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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.

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BUREAU GRAVIMÉTRIQUE INTERNATIONAL

Toulouse

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INTERNAL MATTERS

GENERAL INFORMATION

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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 (82 have been issued as of June 30, 1998 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 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 = topographical map 2 = trigonometric positioning 3 = satellite	(2 char.)
	30	Type of observation 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	(1 char.)
	31-38	Elevation of the station (unit : centimeter)	(8 char.)
	39-40	Elevation type 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)	(2 char.)
	41-42	Accuracy of elevation 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	(2 char.)
	43-44	Determination of the elevation 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	(2 char.)
	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)	(6 char.)
	Simple Bouguer anomaly with a mean density of 2.67. No terrain correction	
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)	(6 char.)
	computed according to the next mentioned radius & density	
86-87	Information about terrain correction	(2 char.)
	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	
88-91	Density used for terrain correction	(4 char.)
92-93	Accuracy of gravity	(2 char.)
	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	
94-99	Correction of observed gravity (unit : microgal)	(6 char.)
100-105	**Reference station**	(6 char.)
	This station is the base station (BGI number) to which the concerned station is referred	
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.)
	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	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 :

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

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).*

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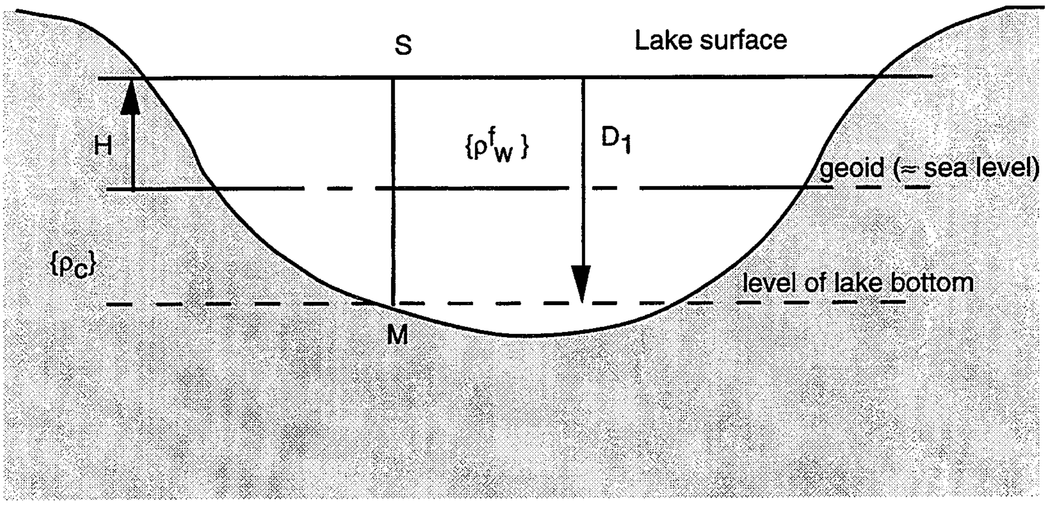
* cf. "On the definition and numerical computation of free air gravity anomalies", by H.G. Wenzel. Bulletin d'Information, BGI, n° 64, pp. 23-40, June 1989.

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



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

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

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

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

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/($\Delta\Delta'$) per degree square

. minimum charge : 150 F

. maximum area : 40° x 40°

3.1.5. Contour Maps of Bouguer or Free-Air Anomalies

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

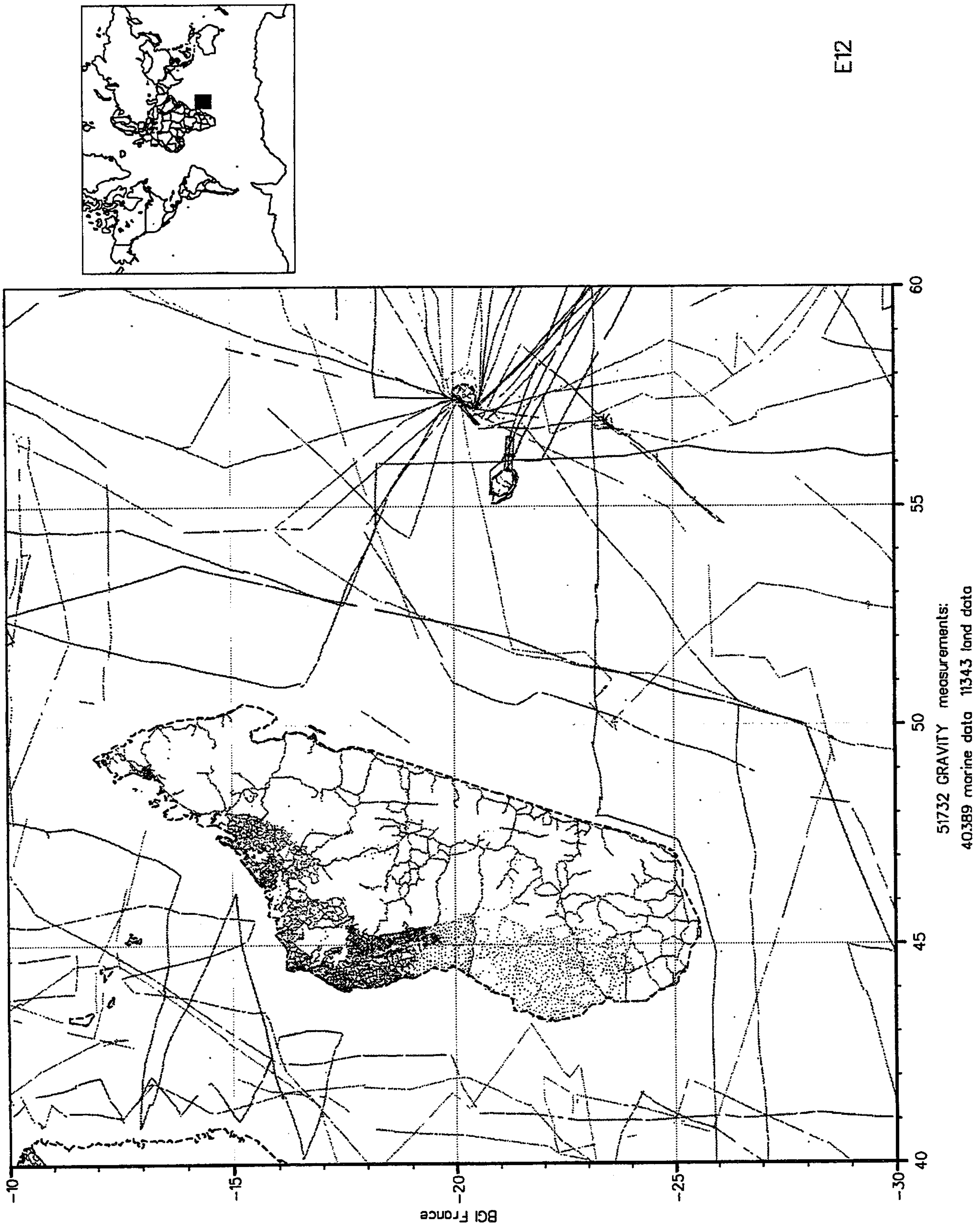
(Vol. 1 and 2)	*1979*	*150 FF*

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

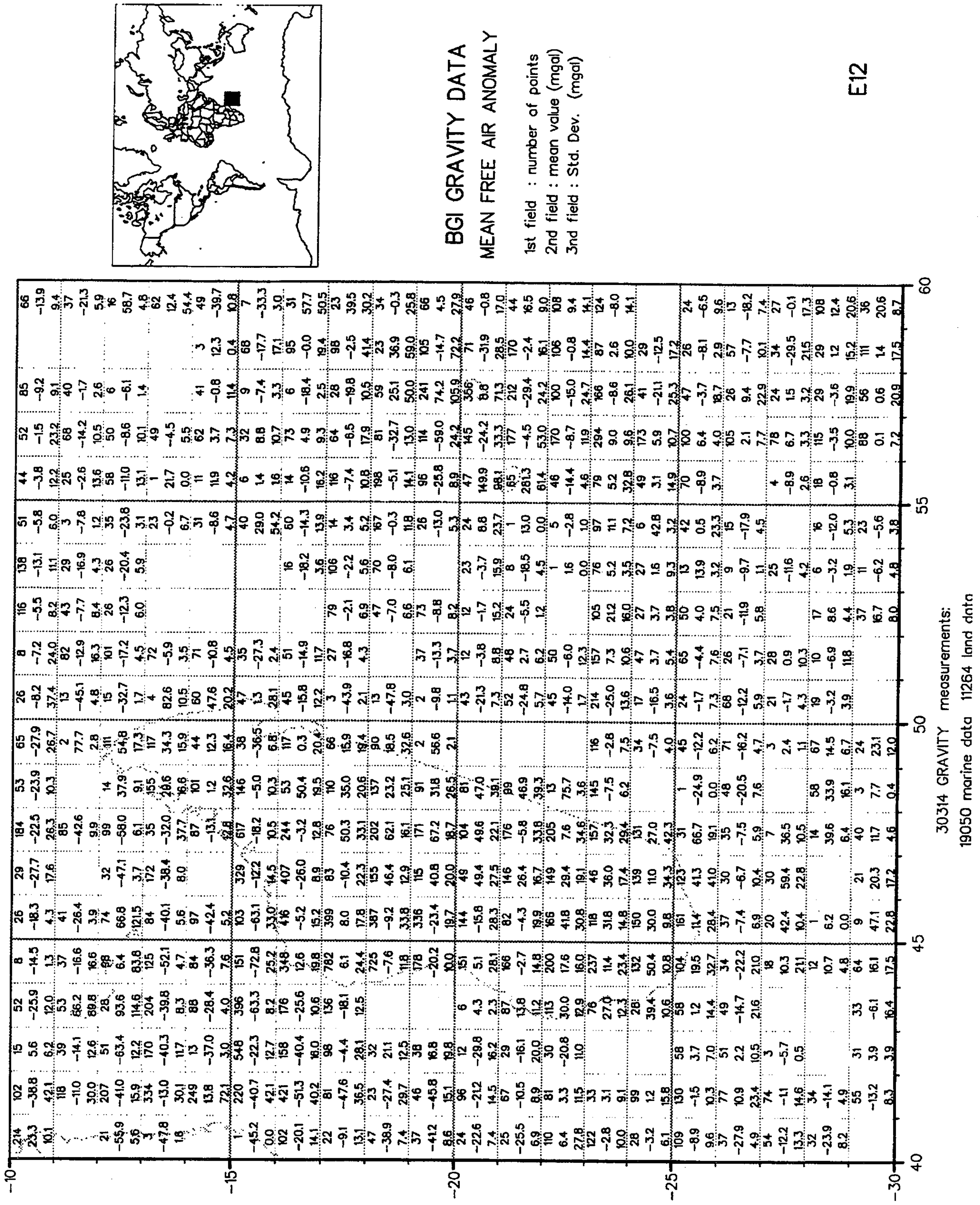
. Colour copy : price according to specifications of request.

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

DIRECTING BOARD

BGI Directing Board Meeting
held at the 2nd Joint Meeting of the IGC/IGeC in Trieste
on Wednesday, 9th September 1998

Present:
I. Marson, G. Balmino, W.Torge, G. Boedecker, R. Forsberg, F. Sansò, J.E. Faller, P.P. Medvedev, H.-G. Wenzel, M. Becker, B. Richter, L. Robertsson, E. Klingele, N. Courtier + *J.P. Barriot (invited).*

Report of the Director of BGI.

Balmino reviewed the present and future activities of the BGI with emphasis on recent progress made in the development of the web server, the production of CD-ROMs, availability of relative and absolute station descriptions and the archival of absolute gravity data. The full report was unanimously approved by voting members.
The term for the BGI director is limited to twenty years and must shortly be filled by a new candidate. Marson expressed his, and the board's, deep admiration and gratitude for Balmino's excellent work and direction of the BGI over the last twenty years.

Report of the President of the IGC.

Marson reviewed the meetings that have taken place (Graz, Tokyo, Trieste) and the continuing integration of the IGC and IGeC. A midterm meeting will be held in 2000 in Canada. The Trieste meeting was successful with 113 participants, a full and interesting program and costs covered by registration fees. The conference was able to host some scientists from developing countries and Central Europe.

Progress has been made in the two regional gravity initiatives: Absolute gravity observations have now been made in many countries of Central Europe. The IGC supported a training course in gravimetry, held in Cairo, which was well attended by people from Arab and African countries. Previous courses have been held in the Ivory Coast and Nigeria.

Reports of the Working Groups of the IGC.

WG-2 World Gravity Standards. G. Boedecker.

The activity report for 1995-1998 was presented and is appended.

WG-6 Intercomparison of Absolute Gravimeters. L. Robertsson.

An International intercomparison was held in Sevres in 1997. Fifteen absolute gravimeters participated. As the accuracy of absolute gravimeters is now starting to exceed the precision of relative gravimeters, the comparison was made by both a relative network and by having each absolute meter measure at multiple locations. Detailed results were presented at the Trieste conference and published in the Proceedings.

WG-7 Monitoring of Non-Tidal Gravity Variations. B. Richter.

Richter presented a project proposal entitled: "A gravity network for ground truth for satellite missions". The project targets Europe with an action plan for the next two years to:

- improve the superconducting gravimeter network in Europe
- recompute the existing data sets in a uniform manner

- collect and analyze data sets from European Stations.

The Board agreed that the working group should proceed with the proposal and gave a mandate to Marson to establish an international scientific mandate for the project.

WG-8 : Relative Gravity Network for 1997 Absolute Gravimeter Intercomparison. M. Becker

For the 1997 Sevres intercomparison, twenty five participants using twelve relative gravimeters made transfer and gradient measurements. A calibration line and the BKG moving platform were also used. Detailed results were presented at the Trieste conference and will be published in the Proceedings.

National Proposals for hosting BGI.

A widely distributed call for proposals to host the BGI elicited many letters of support but only one proposal, made by a consortium of ten French organisations, was received. Marson and Balmino presented the detailed proposal to the board. The text of the proposal and letters of endorsement were distributed to the Board.

The International Gravity Commission received the national proposal to continue hosting and running the Bureau Gravimetrique International in France from the Comité National Français de Géodésie et Géophysique. The proposal, structured as requested, contains the endorsement letters of ten participating members: Bureau de Recherches Géologiques et Minières (Orléans), Centre National d'Etudes Spatiales (Toulouse), Ecole et Observatoire des Sciences de la Terre (Strasbourg), Ecole Supérieure des Géomètres et Topographes (Le Mans), Institut Géographique National (Paris), Institut National des Sciences de l'Univers (Paris), Institut de Physique du Globe de Paris (Paris), Laboratoire de Géophysique et Tectonique (Montpellier), Institut Francais de Recherche Scientifique pour le Développement en Coopération (Paris), Service Hydrographique et Océanographique de la Marine (Brest). This large partnership puts together, around and within the BGI, most of the expertise and means presently available in France in the field of gravimetry.

The proposal also includes the nomination of Dr. Eng. Jean-Pierre Barriot, Research Engineer at the Dept. of Earth and Planetary Geodesy, CNES, Toulouse, as Director of BGI.

The Board carefully examined the proposal and supporting documents and, after deep discussion unanimously approved it in its completeness. Marson will forward the proposal and the recommendation of the Board to the IAG General Secretary who will ask the IAG Executive Committee for formal approval. The proposal will then have to be formally accepted by IUGG and FAGS in 1999.

Proposals for nominations of the IAG Officers 1999-2003.

