1989.

Following agreements between SGM, National Observatory (ON), Rio de Janeiro, and Sao Paulo University (USP), Brazil, Instituto Geográfico Militar (IGM) and Rosario University (RU), Argentina, several international relative gravimetric ties were carried out between July and October, 1987. The objective of these ties was to connect the gravity nets of Argentina and Brazil with Uruguay, and thus control the gravity datum of Uruguay which was derived only from the observations in 1962 and 1967 (see 2.2.2), and to derive an approximate shift for transforming from the Potsdam Gravity System to IGSN71.

Five stations of the Brazilian Fundamental Gravity Net (Uruguayana, Santana Do Livramento, Bagé, Pelotas = IGSN71 Nr. 43812B and Chui) were connected with the Aeropuerto de Carrasco along four profiles, each of them including two or three nodals stations of the Uruguay Net (see Fig. 2). Five LCR gravimeters were used (G602 and G622/ON, G454/USP, G013 and G703/SGM). The survey was carried out by four observers who travelled by car more than 4,600 km within 172 hours.

To Argentina, a short tie was established between Monte Caseros Airfield station and Nodal Bella Union in Uruguay. Three LCR gravimeters were employed for six connections: G679/IGM and RU, G013 and G703/SGM. The bad road conditions between Monte Caseros and Monte Caseros Airfield caused tares in G679, so that some of the readings had to be eliminated. The calculation of these ties showed a difference of -1 μms^{-2} to Argentina, which not appeared between the connection to Brazil.

In 1989 four relative ties were agreed upon IGM and the Tucuman University (TU), Argentina, taking advantage of the new Paysandu absolute station (see 1.2). Four LCR gravimeters (G013 and G703/SGM, G679/IGM and G945/TU) were used for the lines Nodal Mercedes —Miguelete (IFE-No. 313), Paysandu (IFE-No.232) —Parana, Nodal Salto— Concordia, Nodal Salto - Monte Caseros (Fig. 2). A further tie between Paysandu (IFE-No.232) and Toledo (IFE-No.222) was made with the SGM's gravimeters. As the scale factors for G679 and G945 were not known, the results of those gravimeters were not included into the evaluation, and the ties remained with the two SGM's gravimeters.

2.3 Data processing

With the new absolute and relative gravity data available until 1993, and taking the high quality and homogeneity of the national network and its densification into account, an integration through a common adjustment was felt to be necessary. Through an agreement between IFE and SGM, this adjustment was performed in May, 1995, with participation of experts from both sides. In Fig. 3 all gravity stations participating in the adjustment are plotted. The gravity profiles along the main road connections become visible. The connection stations in Brazil and Argentina may also be identified.

The software package GRAV (version 1.5, author: Prof. Dr.-Ing. H.-G. Wenzel, University of Karlsruhe, Germany) was used to process all related gravity measurements. This system contains FORTRAN77 coded programs and is executed in two subsequent steps. First, a preprocessing is performed to obtain apriori calibrated readings with applied earth tides, air pressure (optional) and instrumental height (optional) reductions. In a second step, the whole gravity network is processed using least squares adjustment. A combination of absolute and relative measurements is possible.

GRAV is available for MS-DOS and UNIX computers. There is no limitation for the number of relative observations. The restrictions for the number of stations, gravity meters and absolute gravity measurements depend only on the computer memory (RAM).