A small selection committee was formed (Marson, Balmino, Faller) to provide some nominations for the IAG. Nominations from individuals are invited and may also be presented directly to the IAG.

Other Matters.

Medvedev reported on some recent Russian advances in gravimetry and geodesy. The Board recognised the valuable work being performed by the Russian Academy of Sciences in these fields and wished to express its support for closer collaboration and an enhanced exchange of data. The Board gave a mandate to Marson and Forsberg to communicate with the Russian Academy of Sciences for the relevant actions.

N. Courtier, Secretary, 10 September, 1998

International Association of Geodesy - International Gravity Commission

IGC-Working Group 2: World Gravity Standards

Activity Report 1995-1998

The work of IGC-WG2 is based on the **terms of reference** as communicated Nov. 30, 1995:
" In collaboration with BGI and under the guidance of the IGC

1. to provide advice and guidance to the international scientific community with respect to improvements to national and regional gravity networks in order to ensure homogeneity of reference gravity values required to satisfy geodetic, geophysical and standardization needs.

2. to coordinate the establishment of the IAGBN with an accuracy in accordance with advanced state-of -the-art absolute gravity meters, now better than 10 10^{-8} ms^{-2}.

3. to encourage and pursue activities towards the integration of other network data, e.g. co-location of IAGBN with IGS etc., for the study of the system Earth."

The Changing Role of Gravity Reference Networks

The classical approach to ensure **global homogeneity** for gravity observations has been to determine absolute gravity at few stations and to tie these by relative observations to establish several orders of subsequent networks. This approach has been dictated by the high costs of absolute gravimetry and low costs for relative observations. With the continuing development of mobile absolute meters, the number of absolute stations steadily increased and hence the character of reference networks (for details cf. Torge 1997, IAG Rio). One example is the German national gravity base net DSGN1994 where the 1st order net is determined by absolute observations only without relative ties between the base stations. Relative ties with subsequent adjustment computations are a matter of subsequent orders only. Hence, one major objective of the IGC with respect to global gravity standards is not ***networks*** but proper ***calibration*** of absolute instruments which is cared for by WG6.

A supplement to the previous task is to ensure **homogeneity** also at **sea**. For the purpose of marine gravimetry, reference stations in convenient harbours are required. Similarly, for airborne gravimetry, reference stations at airports are necessary. In these cases, precision need not be that high.

Another task of global gravity reference networks is to contribute to the study of **global changes**. For this purpose it is particulary interesting to integrate these stations with e.g. precise geometric stations. Towards this aim, there is overlap with the GGP project and WG7.

International Absolute Gravity Basestation Network - IAGBN

The IAGBN includes two subsets:

IAGBN-A was intended as a closed set of stations for which 36 sites had been selected to support both of the above aims, in particular the global changes investigation. For this reason, many of them were proposed for collocation at space geodetic sites, as soon as they met the site selection criteria. In the IAGBN catalogue issued 1995, 20 IAGBN-A stations have been included.

The remaining sites are situated in Siberia, Africa and on remote islands. In order to promote the establishing of IAGBN-A stations in Siberia, a joint proposal was set up and submitted to INTAS for funding in 1998. This application was not among the 15.7% successful; but the judgement of the jury was not so bad, hence an update will be submitted again next year.

As to Africa, there are absolute observations in South Africa. Also, there are first steps to develop a 1AGBN/FRCN (Fundamental and Reference Calibration Network) station in Ghana.

It has to be stated that the original idea to collect as far as possible raw standardized observation data for possible later reprocessing proved to be unrealistic.

At the discussion on the FRCN on the occasion of the IAG general assembly at Boulder 1995, 1 have advocated to recognize the important role of absolute gravity in the FRCN concept. I also emphasized the importance of an even global coverage; the carefully selected IAGBN-A sites were recommended for further use.

Subsequently, I was asked to represent the 'gravity community' (i.e. IAG sec.3) within the "IAG/CSTG Working Group on the... FRCN'. At a meeting in Paris on Oct. 17, 1996, the discussion continued on what should be the basic criteria for the design of FRCN. In particular, a controversy built up whether to try to follow scientific arguments or just to rely on the existing observatories; in the latter case, e.g. the global distribution would be non optimum but the advantage would be that no existing observatory would be questioned. It appears that the future direction will be just to rely on existing observatories. The meeting "Towards an Integrated Global Geodetic Observing System" in October in München will provide new information.

IAGBN-B has been created as an open collection of stations where absolute gravity has been observed that are not merely experimental observations but warrant a good standard.

According to previous agreement and in accordance with the tasks of both WGII and BGI the data collection of IAGBN-A and -B has been transferred to BG1 on January 31, 1997.

National Gravity Base Networks

A number of now national base nets have been established or upgraded in the past few years, e.g, Dubai, Uruguay, Oman, Germany, just to name a few examples. WG2 has been contacted by Iran, Ghana and Egypt for assistance in establishing a national base net.

The Egyptian network project has been supported through a seminar Dec. 28., 1995-Jan. 4, 1996. An international Training Workshop on Gravimetry was held at Cairo Nov. 23 - Dec. 5, 1996, with participants from nearly all Arab and a number of African countries. My personal funds in both cases came from German sources.

The Ghanaen project is under work.

Further activities within the European gravity base net will not be detailed here.

Reference Stations for Marine Gravimetry

One company (LCT) and one university institute (Spain) requested the catalogue of gravimetric reference stations along European coasts in 1996/7, produced some 10 years ago. Consequently, there seems to be a continuing need for marine reference stations.

My Comments on Future Developments

WG2 contributed to all tasks given in the terms of reference quoted above.

IAGBN-A: The collocation and merging of IAGBN-A with any type of FRCN should be encouraged. Likewise, a global coverage as even as possible should be pursued, The question about compromises e.g. w.r.t. station locations is not an easy one (more active but less good stations?).

The gravity community would be more powerful in pursuing its interests in the concert of other geosciences, if we would first try to converge/merge/unite the various gravity-related networks such as GGP, "Global Gravity Monitoring Network" (WG7) and IAGBN and then channel this into concepts like FRCN.

IAGBN-B: The collection of absolute observations and station site description sheets should be continued as a standard label and procedure for absolute observation suitable for reference purposes.

Merging data sets is everyday work of BGI. Therefore, any imperfections of standardisation should become obvious from that work and should result in activities of WG2 (or others).

The label "IAGBN' should be maintained.

The need for further marine gravity reference stations should be explored.

Considering
- the changing role of gravity reference networks (see 1 St. Paragraph),
- the convergence of 1AGBN with other networks,
- the experience of BG1 w.r.t. standardization - or lack of standardization,
- the role of the other working groups,

the role of WG2 may be open for redefinition.

Gerd Boedecker, Chairman

August 31, 1998

PART III

CONTRIBUTING PAPERS

UPDATE ON THE FINNISH GRAVITY REFERENCE NETWORK

Jussi Kääriänen and Jaakko Mäkinen

Finnish Geodetic Institute (FGI), Masala, Finland

The following is taken from publication n° 125 of the FGI, entitled :

"The 1979-1996 Gravity Survey and Results of the Gravity Survey of Finland 1945-1996"

by Jussi Kääriäinen and Jaakko Mäkinen.

It gives historical and recent detailed information on the first order gravity net of Finland, including the description of new first order stations and a new Bouguer anomaly map of Finland.

We only include in this short note, for the usage of gravimetrists :

Table 5, page 11 of the original publication

Table 6, pages 12-13

as well as the description of the 5 new stations (appendix 1 of the publication).

Table 5. Corrections to gravity values and other changes at the First Order Gravity Net stations, with regard to Table 3 of KIVINIEMI (1980). *Changes in appearance of the site since the documentation by* KIVINIEMI (1964) *are commented even when they do not require a correction to gravity.*

Station		Correction	Remarks
Number	Name	mgal	
470002	Turku	+0.06	Underground construction work.
240001	Helsinki		Recurrent construction work in the surroundings. Station no longer maintained.
620001	Hamina	+0.04	Stairs rebuilt. Height now 17 cm lower.
620004	Noormarkku		Error in table. Height should be 31.00 m.
620005	Lapväärtti		Some steps renewed. Negligible gravity change
620008	Mikkeli	-0.28	Underground construction work.
620012	Viitasaari		Destroyed. Replacement is 880001 at almost the same location.
620015	Vimpeli		New stairs identical with the original. Negligible gravity change.
620016	Kärsämäki		About 0.1 m of soil spread in station surroundings. Negligible gravity change.
620018	Kajaani airport		Destroyed. No replacement.
620019	Oulunsalo	+0.05	Stairs rebuilt.
600465	Kemi airport		Destroyed. No replacement.
590654	Rovaniemi airport		Destroyed. No replacement.
620024	Sodankylä		Destroyed. Replacement is 981001..
560449	Ivalo airport		Destroyed. Replacement is 791001.
600464	Ivalo		Destroyed. Replacement is 791002.
600329	Karigasniemi		Excavation between station and road. Soil spread around. Negligible gravity change.

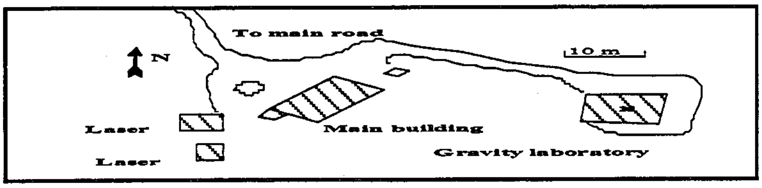
Table 6. Summary of First Order Gravity Net, in order of latitude. The horizontal co-ordinates are in the National Grid Coordinate System and the heights in the N60 -system. Changes are marked with an asterisk and commented in Table 5. Misprint in Oulunsalo latitude corrected, Sodankylä 981001 added. Sept 24, 1998, JM.

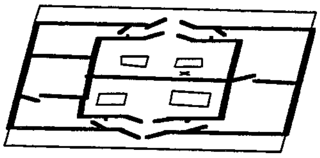
Number	Name	Latitude north	Longitude east	Height metres	Gravity mgal
511293	Hanko	59°49'28"	22°58'25"	17.11	981 900.94
240001	Helsinki	Not maintained			
680001	Helsinki 2	60°11'03"	24°57'08"	30.02	898.53
951001	Metsähovi AB	60°13'01"	24°23'56"	55.29	916.95
770001	Metsähovi AA	60°13'02"	24°23'54"	55.02	917.06
590652	Olkkala	60°26'43"	24°21'23"	31.80	964.57
470002	Turku	60°26'55"	22°16'49"	46.11	938.97*
620001	Hamina	60°34'11"	27°12'16"	12.03*	919.63*
620002	Forssa	60°48'57"	23°38'13"	112.16	948.30
591150	Lauritsala	61°04'18"	28°16'13"	104.69	954.25
620003	Asikkala	61°12'50"	25°29'13"	110.57	972.58
620006	Tampere	61°30'08"	23°46'22"	97.78	994.71
620009	Parikkala	61°32'40"	29°30'06"	81.31	982 024.67
620004	Noormarkku	61°35'49"	21°51'53"	31.00*	003.32
620008	Mikkeli	61°41'31"	27°16'32"	119.42	022.98*
620007	Jyväskylä	62°14'34"	25°44'34"	143.71	036.63
620005	Lapväärti	62°14'48"	21°31'32"	14.14	064.67
620011	Varkaus	62°19'11"	27°54'34"	87.64	074.72
510394	Alavus	62°35'18"	23°37'24"	107.29	061.40
620031	Joensuu	62°35'41"	29°45'23"	86.55	083.39
620030	Ilomantsi	62°39'50"	30°56'23"	161.65	070.91
620010	Kuopio	62°53'28"	27°41'16"	103.74	103.27
620012	Viitasaari	Destroyed, new station is 880001.			
880001	Viitasaari	63°04'25"	25°51'31"	119.94	104.74
620013	Koivulahti	63°09'40"	21°50'31"	9.64	099.67
620015	Vimpeli	63°09'42"	23°49'26"	74.36	103.08
620029	Nurmes	63°32'32"	29°08'22"	117.99	982 141.97
620017	Iisalmi	63°33'31"	27°10'58"	107.24	149.17
620014	Kokkola	63°50'16"	23°07'54"	8.03	170.45
620016	Kärsämäki	63°58'30"	25°46'10"	113.40	166.79
550650	Kuhmo	64°07'36"	29°30'39"	168.78	177.77
460646	Kajaani	64°13'19"	27°44'10"	147.63	170.90
620018	Kajaani airport	Destroyed.			
501105	Ämmänsaari	64°53'06"	28°54'25"	201.40	219.10
590653	Oulu airport	64°55'45"	25°22'17"	14.08	236.28
620019	Oulunsalo	64°56'08"	25°25'28"	8.7	240.58*
540385	Kurenalus	65°21'26"	26°59'52"	114.03	252.80
620020	Kemi	65°43'56"	24°34'04"	11.92	301.51
600465	Kemi airport	Destroyed.			
620028	Kuusamo	65°57'44"	29°11'10"	259.28	272.39
620027	Rovaniemi	66°29'40"	25°43'59"	88.10	345.23
590654	Rovaniemi airport	Destroyed.			
620021	Pello	66°47'48"	23°59'44"	92.99	365.79
620026	Salla	66°49'49"	28°40'40"	218.84	318.50
620024	Sodankylä	Destroyed, new station is 981001, same coordinates and g.			
981001	Sodankylä	67°24'47"	26°35'56"	183.45	374.89
620022	Muonio	67°57'10"	23°40'36"	247.26	412.31
620025	Laanila	68°24'47"	27°24'44"	311.76	443.25
560449	Ivalo airport	Destroyed, new station is 791001.			
791001	Ivalo airport	68°36'26"	27°25'20"	144.13	497.03
600464	Ivalo	Destroyed, new station is 791002.			
791002	Ivalo	68°39'45"	27°32'30"	127.96	502.00
620023	Kilpisjärvi	69°06'34"	20°45'55"	527.30	390.20
600329	Karigasniemi	69°24'18"	25°52'48"	164.78	523.66
1	Hammerfest	Destroyed.			

Appendix 1. Descriptions of new first order stations.

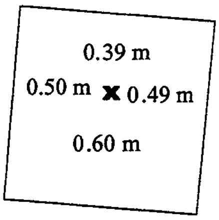
Stations 951001, 770001, 791001, 791002, and 880001 are described, in this order. Coordinates are given in Table 6.

Number: 951001
Station: Metsähovi AB
Location: In the gravity laboratory at the Metsähovi geodetic observatory



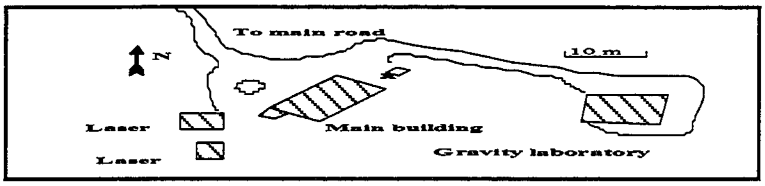


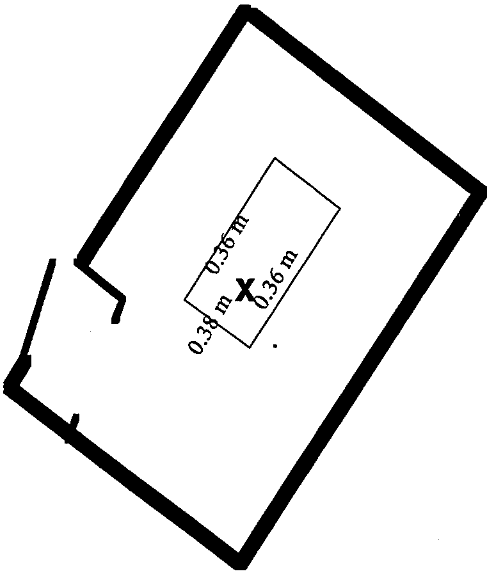
Gravity laboratory



Position on pier

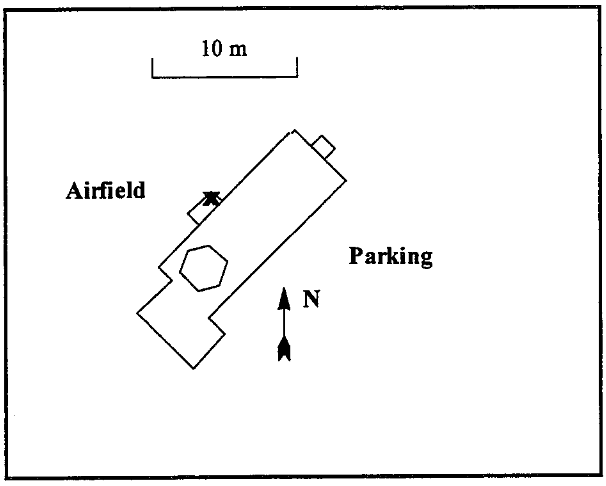
Number: 770001
Station: Metsähovi AA
Location: In a small hut at the Metsähovi geodetic observatory

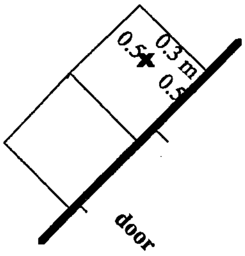




Floor plan of the hut, position on the pier

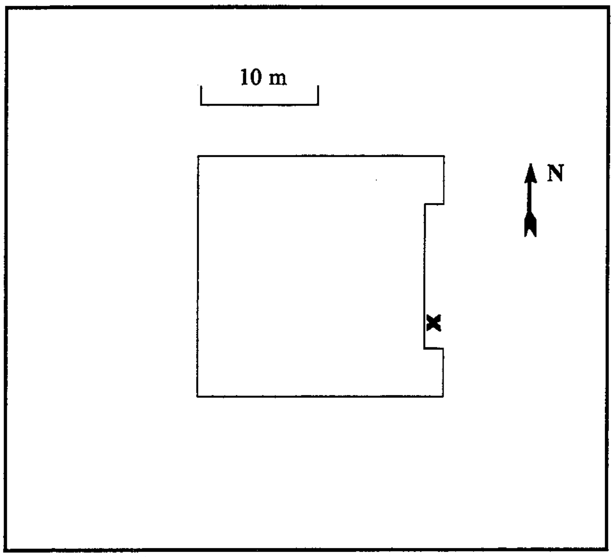
Number: 791001
Station: Ivalo airport
Location: On the doorstep of Ivalo airport control building

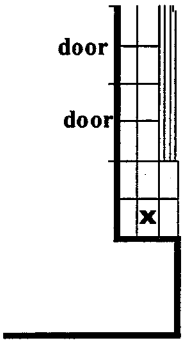




Detail on doorstep

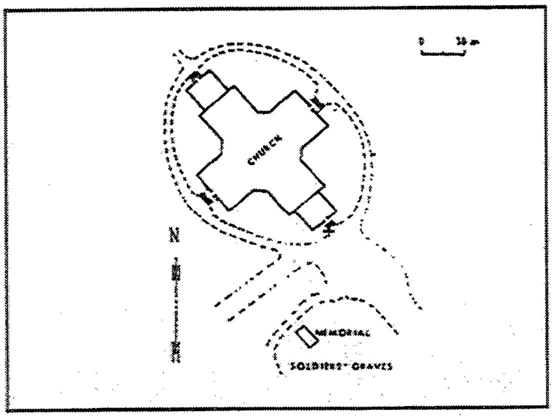
Number: 791002
Station: Ivalo
Location: On the steps of Ivalo church

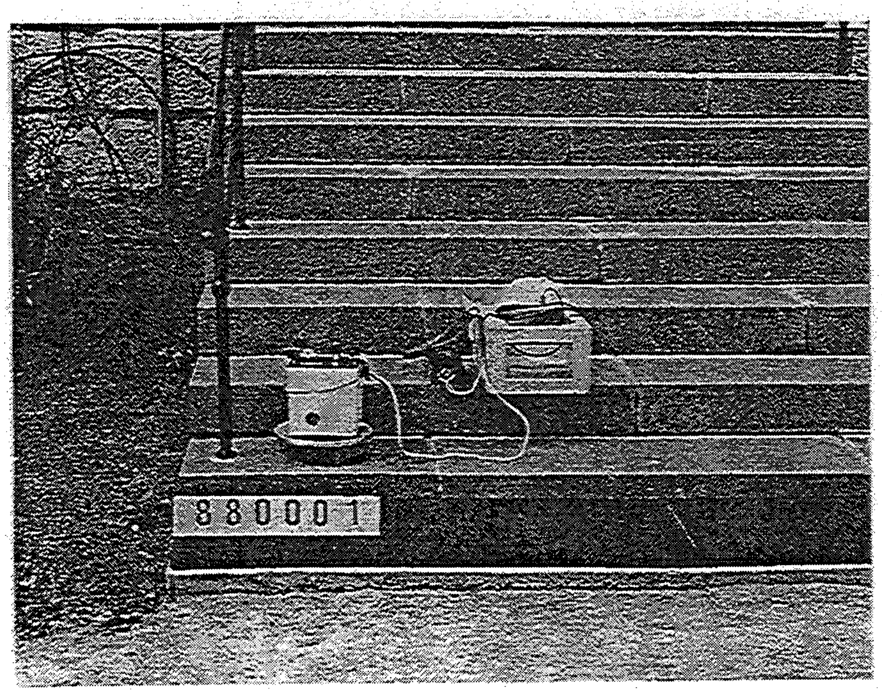




Detail on steps

Number: 880001
Station: Viitasaari
Location: On the steps of Viitasaari church.





Gravity changes with time in Yunnan and Beijing observed by absolute gravimetry

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Abstract

In the middle of the 1980s, the State Seismological Bureau (SSB) established a gravity network in the Western Yunnan Earthquake Prediction Experiment Area (WYEPEA). The network is located in the north-western part of Yunnan province of China, and includes more than 130 gravity stations. Repeated gravity surveys have been performed 2 - 3 times a year by relative gravimetry, and continued until today. Absolute gravimetry was introduced in the 1990's in order to stabilize the network with respect to the absolute gravity level and the calibration of relative gravimeters, as well as to monitor long term gravity variations with time. The absolute gravity network was planned and surveyed within the frame of a cooperation project between the Institute of Seismology, SSB, Wuhan, China (ISSSB) and the Institut für Erdmessung (IFE), University of Hannover, Germany. Three observation campaigns were performed in WYEPEA, in 1990, 1992 and 1995, with additional absolute measurements in Beijing (1990/1992), Wuhan (1990) and Kunming (1990, 1992 and 1995).

This paper compares the results of absolute measurements in the three epochs, and evaluates their reliability by comparisons with gravity data obtained by other gravimeters. Gravity changes on the individual stations are discussed in more detail, taking gravity changes due to ground water variations and crustal deformations into account. Larger gravity changes at some stations can be mainly explained by those effects, while large-scale long term gravity variations with time could not be detected.

1. Introduction

After the 1966 Xingtai Earthquake (Ms = 7.2), repeated gravity measurements started around the main seismic zones all over China. Today this gravity control system comprises 34 regional networks and 11 profiles, with about 3000 stations and an average distance of 26 km.

In 1980, the Western Yunnan Earthquake Prediction Experiment Area (WYEPEA) was established by SSB, in order to study the frequently occurring earthquakes in the north-western part of Yunnan province. Older gravity measurements in the area were revised by the Institute of Seismology, State Seismological Bureau (ISSSB), Wuhan, and the Yunnan Provincial Seismological Bureau (YPSB) in 1985, and expanded to a larger network comprising more than 130 gravity stations. Since that time gravity surveys have been carried out 2 to 3 times a year, employing LaCoste and Romberg (LCR) relative gravity meters. The precision of the network is estimated to ± 0.07 ... 0.1 μms^{-2}, and ± 0.02 ... 0.03 μms^{-2} (0.01 μms^{-2} = 1 µgal) at local micro-networks.
Relative gravimetry is an economic method for gravity measurements, and consequently applied in many regions for studying non-tidal gravity variations (e.g. Torge 1993). Problems inherent to relative gravimetry are the absolute gravity deficiency, as well as calibration errors and drift effects, leading to an accuracy decrease at larger gravity differences and distances. Obviously, absolute gravimetry can support relative techniques at those problems. As absolute gravimetry carries the gravity standard through the instrument into the area of investigation, the connection to a global or national reference is no longer necessary (Torge 1998).

Consequently, absolute gravity measurements were introduced into the WYEPEA gravity control network, within the frame of a cooperation between ISSSB and Institute für Erdmessung (IFE), University of Hannover, Germany, supported by SSB, Max Planck Society and German Research Society. Absolute gravity determinations were carried out by the free-fall gravimeter JILAG-3, operated by IFE since 1986 (Torge et al. 1987), and developed by Prof. Faller and coworkers at the Joint Institute for Laboratory Astrophysics (JILA), Boulder, Colorado, U.S.A. (Faller et al. 1983). Altogether 12 absolute stations have been established, six of them located in WYEPEA and two of them at Kunming, Wuhan and Beijing, respectively (see section 2), Fig. 1. Six stations have been observed three times, in 1990, 1992 and 1995, and three of them two times, in 1990 and 1992. Relative ties between the absolute stations were performed by several LCR gravimeters, in order to control the absolute values with respect to gross errors. In addition a microgravity net and a gravity profile were established at selected fault zones through LCR gravimeters, which were also used to determine the vertical gravity gradients at the absolute and at the gravity profile stations. More details on the JILAG-3 gravimeter and data acquisition and evaluation can be found in Torge et al. (1990), Timmen (1994), Röder (1994). A detailed description of the gravity surveys in WYEPEA is given in Torge et al. (1998).

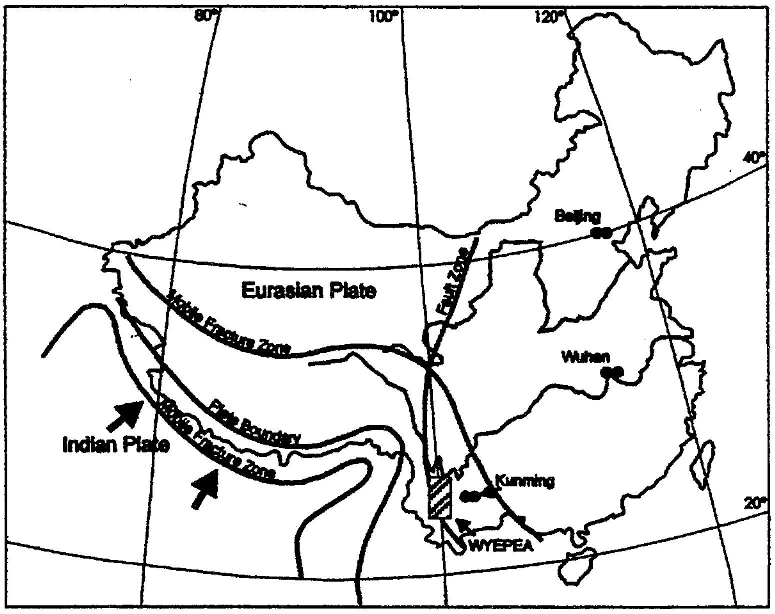

Fig. 1 Location of Western Yunnan Earthquake Prediction Experiment Area (WYEPEA) and absolute gravity reference stations Beijing, Wuhan, and Kunming

Main objectives for introducing absolute gravimetric techniques into the WYEPEA gravity control were

- to provide the absolute gravity level to the relative gravity networks regularly observed since 1985,
- to provide a proper basis for deriving the calibration factors of the LCR gravimeters employed,
- to provide a basis for connecting separated relative networks, and improve their accuracy,
- to study long-term non-tidal gravity variations directly from absolute gravity values.

In the following we concentrate on the last objective, taking into consideration the investigations on the relations between gravity changes and earthquake activities (Jia 1996, Jia et al. 1996, 1997), and water level variations (Jia et al. 1995), in that area.

2. Results and accuracy estimates of absolute gravimetry

2.1 Absolute gravity determinations

Twelve absolute stations have been established in China among 1990 and 1995, using the JILAG-3 free-fall instrument of IFE (Torge et al. 1998). The station locations in the WYEPEA are shown in Fig. 2, and the results of the stadion adjustments are given in Table 1. The gravity values have been obtained by carrying out 1000 to 2000 drops per station, observed over one to two days. The standard deviation per drop varied between ± 0.1 and ± 0.6 μms^{-2}, and the standard deviation of the mean gravity value (precision) is between ± 0.005 and ± 0.041 μms^{-2} (mean value ± 0.015 μms^{-2}). For the reduction of the absolute value from the reference height (between 0.8 and 0.9 m) to the ground floor marker, the mean vertical gravity gradient of the station, observed with LCR gravimeters at each absolute determination, has been used, which should add not more than ± 0.01 to ± 0.02 μms^{-2} to the error budget of the ground floor value.

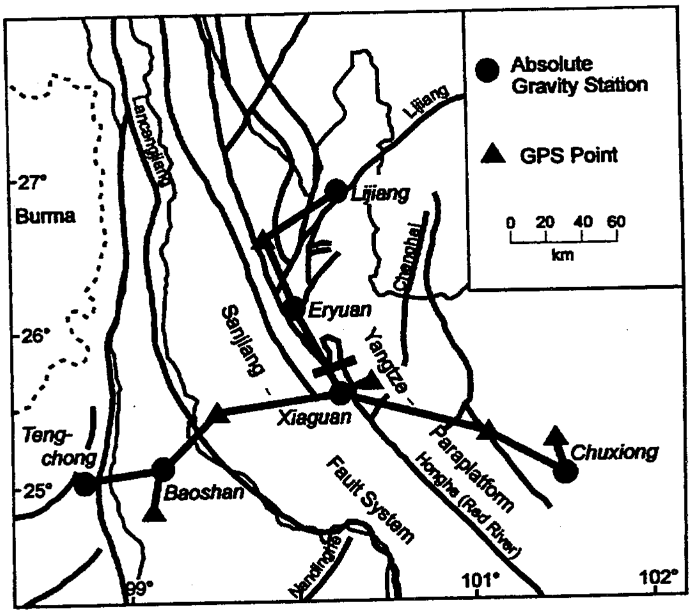

Fig. 2 Location of JILAG-3 absolute gravity stations in WYEPEA, relative gravimetry ties, and connected GPS control stations

Table 1. JILAG-3 absolute gravity results in China 1990/1992/1995

station	gravity: g_{floor} (μms^{-2})		
	epoch 1990. 04/05	epoch 1992.05	epoch 1995.03/04
Heilongtan AS 6501	9783477.08	9783476.96	9783476.90
Yemaoshan AS 6502	9782313.34	9782313.12	9782313.14
Chuxiong AS 6503	9783749.11	9783749.14	9783749.05
Xiaguan AS6505	9783468.03	9783467.92	9783467.97
Baoshan AS6506	9783878.56	9783878.47	9783878.46
Lijiang AS6507	9782868.62	9782868.64	9782868.63
Eryuan AS6508	-	9783280.77	9783280.79
Tengchong AS6507	-	-	9784171.85
Wuhan Univ AS4301	9793488.64	-	-
Wuhan IOS AS4302	9793510.18	-	-
Xiangshan AS1002	9801292.67	9801292.57	-
Baijiatan AS1003	9801105.72	9801105.61	-

2.2 Accuracy of the JILAG-3 absolute gravity values

The accuracy of the JILAG-3 results depends on instrumental and environmental errors sources, and is estimated to ± 0.05 μms^{-2}, on the average. It strongly depends on local site conditions, and may be better at most of the stations in China, with stable ground floor and environment, and low man-made disturbance.