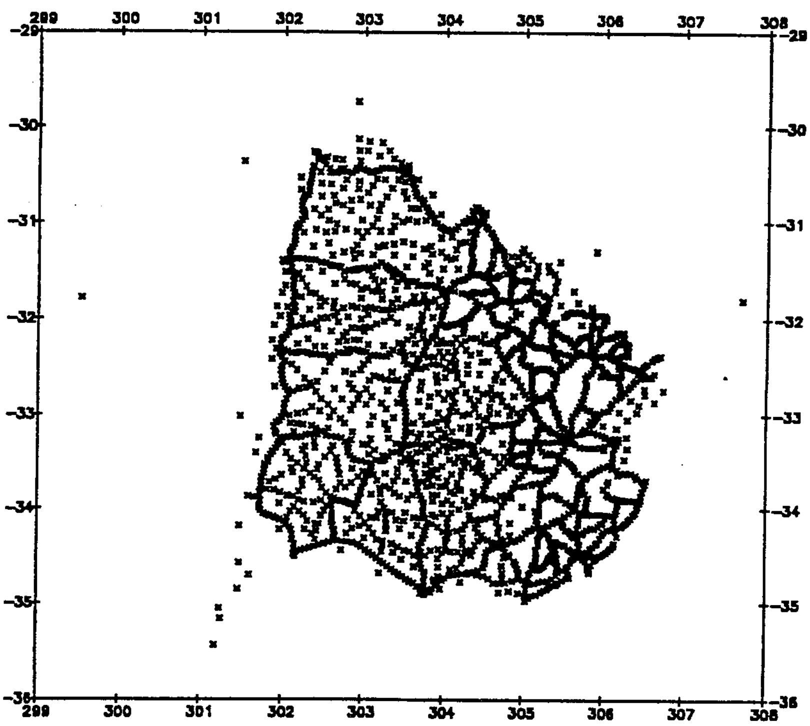

Fig. 3: Gravity stations of the Uruguayan National Gravimetric Network with tied station in Brazil and Argentina

2.3.1 Precalibration and reductions

The original gravity measurements from LaCoste&Romberg gravimeters are readings in Counter Units (1 CU ≈ 10 μms^{-2} for model G gravimeters). The manufacturer provides an individual calibration table for every LCR (model G) instrument. The apriori calibrated observation is obtained by:

$$z' = F(z), \text{ with } F(z)\text{: manufacturer's calibration function} . \tag{2.1}$$

In general, the calibration has an accuracy of better than 1.10^{-3} in scale. z' is a function of time t, because temporal gravity variation due to earth tides, air pressure and groundwater level changes affect the measurement. In the national network of Uruguay, only earth tide reductions (corresponding to 1.3.2) have been applied. For all LCR gravimeter setups, a constant instrumental height and a constant vertical gravity gradient is assumed. The uncertainties due to this neglects may cause errors of up to 0.1 μms^{-2} in some cases which cannot be avoided.

2.3.2 Observation equations

For precise field measurements, an improved calibration function has to be determined by the user. The adjustment of the lever system for different readings is modelled by a low degree polynomial, while periodic errors due to measuring screw errors and gear eccentricities cannot be determined from the network adjustment. As a calibration line for periodical error determination is not available in South America, uncertainties of more than 0.1 μms^{-2} in the gravity results are possible, in particular if a point is occupied only by one gravimeter (no error minimizing by averaging).
The observation equation for an individual measurement is given by:

$$l = g - N_0 - Y . z' . \tag{2.2}$$

The observable l corresponds to the precalibrated measurement z'. g (point gravity value), N_0 (instrumental level, varying with time) and Y (user defined calibration factor) are the unknown parameters to be determined. In Uruguay, the maximum gravity difference is ~ 5000 μms^{-2}. Therefore, a single factor Y is sufficient for the user calibration function.
To minimize the number of unknown parameter in the adjustment model, the difference of measurements at two adjacent stations i and j is introduced as "quasi" observation:

$$\Delta l_{ij} = l_j - l_i = g_j - g_i - Y.\left(z_j' - z_i'\right) \quad . \tag{2.3}$$

Drift behaviour (time dependent change of N_0) of a gravimeter may be modelled as $N_0 = N_0(t)$ over continuous measurement epochs (one day), if the necessary redundant observations have been performed. For the network of Uruguay, drift modelling yielded no reliable results, consequently it was not considered in the observation equation of the final adjustment. For absolute observations the observation equation in the network adjustment is simply

$$L_{station} = g_{Station,\ h\ =\ 0.000\ m} \cdot \tag{2.4}$$

2.3.3 Network adjustment

The fundamental network of Uruguay (observed between 1967 and 1993) was evaluated by a common adjustment of all available relative and absolute gravity measurements. Altogether, 5447 relative gravity measurements were introduced. Four absolute gravity stations (Toledo, Rivera, Paysandu, Bueno Aires) served for level and scale definition (see 1.2). Tab. 2 summarizes the adjustment details. The total gravity range is 4914 μms^{-2}, which is well covered by the absolute stations. For every relative gravimeter a linear calibration factor was adjusted to improve the manufacturer calibration table.