Repeatability is an important characteristics of the gravimeter system, if results of JILAG-3 for different epochs are compared. It is regularly controlled on the reference station Clausthal, located on hard bedrock and with low microseismicity. Over 10 years the r.m.s. scatter around the mean value is only ± 0.04 μms^{-2}, indicating the long-term stability of the JILAG-3 system. An accuracy control is available through the international absolute gravimeter comparisons at the BIPM, Paris, France, where JILAG-3 participated in 1986, 1989, 1994 and 1997. At the 1994 comparison, the JILAG-3 result deviated by only + 0.02 μms^{-2} from the mean gravity value derived from 12 instruments (Marson et al. 1995).

The accuracy of the JILAG-3 results in China can be evaluated by comparing them with independent data sets, obtained by other absolute instruments or by relative gravimetry.

Absolute gravity measurements started in China in 1980, and besides JILAG-3, the following instruments have been used:

- NIM-I, NIM-II and NIM-3: National Institute of Metrology, Beijing, (Guo 1991, Qiu 1993),
- IMGC: Instituto di Metrologia "G. Colonnetti", Torino, Italy, in cooperation with National Bureau of Surveying and Mapping (Xu et al. 1986),
- JILAG-5: Finish Geodetic Institute, Helsinki, in cooperation with National Bureau of Surveying and Mapping (Mäkinen et al. 1993),
- FG-5-101: Institut für Angewandte Geodäsie, Frankfurt/Main, Germany, in cooperation with National Bureau of Surveying and Mapping (Chen et al. 1995, Qiu and Wen 1997),
- FG-5-112: Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, China (Hsu et al. 1997).

The results of these published measurements are compared with the JILAG-3 results in Table 2. If we neglect the comparison with IMGC (long time interval between the measurements, and multiposition experiments at more recent absolute gravimeters), and the NIM-II result in Yemaoshan, the r.m.s. discrepancy between JILAG-3 and the other data sets is ± 0.11 μms^{-2} (bias = -0.02 μms^{-2}, n = 13). Taking only the comparisons with JILAG-5 and FG5-101 into account, with time differences not larger than one year (n = 3), we have an r.m.s. discrepancy of only ± 0.07 μms^{-2}. These values are in good agreement with the error estimates for the absolute results, if we also take eventual different reduction models and local environmental effects (groundwater changes) into account.

At the JILAG-3 gravimetric surveys in WYEPEA, the absolute stations have been connected by relative measurements, employing 4 LaCoste and Romberg gravimeters. The accuracy of the relative ties is at the order of ± 0.1 μms^{-2} for long distances, due to limitations at drift control. Consequently only gross errors at the absolute stations can be detected. In Beijing, Wuhan and Kunming, two absolute stations have been established in close neighborhood ("twin stations"), and also connected by relative measurements. The accuracy of these short connections should be around ± 0.05 μms^{-2}, which allows to control the (relative) accuracy of the absolute values. Table 3 gives the gravity differences for the twin stations derived from absolute and relative gravimetry.

Table 2. Comparison of JILAG-3 results with other absolute determinations

station	instrument	epoch (year. month)	gravity (µms^{-2})	Δg JILAG-3- other instr. (µms^{-2})	remarks
Heilongtan 6501	JILAG-3	1990.04	9783477.08		closest value for comparison
		1992.05	76.96		
		1995.03	76.90		
	IMGC	1981.10	77.36	- 0.28	
	NIM-II	1986.03	77.17	- 0.09	
	JILAG-5	1990.05	77.08	0.00	
Yemaoshan 6502	JILAG-3	1990.04	9782313.34		- " -
		1992.05	13.12		
		1995.03	13.14		
	NIM-II	1986.03	12.51	+ 0.83	
Xiaguan 6505	JILAG-3	1990.04	9783468.03		- " -
		1992.04	67.92		
		1995.04	67.97		
	NIM-II	1986.04	67.88	+ 0.15	
Lijiang 6507	JILAG-3	1990.05	9782868.62		- " -
		1992.05	68.64		
		1995.04	68.63		
	NIM-II	1986.04	68.70	- 0.08	
Wuhan (Univ.) 4301	JILAG-3	1990.05	9793488.64		
	IMGC	1981.09	87.96	+ 0.68	
	FG5-101	1993.10	88.59	+ 0.05	
	FG5-112	1996.05	88.63	+ 0.01	
Wuhan (IOS) 4302	JILAG-3	1990.05	9793510.18		
	FG5-112	1996.04	10.00	+ 0.18	
Xiangshan 1002	JILAG-3	1990.05	9801292.67		mean value of JILAG-3 for comp.: 9801292.62
		1992.05	92.57		
	NIM-II	1990.10/12	92.60	+ 0.02	
		1991.01	92.72	- 0.10	
Baijiatan 1003	JILAG-3	1990.05	9801105.72		mean value of JILAG-3 for comp.: 9801105.66
		1992.05	05.61		
	NIM-II	1986.03	05.64	+ 0.02	
	NIM-3	1988.06/11	05.88	- 0.22	
	JILAG-5	1990.05/06	05.76	- 0.10	
	FG-5-101	1993.09/10	05.74	- 0.08	

Table 3. Gravity differences between "twin stations" from absolute (JILAG-3) and relative gravimetry in μms^{-2}

time	1990			1992			1995		
station	abs.	rel.	|diff.|	abs.	rel.	|diff.|	abs.	rel.	|diff.|
1002 Beijing 1003	-186.95	.91	0.04	-186.96	.98	0.02	--	--	--
4301 Wuhan 4302	+21.54	.41	0.13	--	--	--	--	--	--
6501 Kunming 6502	1163.74	.70	0.04	1163.84	.77	0.07	1163.76	.83	0.07

With an r.m.s. discrepancy of ± 0.07 μms^{-2}, we again find a good agreement with the a priori error estimates for the absolute and the relative data (± 0.05 μms^{-2} each).
Another accuracy control is possible by utilizing the results of relative gravimetry carried out since 1985, in order to investigate the regional behavior of gravity changes with time in Western Yunnan (Jia et al. 1997). From the contour maps of relative gravity variations with time, the gravity changes between the epochs of absolute measurements have been derived and compared with the absolute results (Table 4).

Table 4. Comparison of gravity changes with time in Yunnan, derived from absolute and relative gravimetry

	g_{92-90} (μms^{-2})		g_{95-92} (μms^{-2})		g_{95-90} (μms^{-2})	
station	abs.	rel.	abs.	rel.	abs.	rel.
Chuxiong	+ 0.03	- 0.08	- 0.09	+ 0.03	- 0.06	- 0.05
Xiaguan	- 0.11	+ 0.04	+ 0.05	- 0.01	- 0.06	+ 0.03
Baoshan	- 0.09	+ 0.13	- 0.01	- 0.01	- 0.10	+ 0.12
Lijiang	+ 0.02	+ 0.04	- 0.01	- 0.06	+ 0.01	- 0.02
Mean	- 0.04	+ 0.03	- 0.02	- 0.01	- 0.05	+ 0.02

The mean differences in Table 4 agree within a few 0.01 μms^{-2}, indicating that significant regional gravity changes did not occur. The r.m.s. discrepancy between the absolute and the relative differences is ± 0.12 μms^{-2}, which again is compatible with the error estimates of ± 0.05 μms^{-2} for the absolute values, and ± 0.06 μms^{-2} for the relative results.

We conclude that the accuracy for the JILAG-3 absolute gravity values observed in China in 1990/1992/1995, is ± 0.05 μms^{-2} or better. As a consequence, only gravity changes of ± 0.1 μms^{-2} or larger should be discussed in the following, while smaller variations may be assumed to be within the noise level of the JILAG-3 system.

3. Analysis of gravity changes at the absolute stations

3.1 Epoch comparison of JILAG-3 results

From the JILAG-3 absolute gravity measurements in 1990, 1992 and 1995, the gravity differences given in Table 5 have been derived.

Table 5. Gravity differences between JILAG-3 results 1990, 1992 and 1995

station	Δg_{92-90} (μms^{-2})	Δg_{95-92} (μms^{-2})	Δg_{95-90} (μms^{-2})
Heilongtan 6501	- 0.12	- 0.06	- 0.18
Yemaoshan 6502	- 0.22	+ 0.02	- 0.20
Chuxiong 6503	+ 0.03	- 0.09	- 0.06
Xiaguan 6503	- 0.11	+ 0.05	- 0.06
Baoshan 6506	- 0.09	- 0.01	- 0.10
Lijiang 6507	+ 0.02	- 0.01	+ 0.01
Eryuan 6508	--	+ 0.02	--
Xiangshan 1002	- 0.10	--	--
Baijiatan 1003	- 0.11	--	--
	- 0.09	- 0.01	- 0.10

The comparison 1992-1990 results in an apparent bias of -0.09 μms^{-2}. As we shall see, environmental effects may have influenced the stations Heilongtan, Xiaguan, Baoshan and Xiangshan, while instrumental effects cannot be excluded at Yemaoshan and Baijiatan. For 1995-1992 no bias was found, and the r.m.s. variation (± 0.04 μms^{-2}) shows that no apparent changes occured in that period. This again indicates the high repeatability of JILAG-3.

3.2 Earthquake, crustal deformation and water level induced gravity variations in Western Yunnan

From previous investigations in western Yunnan, some general statements can be made on gravity variations, induced by earthquakes, crustal deformation and water level changes.

The space-time structure of the gravity changes in western Yunnan and their relation to earthquakes with Ms>5.0 has been studied by Jia et al. (1997). After proper fitting and spatial interpolation of the observed point data, gravity variations between + 0.3 and -0.3 μms^{-2} (maximum values) have been found, occurring over several months up to one year. The complex pattern of this variation field changes with time. While a long-term change is not apparent, the gravity field before strong earthquakes is in many cases changing totally, with characteristic precursors seen over 3 years.

In addition to the redistribution of masses connected with earthquakes activities, vertical crustal movements many cause gravity variations with time. In WYEPEA, height changes are controlled through repeated levelling, with benchmarks set up at the gravity stations. As one result from levelling performed in 1981, 1985 and 1992 by the Deformation Monitoring Center No. 2 of SSB, a contour map of the annual vertical deformation rate between 1985 and 1992 has been derived.

There are pronounced ascending areas in the north and southeast of WYEPEA, while subsidence occurs in the southwest, with maximum rates of +3 and -3 mm/year. At the absolute gravity stations Xiaguan and Baoshan, the height changes are close to zero, while at Lijiang and Eryuan we find about +3 mm/year. Applying the Bouguer conversion factor of -2 $\mu ms^{-2}/m$, the height changes for Lijiang and Eryuan would result in the following gravity changes:

Lijiang: $\Delta g_{92-90} = -0.012\ \mu ms^{-2}$, $\Delta g_{95-92} = -0.018\ \mu ms^{-2}$, $\Delta g_{95-90} = -0.030\ \mu ms^{-2}$,
Eryuan: $\Delta g_{95-92} = -0.018\ \mu ms^{-2}$.

These numbers are not in contradiction to the observed values (Table 5), but remain in the noise level of the absolute gravity data.

Water level changes, either at surface waters or at the ground water, primarily depend on rainfall and the water transfer on the surface and along the upper crustal layers. In addition earthquake's preparation processes and seismic events may change the water level.
The effect of water circulation in the atmosphere and related water level changes on the surface and underground on the gravity field has been studied by Jia et al. (1995), for the complex hydrology of northwestern Yunnan. According to these investigations, short and medium term gravity disturbances may reach 0.1 μms^{-2} or more, with strong local variations. Positive and negative correlation of gravity changes with underground water variations has been observed, which may be explained by the different location of the gravity station with respect to the ground water layers. There should be a positive correlation when the gravity station is located on the Earth's surface, above the water-bearing strata. If the gravity station is underground, that means it is established at caves or tunnels, the situation is different. Water-bearing strata now are partly above and partly below the station level, and correlation with gravity may be either positive or negative, or even zero. This will be discussed more in detail at the individual stations.

3.3 Absolute gravity stations with constant gravity

Taking the accuracy estimates of ± 0.05 μms^{-2} or better for one absolute gravity determination into account, no significant gravity changes occured at the stations Chuxiong, Lijiang and Eryuan (see Table 5). The maximum change is - 0.09 μms^{-2}, and the r.m.s. variation is only ± 0.04 μms^{-2}, which demonstrates the high accuracy (repeatability) of JILAG-3 at those stations. This statement agrees fairly well with the comparison between absolute and relative gravimetry, given in Table 4.

3.4 Absolute gravity stations with gravity changes due to water table variations

At the stations Heilongtan (Kunming) and Xiangshan (Beijing), gravity changes of - 0.1 μms^{-2} and more have been found between 1992 and 1990, adding to - 0.18 μms^{-2} between 1995 and 1990 at Heilongtan (Table 5). We examine these stations separately.

Heilongtan station is located at the Kunming seismic observatory, with a pier on bedrock in a tunnel, 25 m from the entrance. Kunming city is situated south-west of the station. Mountaineous area stretches north and east of the station, with the Songhuaba water reservoir about 4 km away from the gravity station in the north-east, on the other side of the hill. The gravity changes observed by absolute gravimetry in Heilongtan between 1986 and 1996 and water level changes observed close by are given in Figure 3 (gravity value 1996.06 kindly provided by Dr. Wang Yong).