In the stochastic model, the absolute values were introduced with a standard deviation of 0.08 μms^{-2} (empirical estimate), whereas 0.50 μms^{-2} was assumed for the relative observations (gravity differences) during the first evaluation step. Gravity differences, having one common reading $\left(\Delta l_{ij} \text{ and } \Delta l_{jk}\right)$ are mathematically correlated by -0.5. This can be taken into account in the stochastic adjustment model. In addition, a physical correlation is existing but normally not known. Numerous network adjustments performed at IFE showed that neglecting these correlations does not significantly change the adjusted gravity values. For the Uruguay network, no correlations were introduced between relative as well as between absolute measurements.

Tab. 2: Adjustment details of the National Gravimetric Network of Uruguay

no. of. . .	
absolute gravity stations	4
relative gravity points	2376
absolute gravimeters	1
relative gravimeters	8
observed gravity differences	5447
adjustment unknowns	2384

After the first adjustment step, an aposteriori standard deviation was calculated for each LCR gravimeter. This value usually differs from the apriori accuracy estimate. To achieve a proper weighting between readings of different gravimeters, an iteration followed. It stopped when the apriori and aposteriori estimates agreed within 5 nms^{-2}. The weighting of the absolute observations was not changed during the iterations.

During the iteration process, several errors could be identified. They were mostly due to wrong digitizing of the original measurement files (typing errors). After comparison with the analogue files from the field work, nearly all larger discrepancies (several 0.1 μms^{-2}) could be removed. Finally, 15 connections (gross errors) were rejected, which is only 0.3 % of the total data base, cf. Tab. 3.

Tab. 3: Number of used and of rejected gravity differences in the adjustment of the fundamental network of Uruguay

LCR gravimeter	no. of observations used	relative no.	rejected observations	relative no.
G013	2152	39.5%	7	0.3%
G061	2314	42.5%	4	0.2%
G703	881	16.2%	2	0.2%
G945	6	0.1%	/	/
G622	32	0.6%	I	/
G602	32	0.6%	/	/
G454	18	0.3%	/	/
G679	12	0.2%	2	14.3%
total	5447	100.0%	15	0.3%

3. Results

3.1 Absolute gravity measurements

In Tab. 4, the results of the absolute gravity determinations in Uruguay are compiled. In addition, the Buenos Aires gravity value is given. There is an excellent agreement between the two determinations in Toledo, the discrepancy being only 0.01 µms^{-2}. In Buenos Aires two adjacent absolute sites have been occupied in 1989 and 1991 (site change in 1991 because of ground water problems, distance ~ 200 m). A connection by relative gravimetry gave an agreement of 0.04 µms^{-2}. In Montevideo, a tie to LAGSN77 point (Latin American Gravity Standardization Network 1977, McConnell et al. 1979), which is based on IGSN71, gave a discrepancy of -0.5 µms^{-2} (JILAG-3-LAGSN77), cf. Tab. 5. Finally a relative tie to an IGSN71 station in Buenos Aires was performed, resulting in a difference (JILAG3—IGSN71) of + 0.4 µms^{-2}. These comparisons show the improvement of the absolute gravity level by employing a state-of-the-art absolute gravimeter. Other connections between JILAG-3 and existing national networks in South America (see Torge et al. 1994) also indicate, that the absolute level of IGSN71 based networks is correct within a few 0.1 µms^{-2}, with eventually a local bias of up to 0.4 to 0.5 µms^{-2}. Scale errors of some 10^{-4} may occur in the existing networks, while the relative accuracy is ± a few 0.1 µms^{-2}.