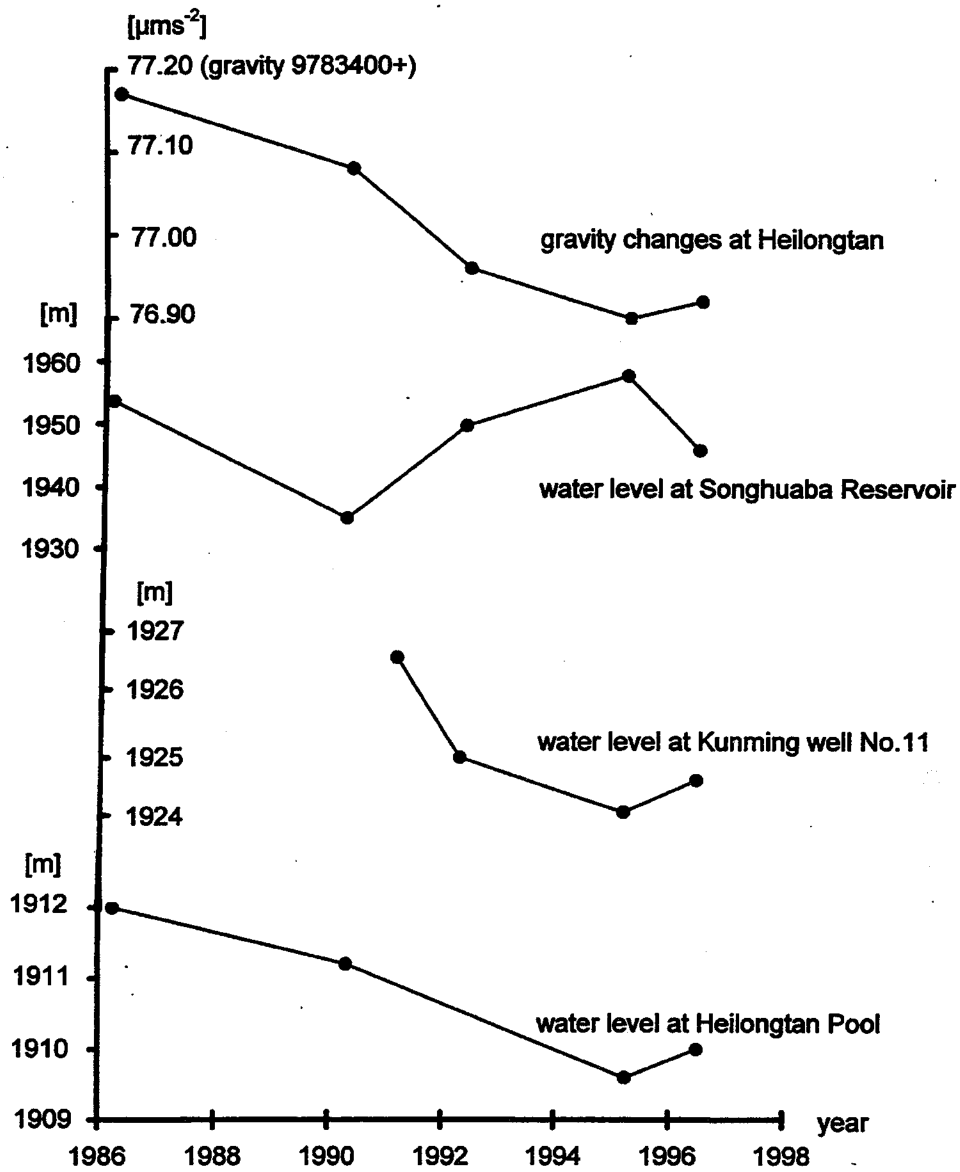

Fig. 3 Gravity changes at Heilongtan (Kunming) absolute gravity station, and water level variations at Songhuaba Reservoir, at No. 11 well of Kunming, and at Heilongtan Pool

No clear correlation has been found between gravity changes and water level variations of the water reservoir. This agrees to model calculations, resulting in gravity changes < 0.01 µms^{-2} from reservoir water level variations. On the other hand, there is a borewell (No. 11 of Kunming), 400 m south of the gravity station. Closed by a tube of 139 m length, this well reflects the underground water situation at depths between 139 m and 271 m. Well observations started in 1991, and a significant positive correlation has been found between water level variations and gravity changes. Water level observations at the Heilongtan Pool support this. Located 1 km south of the gravity station, this pool has an area of 600 m^2. Its water level continously decreased from the middle of the 1980's until 1995, due to increasing water supply for agriculture and industry. For protecting the environment, the water supply was stopped in 1995, and the water level gradually increased since then. As the Heilongtan pool is mainly supplied with spring water, the development until 1995 corresponds to a decrease of subsurface water, with subsequent restoring of the previous water level. Again we find a positive correlation between water level changes at Heilongtan Pool and gravity changes. As a result we may state that gravity changes at Heilongtan are caused by underground water changes, with a gravity decrease of more than 0.2 µms^{-2} over 9 years, and an increase after 1995 (Fig. 3).

Xiangshan station is located at the observation room of Xiangshan seismic station. The pier is set up on bedrock and very stable, with practically no influence from man-made disturbances. Since 1986, absolute gravity measurements have been carried out by the NIM-II gravimeter, in order to investigate gravity changes with time, with altogether 23 gravity determinations between 1986 and 1994 (Guo 1991, Chen et al. 1995). A ground water well is close to the station, delivering water level measures for the time of gravity measurements. The results are given in Fig. 4 for the period 1988 to 1994. We clearly recognize a positive correlation between groundwater and gravity changes, with a maximum of - 0.21 μms^{-2} between 1989 and 1993, and a higher gravity decrease of 0.15 μms^{-2}/6 years. This is in agreement with JILAG-3 results (Table 5).

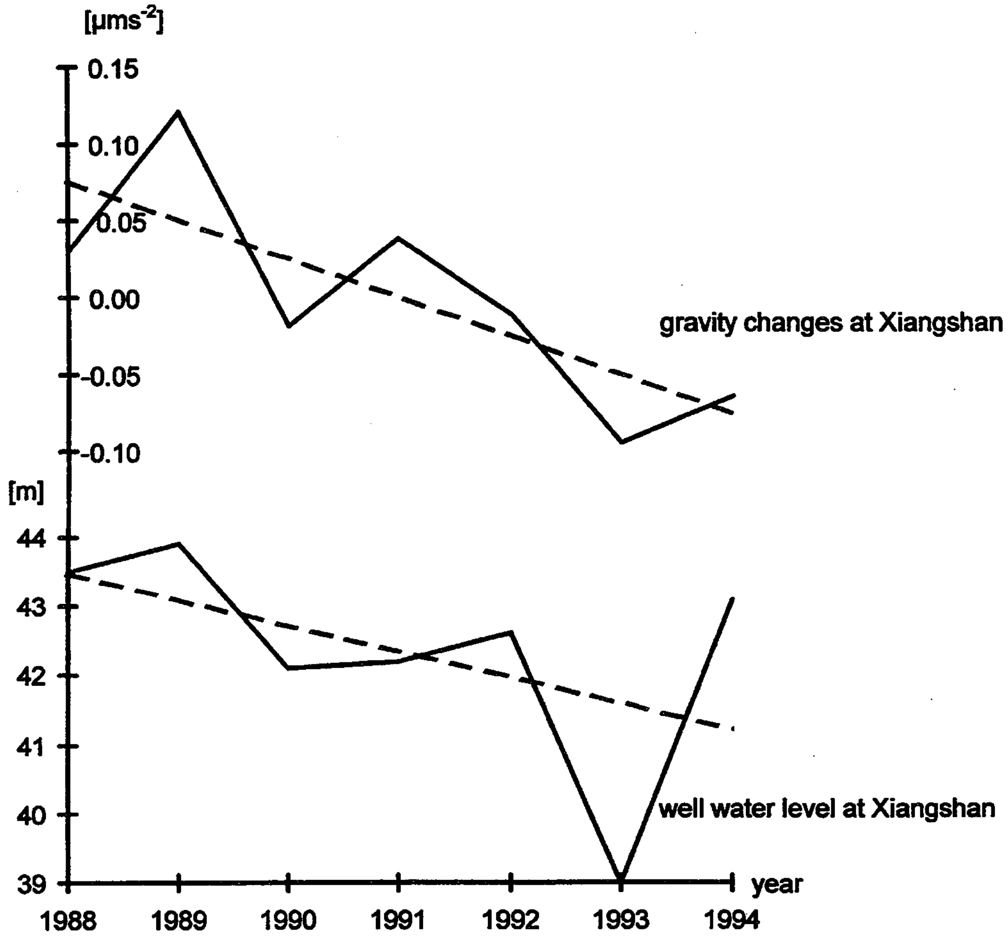

Fig. 4 Gravity changes at Xiangshan absolute gravity station, and ground water level variations at a well close to the station, after Guo (1991) and Chen et al. (1995)

3.5 Absolute gravity stations with gravity changes due to seismic activity

Seismic activity probably has caused the long-term gravity changes observed at the stations Xiaguan and Baoshan. Xiaguan station is located in the central part of WYEPEA. The gravity pier is on bedrock in a tunnel, 60m from the entrance and covered by a hill, with about 40 m rock formation above the station. Microseismicity is low, and controlled by supplementary measurements. The station is situated at the south edge of Erhai Lake (42 km length, 6 km width), and 8 m above the water level of the lake. East of the lake, the Yuexi borewell reflects the ground water situation at depths between 573 and about 800 m. From Table 2 and Table 4, we may conclude that the absolute gravity values of JILAG-3 are well controlled and gravity changes (Table 5) may be related to water level changes as observed at Erhai Lake and Yuexi well (Fig. 5). A negative correlation between gravity and water level changes has been found, both for Erhai Lake and for Yuexi well. Nevertheless, model calculations for water level changes of Erhai Lake result in gravity variations of only a few 0.001 μms^{-2}. As an example the water level rise of 0.22 m, observed from 1990.04 to 1992.04 gives a gravity change of only + 0.0018 μms^{-2}, which is below the noise level and even has opposite sign than the observed gravity changes.

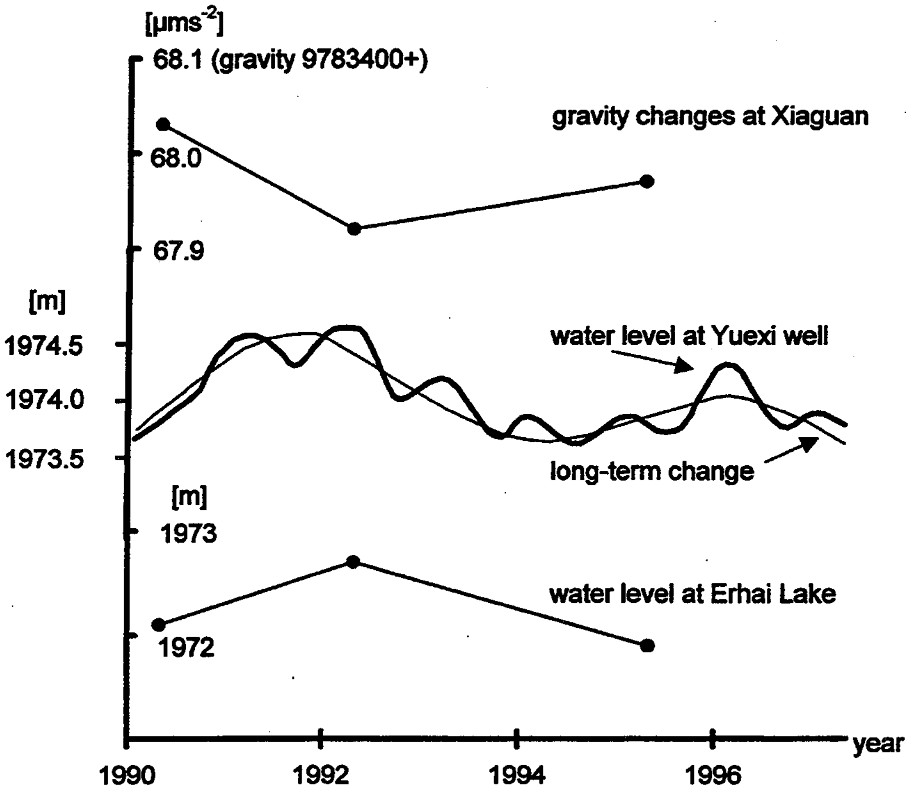

Fig. 5 Gravity changes at Xiaguan absolute gravity station, and water level variations at the Yuexi well and Erhai Lake

We have therefore studied in more detail the relation between precipitation and water level behaviour of Erhai Lake and Yuexi well and the correlation with seismicity. First of all, there is a clear annual variation of the water level at Yuexi well, as well as at Erhai Lake. Less rainfall in 1992 to 1994 resulted in lower water level, which increased after 1995. This indicates that surface and underground water level mainly depend on rainfall, but with some special features. There is a phase lag between the water levels of Erhai Lake and Yuexi well. The highest annual water level at Erhai Lake displays at the end of the rainfall season (end of October to early November), while the highest water level of Yuexi well appears only in March of the following year. This is due to the complex crustal layer structure (clay and gravel alternating) of the area, which postpones rainfall penetration through the crust by about 5 months. In addition there is a long-term water level change at Yuexi well, with increase from the early 1990 to the end of 1991 and a decrease until the middle of 1994, followed by an increase until 1996, and a subsequent decrease (Fig. 5). This long-term variations reflect the stress situation in the crust. Two strong earth quakes (Mizina with Ms= 6.7 at the China/Burma border in June 1994, Lijiang earthquake with Ms = 7.0 about 150 km north of Xiaguan in February 1996) occured in that period. The negative correlation between gravity changes and the long-term water level variations at Yuexi well thus may be triggered by seismic activity.

According to Table 5, the station Baoshan has experienced a gravity change of - 0.1 μms^{-2} between 1990 and 1992, and then remained unchanged. Relative gravimetry with + 0.1 μms^{-2} gives a change of opposite sign (Table 4), while an independent control by other absolute data is not available. Underground water level in the surroundings is controlled by two wells, located south-east and north of the station, at the central part of the fault zone. As the upper parts are closed, the well water level thus only responds to water variations occurring at depths lower than 80 m. Due to the good damping of the several upper clay and coal layers, this level is practically free from rainfall and surface water effects. The water level records from well No. 1 indicate, that the level is very stable over long time, and especially in the period 1990 to 1995, considered here (Fig. 6). This is confirmed by observations of the water level of a subriver located about 10 km to the west, and of Yiluo pool close to the station, which is used for water supply.

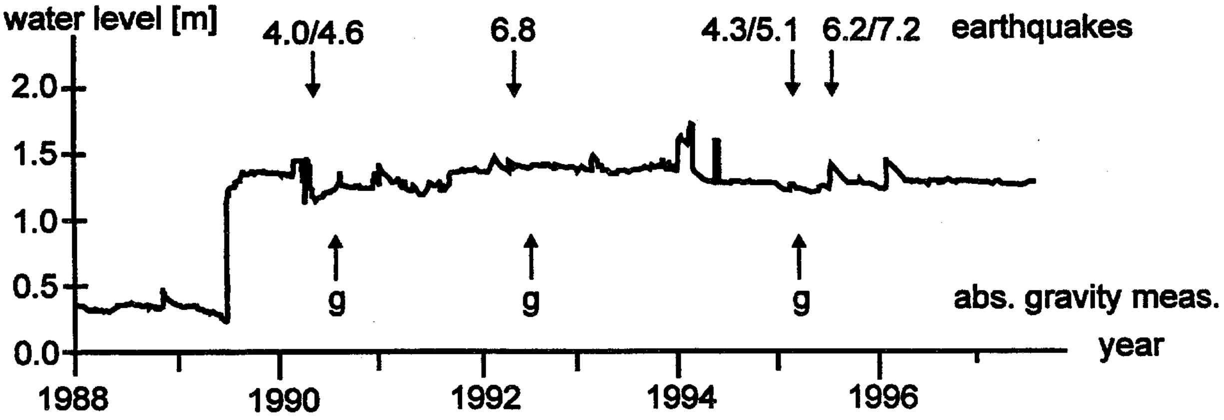

Fig. 6 Water level (daily mean values) at Baoshan well no. 1, earthquake occurence around Baoshan absolute gravity station, and epoch of absolute gravity measurements with JILAG-3

While long-term water level changes do not exist, short-term variations are obvious, and can be related to the occurrence of earthquakes. Before the 1990 absolute gravity measurements, 4 earthquakes (Ms= 4.0 ... 4.6) occurred about 200 km south-west of the station, and before the 1992 measurements, earthquake activity around the station reached Ms = 6.8. From Fig. 6 we recognize larger water level changes when earthquakes with Ms = 4 ... 5 occurred before the gravity measurements, and two stronger ones (Ms = 6.2 and 7.2 resp.) after them. Gravity data show a negative correlation, e.g. a maximum value in 1990, when water level had a minimum, and a decrease by 0.1 μms^{-2} until 1992, when the water level increased by 0.26 m. The situation is more complicated in 1995, which may be due to different behavior of earthquake preparation. We conclude that the gravity changes at Baoshan are caused by seismic activity. A quantitative study is difficult due to the not well known crustal elasticity, and will be done in future. The difference between the absolute and relative results (Table 4) can be explained by the different time of observation (relative gravimetry on April 5, with water level 1.37 m, and absolute gravimetry on May 8, with water level 1.16 m), in a period just before the earthquake occurrence, in addition to the error budget of absolute and relative gravimetry.