In Fig. 4, scatter diagrams and histograms of the four absolute gravity determinations in Uruguay are presented. The plots for Toledo 1989 and 1991 are especially interesting. Although there was no obvious change in the station conditions (e.g. stability), the scatter of the 1991 measurements is about 3 times higher than the 1989 scatter. In addition the weak periodical behaviour in the drop sequences of the two 1989 occupations is no more visible in the 1991 observations. This may be caused by instrumental changes of JILAG-3. For additional control, the JILAG-3 reference station Clausthal in Germany has been occupied before and after the gravity campaigns. From these comparisons which are performed since 1987 no instrumental changes could be detected.

In Annex 1, the results of the absolute gravity measurements are given in more detail, for details of the calculation we refer to chapter 1.3.3. It should be mentioned, that the standard deviation s_{mean} of the Toledo 1991 result (s_{mean} = 0.028 µms^{-2}) is less than of the Toledo 1989 result (s_{mean} = 0.042 µms^{-2}). From the time sequences (Fig. 4) and the s_{drop} values in annex 1, a better result should have been expected for the 1989 determination. This indicates the influences of systematic errors in the 1989 results, which have not been completely reduced by averaging over 300 drops.

Tab. 4: JILAG-3 absolute gravity results in Uruguay and Buenos Aires 1989/91

station	IFE-No	epoch	ϕ [deg]	λ [deg]	H [m]	dg/dH [μms^{-2}/m]	g_{floor} [μms^{-2}]
Rivera	212	3/89	-30.90	304.46	213	-3.08	9793443.77
Toledo	222	3/89	-34.74	303.91	65	-3.07	9797158.55
Toledo	222	12/91	-34.74	303.91	65	-3.07	9797158.56
Paysandu	232	12/91	-32.38	301.97	61	-3.04	9795235.26
Buenos Aires	313	11/91	-34.57	301.48	13	-2.48	9796891.41