3.6 Absolute gravity stations with gravity changes of unknown origin

At Yemaoshan (Kunming) we find a large gravity change of -0.22 μms^{-2} between 1990 and 1992, and constant gravity after 1992 (Table 5). The relative ties to the "twin" station Heilongtan agree with the absolute results, within the error estimates (Table 3).

At Baijiatan (Beijing), gravity changed by -0.11 μms^{-2} between 1990 and 1992. The absolute gravity difference to the "twin" station Xiangshan differs by 0.04 μms^{-2} from the relative difference (Table 3).

At the moment, we cannot affirmatively explain these discrepancies, and have to suspect certain unfavorable conditions during the measuring processes. Following reasons might explain these results:

- opening of the vaccum chamber before the measurements at Heilongtan and Yemaoshan in 1990, and at Baijiatan in 1990. Residual errors of that type may reach more than 0.1 µms^{-2} as demonstrated at other campaigns,
- underground water changes around these stations. There is no information about eventual changes of this type, but we cannot exclude that they may reach 0.1 µms^{-2} or more, as demonstrated for other stations.

Additional investigations on the influence of environmental effects are recommended for these stations.

4. Conclusions

From the analysis of the gravity changes observed by the absolute gravimeter JILAG-3 in western Yunnan and in Beijing, between 1990, 1992 and 1995, we come to the following conclusions:

- repeatability, accuracy and reliability of the JILAG-3 results have been well controlled by repeated measurements on reference stations, and by comparisons with independent data from absolute and relative gravimetry. For the observation campaign in China, an average accuracy of ± 0.05 µms^{-2} can be assumed, and repeatability is better especially on stable stations not influenced by environmental disturbances,
- large-scale long-term gravity variations cannot be derived from the observations 1990 to 1995, the gravity field being stable on the few 0.01 µms^{-2} level, as demonstrated by some stations in the western Yunnan area,
- local gravity variations may reach 0.1 µms^{-2} or more, over a few years. This is due mainly to groundwater-table changes, partly in connection with seismic activity,
- instrumental or station specific effects may play a role at two stations, where gravity changes larger than 0.1 µms^{-2} have been found.

Absolute gravity thus has demonstrated its potential to contribute to investigations on recent geodynamic processes. The absolute gravity control net established in western Yunnan provides a solid basis for detecting long-term gravity changes of local and regional character, by later repetition surveys.

Acknowledgments

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A new detailed gravity dataset in the Netherlands

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1 Abstract

In the period 1990-1994 more than 13.000 relative gravity measurements have been carried out at about 8.000 stations in the Netherlands. The average distance between these seconds order gravity stations is 2 km. Every station is located near a NAP (Amsterdam Ordnance Datum) height benchmark. LaCoste-Romberg G gravimeters were used for the measurements. For the adjustment the network was split in 10 parts, each containing about 800 stations. Every part is connected with at least 3 absolute gravity points from the Netherlands gravity datum 1993 (NEDZWA93).

The correspondence of the overlapping stations of the 10 parts of the network is better than $0.1.10^{-5}$ ms^{-2}. In a further analysis, stations which have been visited only once, have been controlled by comparison with predicted values from neighbour values. 30 stations have discrepancies larger than $2\text{-}10^{-5}$ ms^{-2}. Most of these appeared to have coordinate errors, a few of them were really erroneous and were removed from the data set.

The final precision of the gravity values is estimated to be $0.1\text{-}0.3\text{-}10^{-5}$ ms^{-2}, based on overlapping projects, analysis of instrument behaviour, and the control procedure.

For the IJssellake, an inland lake in the Netherlands, and Waddensea. Bouguer gravity anomalies are available from a campaign in the 1950's. These have been corrected for systematic errors by comparison with the new data near the coast of the lake. For the most southern area of about 200 km^2 , also old data was available. These 200 values have been tested at 20 sites, showing agreement at $10\text{-}10^{-8}$ ms^{-2} level. The three datasets together are covering the complete Netherlands area.

The goal of the project was to build up a gravity dataset in order to enable the computation of a cm-precision relative geoid model, which has been done successfully. The complete dataset is now made available for scientific and commercial purposes.

2 Introduction

In 1989 it was decided to compute a cm-precision geoid for the Netherlands. Detailed gravity information was required for this purpose, but not available, so it was necessary to measure a new second order gravity network covering all of the Netherlands. The measurements are mainly performed by the Survey Department of Rijkswaterstaat (MD), while the processing of the data was done as a cooperation of MD and Delft University of Technology. Based on a test network in the south-eastern part of the Netherlands and the analysis of an old Bouguer anomaly map, the general gravity signal could be analysed. As there was only one relative gravimeter (LaCosteRomberg type G) available, a second one was purchased. In 1990 the measurements of the second order gravity network were initiated. At the end of 1994 the measurements were completed. The project supplies us with more than 13.000 relative measurements between nearly 8.000 second order stations, which are all located near height benchmarks of the Netherlands height system NAP.

3 Set-up and measurements of the second order gravity network

Based on the signal analysis of the test network in south-east Netherlands and the old map, and on the demands on the geoid precision from the local data, it was decided to create a gravity network with a station density of about 1 point per 5 km^2. Because of the positions of the levelling benchmarks, the resulting density appeared to be 1 point per 4 km^2. The second order gravity stations are all located near NAP height benchmarks, so that accurate heights, required to compute gravity anomalies, were easily available for all stations. These anomalies are needed for the geoid computation.

The gravity network construction is based on closed circles of measurements. Every half day, two closed and connected circles ('8') were measured, see figure 1 left. This yields a control over the instrument drift. The measurement circles of different days are connected by measuring again at stations of previous days, see figure 1 right. In the office schemes were made of the measurement circles and marked on topographic maps. On the maps it was also indicated what was the best way to drive, keeping in mind the presence of highways, railways and rivers, so that transportation during field work could be done in an optimal way.

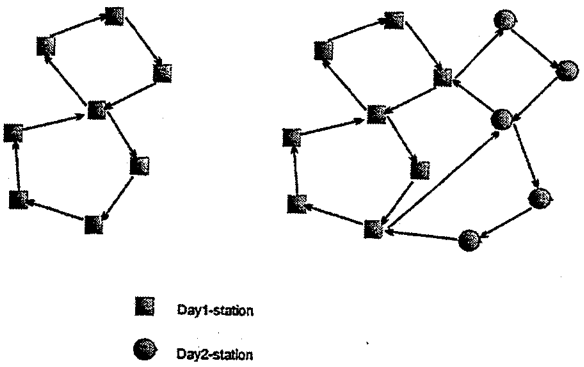

Figure 1: *Linked measurement circles ("8") (left) and linked 8's of separate days (right).*

The entire project was subdivided into local area projects comprising about 300 measurements at 200 stations. The total number of stations visited is nearly 8.000, with a planned number of measurements of 13.000. Because of financial reasons it was decided not to visit all stations more than once. The station positions are indicated in figure 6 at the end of the paper, showing the dense and homogeneous dataset.

The crews in the field were supplied with a gravimeter, a measurement scheme and the map. The average number of measurements per working day is about 20. The height differences between height benchmark and the gravimeter could easily be measured using a measuring tape, since the gravimeter could (almost) always be placed right below (or above) the benchmark. Sketches of the measurement position were made if the gravimeter could not be placed in the direct vicinity of the benchmark.

Most of the measurements have been done by personnel of the MD. About 30% of the measurements have been done by private landsurveying companies.

Strict procedures and guidelines were drawn up for the field measurements. In accordance with those guidelines measurements were registered on paper forms. At the end of the project the observations were stored in a data-file in a standard format, allowing direct use by the processing software. These paper forms and data-files were sent together to the MD head quarters.

4 Procedure of adjustment and processing of the network

A complete software package for the analysis and processing of the gravity data was developed. In a first step the multiple readings of each visit to a stations (minimum 3) were averaged and controlled on outliers. Then the local area projects of 300 measurements were adjusted with a least squares adjustment program to find large errors and test the instrumental drift. The adjustment program is based on gravity differences. At least one absolute gravity value has to be input. Next to absolute gravity values for all input stations, estimations for the instrument scale factor and for the instrumental drift are computed. A testing procedure for separate measurements (datasnooping) is included, and precision and reliability measures are computed.

In the second step of the processing, when no large errors remained in the local area projects, these local area projects were combined to province projects. The total area of the Netherlands was divided into 10 province projects, each consisting (on average) of about 800 stations with 1.300 measurements. Because of the (previously described) network set-up, the province projects have an homogeneous and regular character, since the several local area networks are connected by measurements on revisited stations on different days in the different local area projects. The adjustment of these province projects of about 1.300 measurements with 800 stations (unknowns) was performed on HP-9000 735 UX workstations. The average computation time for one province project is about 30-60 minutes.

In the second order measurement set-up, connections were included to first order gravity stations. In the Netherlands about 50 first order gravity stations exist, and based on all relative gravity measurements (about 2000) between these first order stations, and 4 absolute (JILA-G3) gravity measurements in the Netherlands and 3 absolute stations in Germany, a gravity datum NEDZWA93 (De Min, 1995; De Min & Groenewoud, 1995) was created. These gravity values have a precision of 5.10^{-8} ms^{-2} (5 µgal). On average each province project contained six first order stations (with a minimum of three).

The 10 province projects have overlapping stations at the boundaries, caused by the network set-up. The differences of the independently determined double values can serve as an estimation of the external precision of the gravity values. These results are given in figure 2.

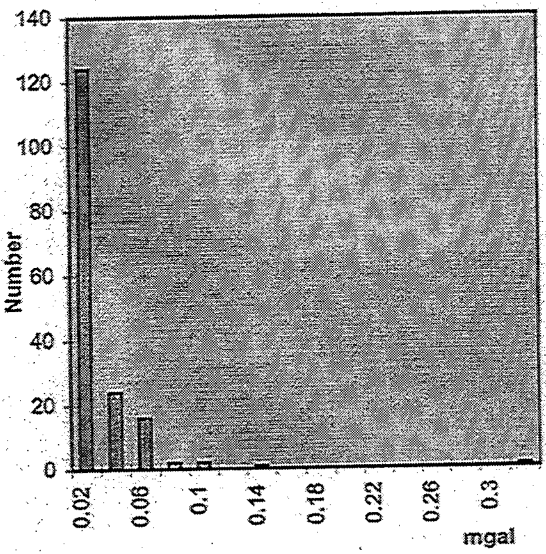

Figure 2: *Differences of 171 stations in the overlap of the 10 projects (in mgal).*

Because not all stations were visited more than once, these stations are not controlled in the adjustment process. So large errors in the measurements can not be detected. Therefore a data control procedure was applied after the adjustment. For all the stations Bouguer anomalies were computed with respect to GRS80. Then for every second order gravity point, a value is estimated based on the neighbouring points within 6 km distance from the point at hand. On average 20 support points were used for the prediction. The prediction was done by least-squares interpolation, which also yields a precision estimate of the predicted value (Heiskanen Moritz, 1967). The applied covariance function for both the prediction and the error computation was computed from the 8.000 Bouguer anomalies, reduced with the global geopotential model values of OSU91A (Rapp et al., 1991). The empirical and model values are given in figure 3.

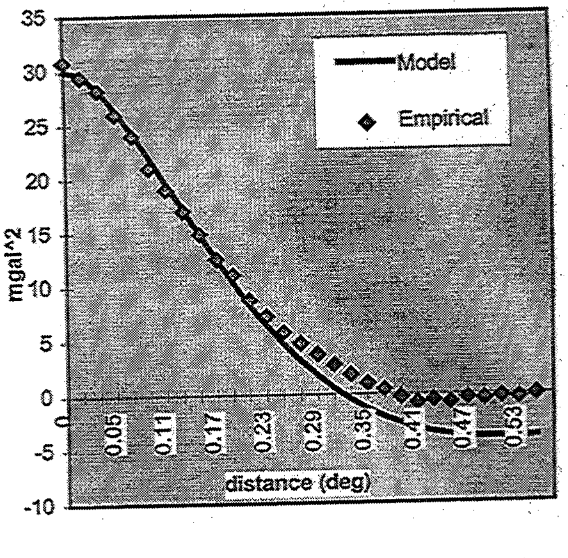

Figure 3: *Signal covariance function of Bouguer gravity anomalies, after subtraction of OSU91A.*

If the difference between the measured and the estimated value is larger than three times the estimated standard deviation, or if the difference is larger than 2 mgal, the measurement forms of that station were inspected again. After the first control computation about 100 points were indicated which could possibly be erroneous. After inspection it was found that for 25 stations the position coordinate values were wrong, so **that** they were located at a wrong position. Therefore they did not correspond to the predicted value by neighbouring points. This also affected the estimation of neighbouring points in the control procedure. In general a wrong position of one station resulted in estimated errors in 2 neighbouring stations as well.

After correcting the position coordinates, about 25 wrong values remained. For some of them typing errors were found on the measurement forms. For about 15 stations no errors could be found, and these were removed from the file.

Figures 4 and 5 show the results of the control procedure.

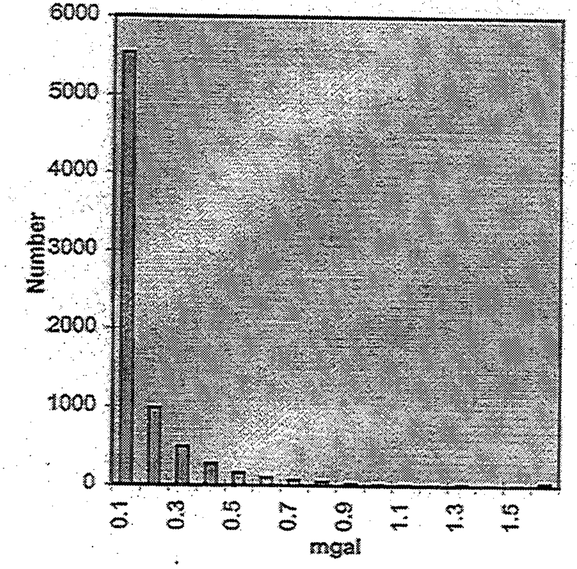

Figure 4: *Differences of 7815 measured values and cross- validation values, in mgaL*

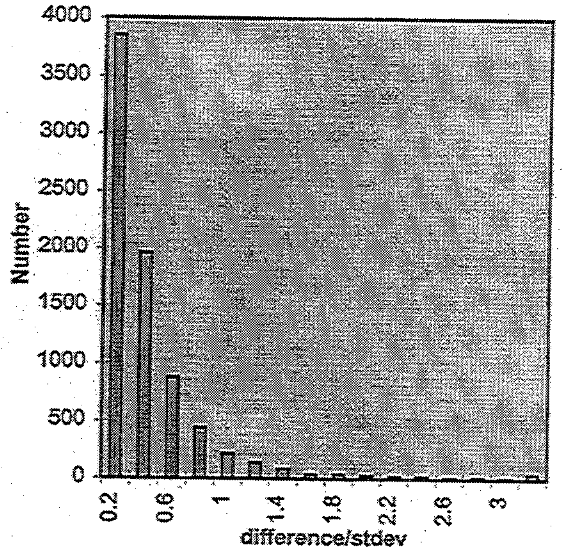

Figure 5: *Histogram of differences (measurement - cross- validation value) divided by estimation precision.*

5 Results

The 10 province projects have 171 stations in overlap. For these 171 stations two independent gravity values are determined. The differences of these independent values give us a good indication of the external precision of the second order gravity values. A histogram of these differences was already given in figure 2. It can clearly be seen that for most of the points the difference is small, that is less than 0.1 mgal. For about 2% the difference is between 0.1 and 0.3 mgal.

The data control procedure of the nearly 8.000 second order gravity values is giving differences between the measured and the estimated values based on neighbouring points. In figures 4 and 5 the histograms of the absolute differences and the differences divided by the precision are given. Figure 4 shows that the standard deviation (rms) of the differences is about 0.1 mgal. According to (Molodenskii et al., 1962) this can be seen as a precision measure. Real gravity estimations will be even better, since the distance to measured points is smaller than in the cross-validation case. In general it means that for most areas in the Netherlands gravity values can be estimated better than 0.3 mgal.

6 Sea-gravity data

For the Ussellake, which is in inner-lake in the Netherlands, and the Waddensea also gravity data is needed for the geoid computation. For this area we used digitised anomalies from an old gravity map. The data have been collected in the 1950's, by measurements on tripods or in tuns at the bottom of the lake. The data in the map is also given on land, so that a comparison could be done. It appeared that systematic differences are present, which are most probably due to the old measurements. The network has been measured as several separate projects, with no precise absolute stations available. Therefor, the sea gravity points have been corrected by a correction function based on the differences on land, using the least squares interpolation technique. From covariance function analyses, it appeared that the sea points have a point noise (random noise per value) of 0.6 mgal. A few new sea gravity profiles have also been added to this file.

7 Limburg dataset

In the southern part of Limburg and - its surrounding area in Belgium and Germany several hundreds of gravity points are available from a geological survey. These results are already in the BGI database. We have revisited 25 of the stations, of which the estimated position coordinates were available (within 10 m). These measurements yielded differences of a few tens of microgals for most stations. Some stations showed larger differences, most probably caused by the difficulty to find the exact location again. Because of this good correspondence, we decided not to measure this area again. The stations of this geological survey within the Netherlands have been included in the new dataset.

Figure 6 shows the distribution of the gravity stations. It shows that a pretty regular distribution is obtained, with an average point distance of 2 km.

Based on the nearly 8.000 new second order gravity values and the IJssellake and Waddensea gravity data, the free-air gravity anomaly map of figure 7 is created. From a comparison with an approximately 40 year old Bouguer anomaly map (transformed to free-air anomalies), with 2 mgal contour lines, it can be seen that the very local structures are quite similar, but that on longer scales (wavelengths from 20-100 km) differences up to 2-3 mgal appear. The geoid effect of these differences would amount up to about 10 cm.

8 Conclusions

In a period of about 5 years a completely new second order gravity network for the Netherlands has been established. The precision of the 8.000 gravity values is estimated to be 0.1 mgal.

For most areas in the Netherlands gravity values can be estimated with a precision better than 0.3 mgal.

The difference with an old dataset amounts up to 2-3 mgal, resulting in differences in geoid heights up to 10 cm.

The gravity results are stored in the database system HIS (Height Information System) of the Survey Department, including site descriptions.

Using these (and other) gravity data a new geoid model for the Netherlands has been computed (De Min, 1996a; De Min, 1996b; De Min, 1996c). This geoid model is widely used now in surveying practice.

Rijkswaterstaat has decided that the datasets are now also available for scientific purposes from Bureau Gravimétrique International of IAG. For commercial purposes the data can be obtained from the Survey Department of Rijkswaterstaat. Individual station information or data for a small area (one topographic map) costs about 30 Euro. The complete dataset, including heights and anomalies of each point, costs about 7500 Euro. More information can be obtained from www.minvenw.ni/rws/mdi/produkt/plaatsbep/prod_ho.htm.

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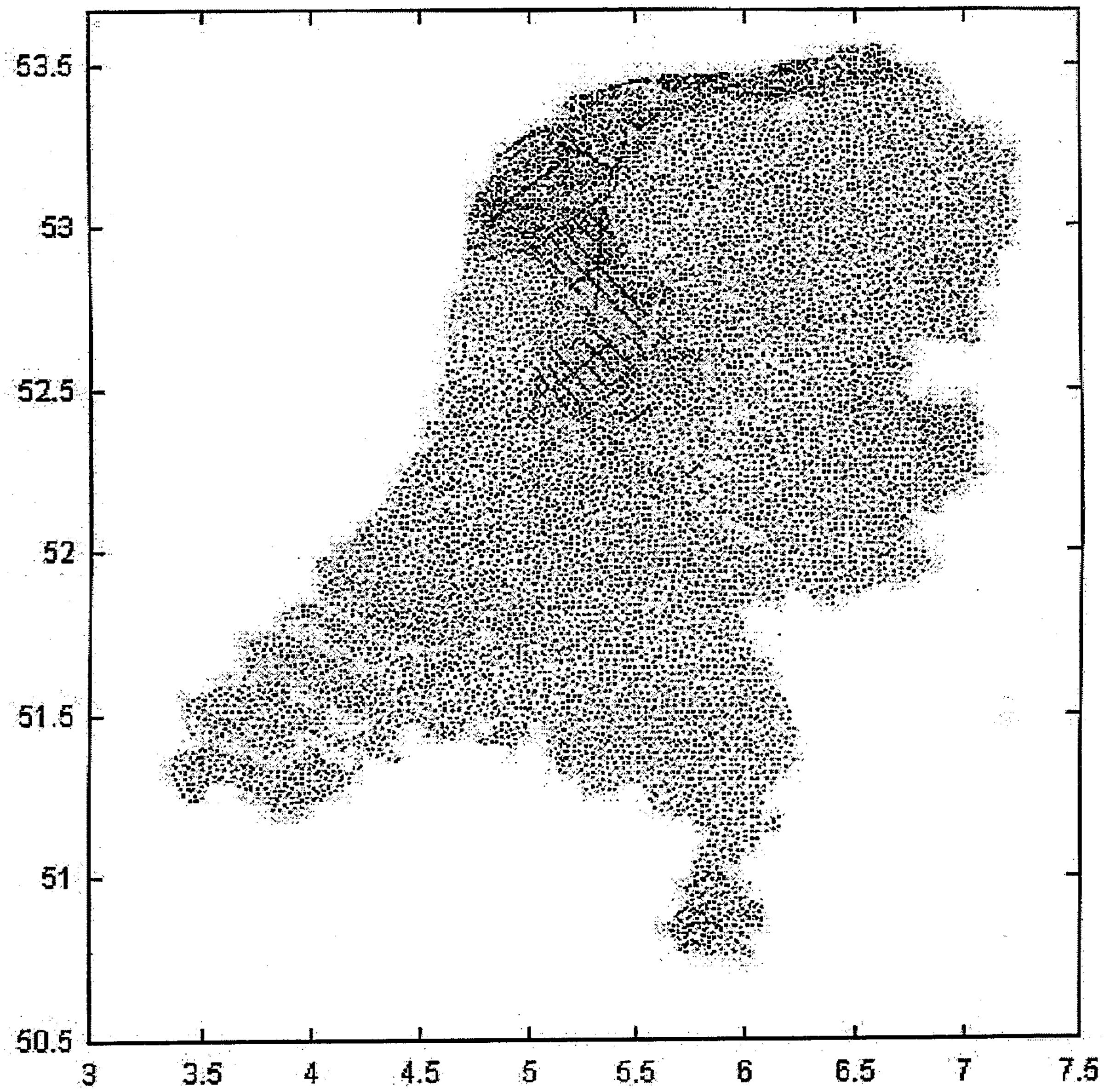

Figure 6: *Distribution of gravity stations*

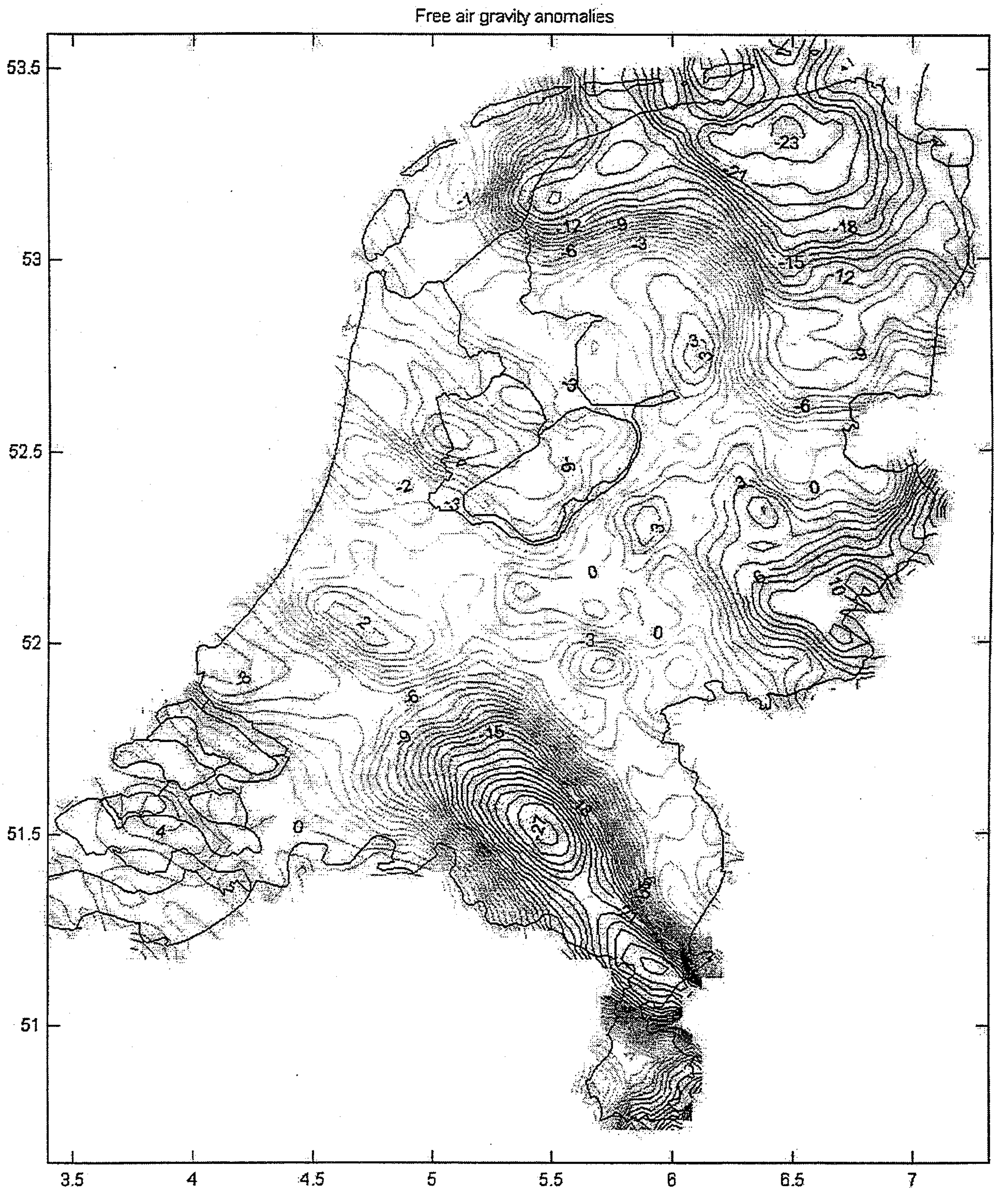

Figure 7: *Free air gravity anomalies (contour interval 1 mgal)*

GRAVITY INVESTIGATIONS OF THE GEOLOGICAL SURVEY OF FINLAND 1995-1997

by

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At the Geological Survey of Finland, gravity measurements are applied together with geological, petrophysical and other geophysical methods (1) to bedrock, crustal and lithospheric studies, (2) to exploration and investigation of ores and mineral deposits, and (3) to investigations of Quaternary deposits and the surface of bedrock. In addition to our own data, the data registers of the Finnish Geodetic Institute, and those compiled in international projects are utilised. Major applications were outlined in two earlier reviews, which cover the years 1987 through 1994 (Elo, 1991; Elo, 1995a).

In the three-year period 1995-1997 the Geological Survey continued gravity surveys as follows:

- Regional gravity measurements:	32065 stations	5220 km^2
- Profile measurements:	64925 stations	1320 km
- Local systematic measurements:	97325 stations	203 km^2

The state of the regional gravity survey (one to six stations per sq. km) by the Geological Survey of Finland is shown on the index map available as a handout (Blue: measured in 1972-1996; Violet: measured in 1997; Red: planned for 1998; Green: measured by the Finnish Geodetic Institute; Yellow: measured by Outokumpu Finnmines Oy).

The current field equipment consists of four Worden, one Sodin, and three Scintrex Autograv CG3 gravimeters; hydrostatic chain levels; optical levelling instruments, and three different types of GPS receivers.

Vatjus-Micro Oy manufactured a new electronic hydrostatic chain level LEVA-20 according to the specifications given by the Geological Survey. The Geological Survey has now four new chain levels of this type in routine use.

Our first GPS equipment was Trimble Pathfinder Basic System consisting of a rover and a base station. The horizontal coordinates of gravity stations were obtained by post-processing. This equipment is now outmoded and has been replaced by a real-time GPS system using RTCM differential corrections relayed using RDS by the Finnish Broadcasting Company. These both systems are capable of determining horizontal position with an accuracy of better than two meters. Unfortunately, the orthometric height is not even as accurate as in barometric height determinations. Starting in 1996, as a subtask of a Geo-Nickel project funded by the European Union, the feasibility of a real-time gps-gravity system giving orthometric heights with an accuracy of better than 3-5 cm has been studied. The equipment consists of two real-time differential two-frequency carrier-phase Ashtech RTZ-12 receivers with all necessary auxiliary devices, and a Scintrex Autograv CG3M gravimeter. Altogether 16 separate field campaigns have been accomplished covering summer and winter seasons and different geographical conditions (Finland, Norway, France and Greece). Test routes have been established for repeated testing of various routines and equipment. When there is an open view to the GPS satellites, measurements with a vertical positioning accuracy of better than 5 cm can be effectively made (1) in real time with station intervals from some meters to a few hundred meters and baseline lengths up to 3-10 km, and (2) with post-processing with station intervals from a few hundred meters to a few kilometres and baseline lengths up to 20 Ian. In full-grown forests, or other similar areas with obstructed view to the sky, when using station spacings substantially less than say 200 metres, GPS must be augmented by e.g. a hydrostatic chain level or a laser ranging and inclinometer device. Moreover detecting errors caused by multipath and obstructed view to satellites requires prolonged observation times. On the other hand, GPS makes the use of other devices much more effective than previously. The effects of local geoid undulations have to modelled in order to obtain best available accuracy in heights above sea level. Determining orthometric heights with the help of GPS has created a new demand for accurate geoids both nationally and internationally. The Finnish Geodetic Institute has given us valuable information both on geoids and on conversions between different coordinate systems and datums. As a conclusion of this theme, our experiments with GPS provide an encouraging and sound foundation for the final stage of the project, which is to design and assemble a real-time gps gravity system and associated software for exploration-oriented regional, semi-regional and local gravity surveys for geological applications.