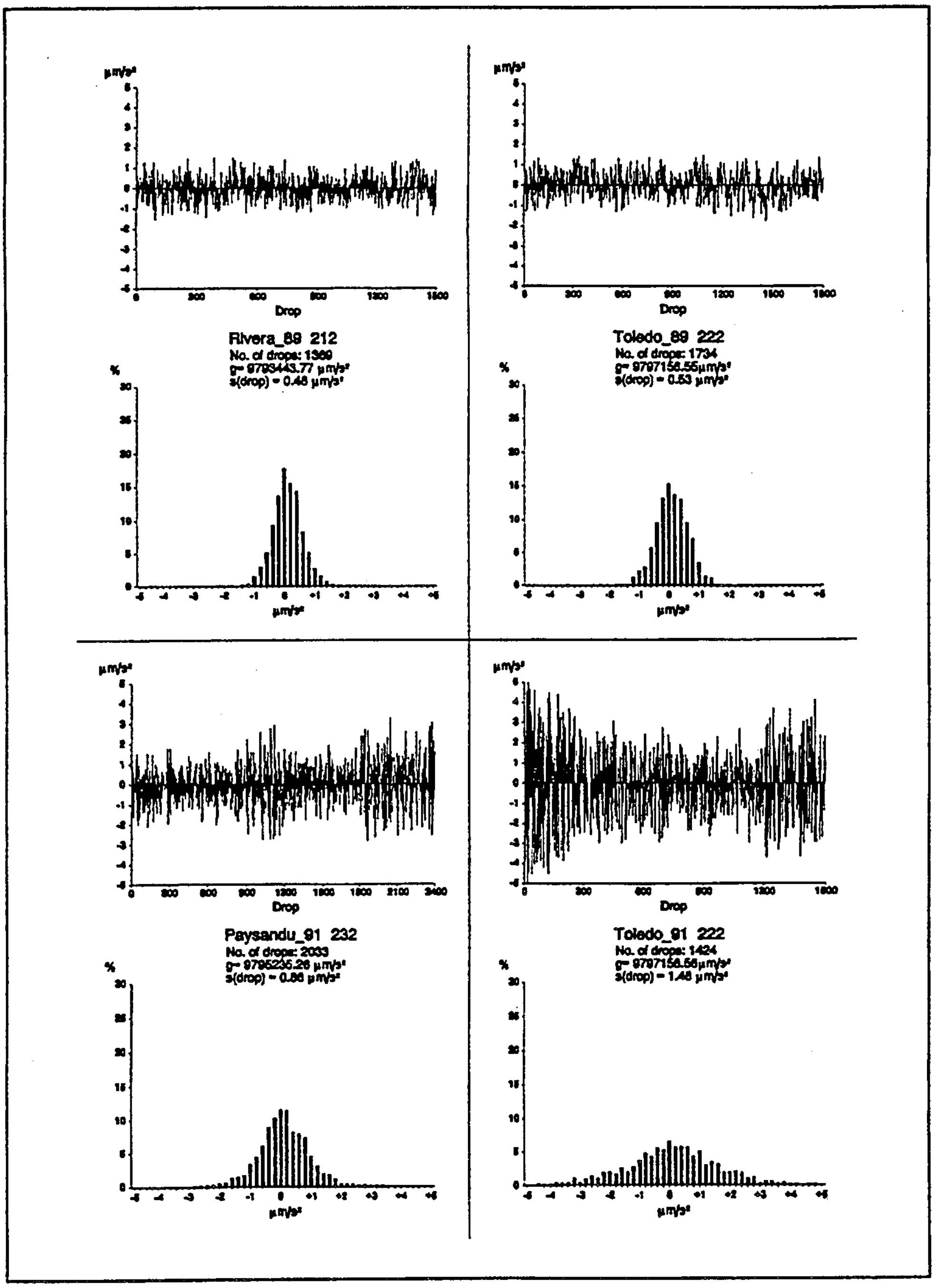

Fig. 4: Time sequences and histograms of JILAG-3 absolute gravity measurements on stations in Uruguay

Tab. 5: Comparison between JILAG-3 and previous datum definitions

station	IFE-no	$g_{IFE(89/91)}$ [µs-2]	$g_{LAGSN77}$ [µs-2]	g_{IGSN71} [µs-2]	$\Delta g_{IFE\text{-}net}$ [µs-2]
Montevideo (ecc.)	223	9797324.14	...4.6	/	-0.5
Buenos Aires*)	311	9796900.71	/	...0.3	0.4

*) gravity datum station IGSN71 "Buenos Aires A" in Migueletes

3.2 The National Gravimetric Network

The final gravity network adjustment was performed by introducing 4 stations with absolute gravity observations following the procedure explained in chapter 2.3.3, cf. Tab. 4 (apriori: $S_{JILAG\text{-}3}$ = 0.08 µms^{-2}, $s_{rel.\ grav.}$ = 0.50 µms^{-2}). For the Toledo station, the 1989 and 1991 measurements were averaged. The mean standard deviation of the adjusted 2376 gravity stations is 0.26 µms^{-2}, the maximum and minimum values are 0.56 µms^{-2} and 0.06 µms^{-2}. Tab. 6 gives the accuracy estimates for one gravity difference measurement with respect to each individual LCR gravimeter and the adjusted linear calibration factors. The uncertainty of the G679 calibration can be explained by the fact that the factor is derived from only 12 observations, performed between 2 points with only 7 µms^{-2} difference. The LCR-G945 has been used only at 6 connections. Consequently a reliable accuracy estimate cannot be derived, and the apriori standard deviation was fixed to 0.50 µms^{-2}. As the network is mainly determined by the LCR G013, G061 and G703 observations, the corresponding standard deviations of about 0.2 µms^{-2} verify the good measurement performance over 26 years (1967 - 1993). The accuracy also did not change with time.
The residuals of the absolute gravity observations are given in Tab. 7. It is not possible to control these measurements by the relative ties because the LCR gravimeters were not constrained by an apriori defined calibration. In addition, the relative connection to Buenos Aires is rather weak.

Tab. 6: Standard deviations of the individual LCR gravimeters (for one gravity difference measurement) and the adjusted calibration factors

LCR gravimeter	standard deviation of one gravity difference [µms^{-2}]	adjusted calibration factor
G013	±0.24	0.99871 ± 0.00004
G061	±0.25	1.00033 ± 0.00007
G703	±0.17	1.00049 ± 0.00004
G945	±0.50	1.00081 ± 0.00016
G622	±0.38	1.00043 ± 0.00008
G602	±0.36	1.00029 ± 0.00007
G454	±0.28	1.00023 ± 0.00007
G679	±0.42	1.00934 ± 0.01803

Tab. 7: Network adjustment results for the absolute gravity stations and the number of relative connections to other stations

station	IFE-no	adjustment residual [µms-2]	adjusted absolute gravity measurement [µms-2]	no. of relative gravity ties
Rivera	212	-0.02	9793443.75 ± 0.08	22
Toledo	222	-0.01	9797158.55 ± 0.07	18
Paysandu	232	+0.05	9795235.31 ± 0.06	12
Buenos Aires	313	-0.03	9796891.38 ± 0.07	2

3.3 Connections to neighbouring countries

The network of Uruguay is connected to 5 stations in Brazil and 2 in Argentina. In addition, by including the IFE absolute station no. 313 (Buenos Aires) into the adjustment, a direct comparison of the absolute gravity level of Argentina and Uruguay was possible. Table 8 shows the differences of the gravity values between the Uruguayan Gravity Network and the networks of Brazil and Argentina. The Brazilian Fundamental Gravimetric Network is based on a 1986 adjustment over 15 IGSN71 gravity stations, and the Argentina Network is adjusted on LAGSN77. We find a difference of about -1 μms^{-2} with Brazil, and different behaviour at the Argentine stations. This agrees with the statements made in (3.1).

Tab. 8: Comparison of the gravity datum with neighbouring countries

Adjusted gravity differences (Uruguay minus Brazil resp. Argentina)				
station name	ϕ [deg]	λ [deg]	H [m]	diff.. [μms^{-2}]
Uruguaiana, Brazil	- 29.74	302.91	60.34	- 1.2
Livramento, Brazil	- 30.90	304.50	183.58	- 0.7
Bagé, Brazil	- 31.30	305.90	202.63	- 0.9
Pelotas, Brazil	- 31.80	307.70	10.99	- 0.5
Chui, Brazil	- 33.70	306.50	13.39	- 0.8
Monte Caseros, Argentina	- 30.26	302.37	52.97	-0.5
Parana, Argentina	- 31.78	299.53	59.98	+0.3

3.4 The Uruguay Gravimeter Calibration Line

Through the new adjustment of the National Gravimetric Network of Uruguay, a precise calibration line for relative gravimeters also could be provided. This line (as part of the network) extends in north-south direction. It contains 7 stations and covers a gravity range of 3571 μms^{-2} which is the difference between the absolute stations Toledo and Rivera. The intermediate stations of the calibration line are located inside/outside of churches and are of easy access. The gravity values of the calibration line stations are listed in Tab. 9. The standard deviations depend on the accuracy of the absolute measurements (introduced as +0.08 μms^{-2}), and on the location of the stations in the gravity network.
Tab. 10 gives the accuracy of the gravity differences between the calibration stations. They are derived from the cofactor matrix of the network adjustment, and consider the correlation between the two corresponding stations. Using this calibration line, the scale factor of relative gravimeters (e.g. LCR meters) now can be determined with a relative accuracy of some parts of 10^{-5}.

Tab. 9: The relative gravimeter calibration line in Uruguay (3751 μms^{-2} range)

station	S GM-no.	gravity	ties
Rivera Abs. (IFE-212)	0004	9793443.75 ± 0.08	22
Nodal Emp. R5-R27	0019	9793407.92 ± 0.11	46
Nodal Tacuarembo	0038	9794219.66 ± 0.07	90
Nodal Curtina	0015	9794625.98 ± 0.11	17
Nodal Peralta	0027	9795051.66 ± 0.11	20
Nodal Durazno	0017	9795969.03 ± 0.06	87
Toledo Abs. (IFE-222)	0003	9797158.55 ± 0.07	18

Tab. 10: Standard deviations of the gravity differences between calibration line stations in [μms^{-2}]

point-no. (SGM)	0004	0019	0038	0015	0027	0017	0003
0004	/	±0.08	±0.05	±0.11	±0.11	±0.09	±0.11
0019	±0.08	/	±0.07	±0.12	±0.13	±0.11	±0.14
0038	±0.05	±0.07	/	±0.10	±0.10	±0.07	±0.10
0015	±0.11	±0.12	±0.10	/	±0.12	±0.11	±0.13
0027	±0.11	±0.13	±0.10	±0.12	/	±0.10	±0.12
0017	±0.09	±0.11	±0.07	±0.11	±0.10	/	±0.06
0003	±0.11	±0.14	±0.10	±0.13	±0.12	±0.06	/

4. Conclusion

Due to the JILAG-3 absolute measurements, the National Gravity Network of Uruguay now also refers to the IAGBN (International Absolute Gravity Basestation Network, Boedecker and Fritzer 1986), and thus contributes to the establishment of a homogeneous gravity standard in South America, within an accuracy of ±0.1 μms^{-2} or better. This corresponds to the accuracy of other recent gravity networks worldwide.

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Station results of absolute gravity measurements 1988 to 1991 for the National Gravimetric Network of Uruguay

Rivera (IFE-No. 212)

Run	Date	Drops	$g_{h=0.805}$ [μms^{-2}]	s_{drop} [μms^{-2}]	g_{floor} [μms^{-2}]
1	890318	266	9793441.27	0.52	9793443.75
2	890319	276	9793441.26	0.52	9793443.74
3	890319	273	9793441.32	0.47	9793443.80
4	890319	280	9793441.32	0.40	9793443.80
5	890319	275	9793441.26	0.50	9793443.74
		1370	9793441.29 dg/dh = -3.08 μms^{-2}/m		9793443.77 s = ± 0.031 s_{mean} = ± 0.014

Toledo (IFE-No. 222)

Run	Date	Drops	$g_{h=0.812}$	S_{drop}	g_{floor}
1	890323	289	9797156.11	0.47	9797158.60
2	890323	289	9797156.17	0.53	9797158.66
3	890324	289	9797156.13	0.47	9797158.62
4	890324	288	9797156.08	0.50	9797158.57
5	890324	290	9797155.92	0.62	9797158.41
6	890324	289	9797155.94	0.50	9797158.43
		1734	9797156.06 dg/dh= -3.07 μms^{-2}/m		9797158.55 s = ± 0.104 s_{mean} = ± 0.042

Toledo (IFE-No. 222)

Run	Date	Drops	$g_{h=0.916}$ [μms^{-2}]	S_{drop} [μms^{-2}]	g_{floor} [μms^{-2}]
1	911217	294	9797155.79	2.43	9797158.60
2	911217	276	9797155.67	1.38	9797158.48
3	911217	291	9797155.83	1.07	9797158.64
4	911217	296	9797155.72	0.86	9797158.53
5	911217	267	9797155.76	1.68	9797158.57
		1424	9797155.75 dg/dh= -3.07 μms^{-2}/m		9797158.56 s= ± 0.062 s_{mean} = ± 0.028

Paysandu (IFE-No. 232)

Run	Date	Drops	$g_{h=0.916}$ [μms^{-2}]	S_{drop} [μms^{-2}]	g_{floor} [μms^{-2}]
1	911213	110	9795232.66	0.74	9795235.44
2	911213	135	9795232.05	0.65	9795234.83
3	911213	192	9795232.34	0.77	9795235.12
4	911214	203	9795232.49	0.61	9795235.27
5	911214	189	9795232.47	0.81	9795235.25
6	911214	224	9795232.46	1.33	9795235.24
7	911214	251	9795232.54	0.75	9795235.32
8	911214	239	9795232.60	0.65	9795235.38
9	911214	236	9795232.68	1.25	9795235.46
10	911214	254	9795232.60	1.06	9795235.38
		2033	9795232.48 dg/dh= -3.04 μm^{-2}/m		9795235.26 s= ± 0.185 s_{mean} = ± 0.059