The Geological Survey of Finland has actively participated in several international projects in which also gravity data from several sources has been compiled into large entities. The Mid-Norden project compiled and published among other thematic maps a Gravity Anomaly Map of Central Fennoscandia 1: 1 000 000 together with some explanations and combined it with the results of the Nordkalott project into a Gravity Anomaly Map of Northern and Central Fennoscandia 1: 2 000 000 (Ruotoistenmäki et al., 1996, 1997a, 1997b). The Finnish Leg of the Global GeoTransect includes a crustal cross-section with inferences from the corresponding Gravity Anomaly Map (publications under preparation). In December 1997, in a meeting hosted by Juha Korhonen of the Geological Survey of Finland, an agreement was reached by the Geological Survey of Finland and the Finnish Geodetic Institute from Finland, Northwest Regional Geological Centre from Russia, Sveriges Geologiska Undersökning and Lantmätreriverket from Sweden and Norges Geologiska Undersogelse and Norges Kartverk from Norway to prepare by the end of the year 2000 a Bouguer Anomaly of the Fennoscandian Shield together with other geophysical maps of the same area.

Ruotoistenmäki (1996) presented a versatile method for calculating gravity anomalies of 3D sources using drillhole density data. The interpretation of gravity anomalies in geological, crustal and lithospheric terms is discussed e.g. in the following papers Elo (1997), Elo et al. (1996), Lehtonen et al. (1997), and Plado et al. (1996)

The application of gravimetric methods to investigation of groundwater areas, Quaternary deposits, the surface of bedrock and glaciers is dealt with in the following papers Elo (1995b), Mattsson (1996), Ruotoistenädki et al. (1997c), and Valli et al. (1997),

Meaningful geological interpretations of gravity anomalies cannot be made without knowledge of geological and areal variation of rock densities. To provide such knowledge the Geological Survey of Finland has conducted a national petrophysical mapping program including density determinations on more than 130 000 rock samples. The role of petrophysics is discussed and petrophysical data presented e.g. in the following papers: Lahtinen et al. (1996), Kivekäs (1996 and 1997), Korhonen et al. (1997a and 1997b), and Säävuori et al. (1997a and 1997b).

In the three years under consideration we have witnessed improvements in field techniques due to new technology and an increased demand for both regional and local gravity data.

What we said more than three years ago still holds, that the widespread adoption of microcomputers in geosciences a few years ago increased dramatically the conventional processing and interpretation of geophysical data, but perhaps delayed the development of more advanced systems for data integration, and calculation and optimisation of three-dimensional models for more realistic representation of complex geological structures, until microcomputers currently in use will be replaced by more efficient ones.

We also renew our hopes that in the near future we are increasingly able to incorporate into the interpretation of gravity anomalies a profound understanding of geological and geochemical processes, more advanced computer systems of geophysical modelling, more versatile frameworks for taking into account other geoscientific information and for maintaining composite models, and even numerical modelling of relevant geological processes themselves.

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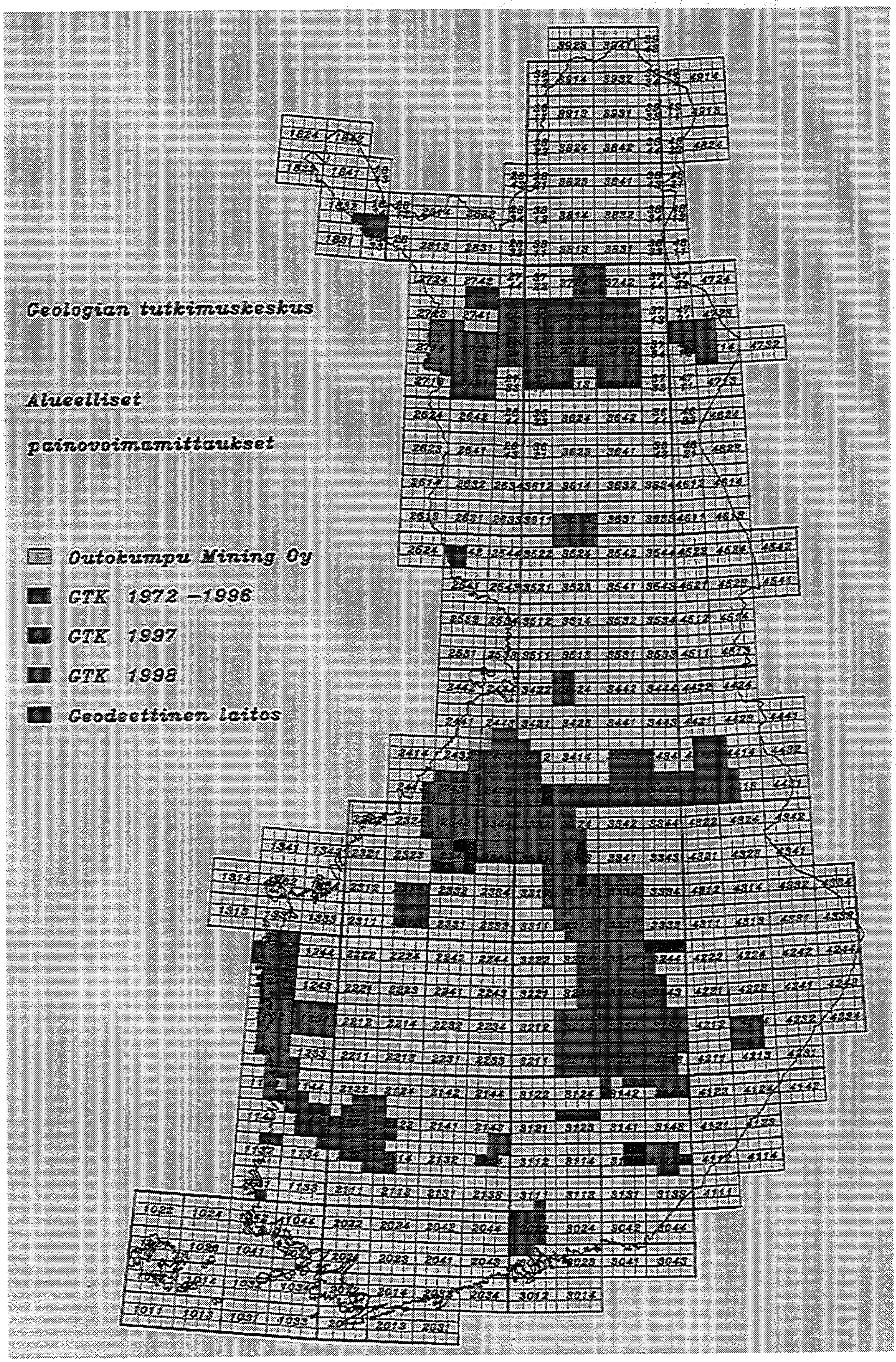

Geologian tutkimuskeskus
Alueelliset painovoimamittaukset
▨ Outokumpu Mining Oy
■ GTK 1972 –1996
■ GTK 1997
■ GTK 1998
■ Geodeettinen laitos

NATIONAL REPORT ON GRAVIMETRY IN FINLAND 1995-1998

The 15th meeting of the International Gravity Commission
Trieste, Italy
5.-12. September 1998

Jussi Kääriäinen
Finnish Geodetic Institute

Introduction.

The latest reports on gravimetric works in Finland were given in the 14th meeting of IGC in Graz and in Geodetic Operations in Finland 1992-1995. The present report covers the period September 1994 - August 1998 i.e. the period between the 14th and 15th meetings of the IGC.

1. Densification of the national gravity network.

The densification of the existing national gravity network with a density of one point per 5x5 km^2 has been continued such that there will be two points or more per each square kilometer. During the reporting period altogether 3361 new points were measured. La Coste&Romberg gravimeters nos G-600 and G-55 were used in these measurements. The point coordinates, height included, were determined using GPS in differential mode. Locations of the measured points are shown in Fig.1.

2. Gravity measurements on the Bothnian sea.

Gravity measurements on the ice of the Bothnian Sea were continued. Due to mild winters the measurements on the ice were possible only in 1996 when 117 new points were established. The LaCoste& Romberg gravimeter no 788 of the Geological Survey of Sweden with full damping was used. The positioning was made by GPS on the transporting helicopter and the water depth was measured using a transportable echo sounding device. The kinematic GPS-mode allowed also the determination of the drift velocities of ice for the Eötvös-correction (RUOTSALAINEN 1997). The point spacing is 5 km in longitude and 10 km in latitude.

The remaining part of the gravimetric survey in the Baltic Sea was completed in October 1996 with shipboard gravimetry as a common inter-Nordic project. The following institutes participated in the measurement: National Survey and Cadastre, Denmark, University of Bergen and Norwegian Mapping Authority, Norway, Geological Survey of Sweden and National Land Survey, Sweden and Finnish Geodetic Institute. The LCR sea gravimeter S-99 was mounted on the gyro platform on the research vessel R/V Håkon Mosby of Bergen University. The cruising speed was 5...10 knots depending on the weather and on the wind direction in particular. The gravity signal and depth and position information were sampled at 10 s intervals. The length of the tracks was 2540 km. There were 21 track crossings to check the results. Before the adjustment the rms value of the crossover differences was 1.19 mgal and after the adjustment 0.57 mgal (D. SOLHEM, personal communication).

The locations of all gravity points, measured in the reporting period are shown in Fig.1 including the cruises of the R/V Håkon Mosby.

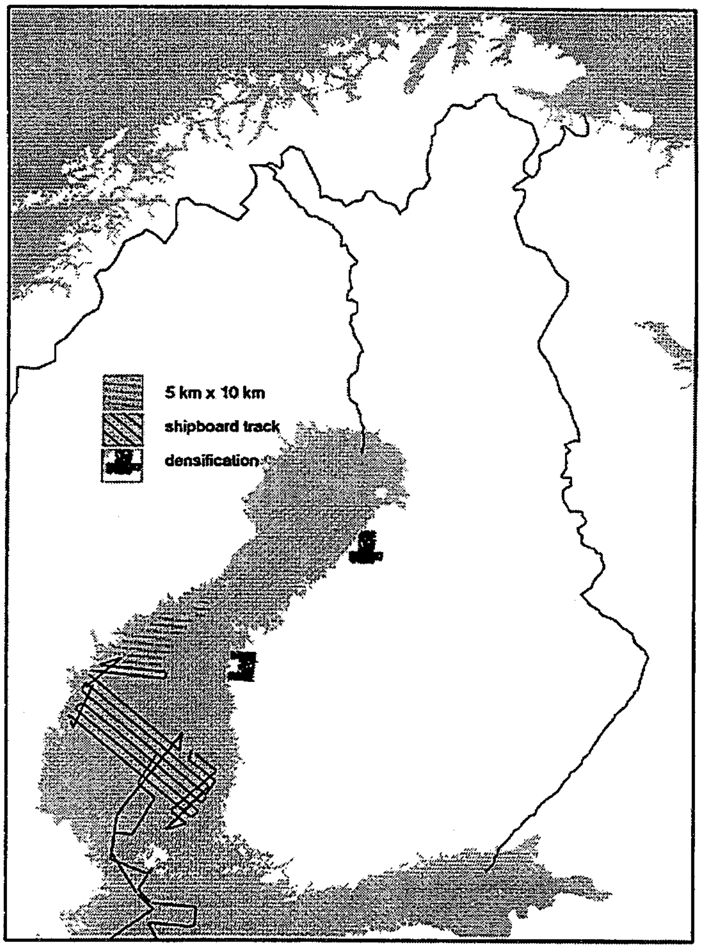
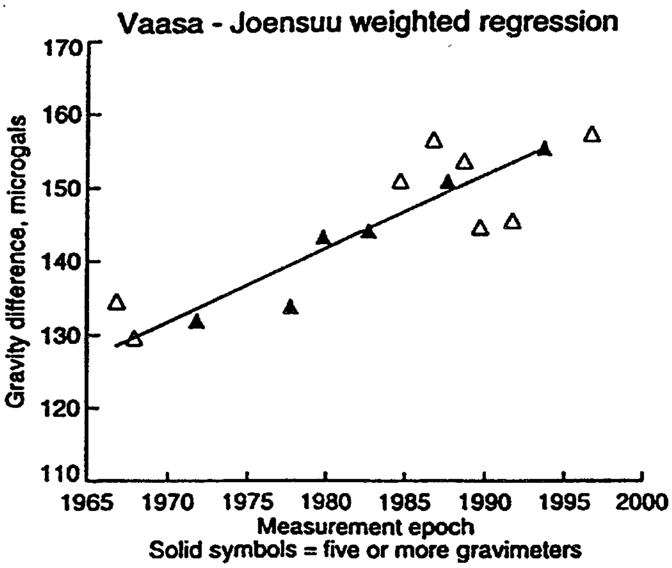


Fig.1. Locations of the gravity points measured in 1995-1998 together with shipboard tracks

3. Measurements on land uplift gravity lines

The measurement along 63° land uplift gravity line was done in September 1996 between Vaasa and Joensuu (Finnish part only) with four LCR-gravimeters nos G-55, G-600, G-54 and G-290. The last two instruments were graciously borrowed by the Land Survey of Sweden. The line was measured three times forth and back and the result landed almost exactly on the continuation of the regression line for measurements 1966-1993 as shown below (MÄKINEN 1997).



4. Absolute gravity measurements.

Since the year 1987 absolute measurements have been carried out with the JILAg-5 instrument. In 1996 The Finnish Geodetic Institute bought another absolute gravimeter JILAg-1 for stationary use in the Metsähovi station.

During the reporting time absolute measurements have been carried out at following stations.

1995 Metsähovi and Vaasa (Finland), Brussels and Membach (Belgium), Clausthal (Germany), Riga,Pope and Viski (Latvia), Borowa Góra, Konopnica and Pivnice (Poland), Suurupi, Kuressaar and Tõravere (Estonia).
1996 Metsähovi (Finland).
1997 Mesähovi (Finland), Strasbourg, (France), Membach (Belgium), Clausthal (Germany), São Miguel, Flores and Faial (Portugal, Azores), Valle de los Caidos and Madrid (Spain), Reykjavik and Höfn (Iceland).
1998 Metsähovi, Vaasa and Sodankylä (Finland) and Höfn again.

Measurements in 1995 at the stations Vaasa and Metsähovi were made in parallel with FG5 no 111 from NOAA.

In 1997 the JILAg-5 instrument participated the international comparison of absolute gravimeters arranged at the BIPM in Sevres.

5. Superconducting gravimeter.

The superconducting gravimeter GWR 020, model TT70 was installed in the new gravimetric laboratory at the Metsähovi observatory in August 1994 and has been recording gravity variations since then.
The instrument has bottom mount and 200 l dewar. For the continuous recording of the groundwater level there is 33 m deep bore hole just outside of the laboratory.
The recordings prove high stability of the installation drift being settled down to appr. 2 µgal/year. In addition to the determination of precise tidal parameters, gravity changes due to the environmental effects like variations in the groundwater level, air pressure variations, free oscillations of the Earth, pole tide and microseismicity have been detected and investigated.
The instrument is participating in the Global Geodynamics (GGP) project launched on 1. July 1997 for 6 years.

6. Gravimetric measurements on the postglacial fault in Pasmajärvi, North Finland.

The measurements on the postglacial fault in Pasmajärvi started in 1987 and have been repeated once in the reporting time, in 1995, using the LCR-gravimeters nos G-55 and G-600. In the Table 1. all the measuring results are given. No significant change in the gravity difference has been found in relation to a reference station, at 14 km distance from the point under investigation.

Year	G55 (µgal)	G-600 (µgal)	mean (µgal)
1987	1406.1	1399.3	1402.7
1989	1413.3	1406.8	1410.0
1991	1405.9	1395.7	1400.8
1993	1403.3	1403.4	1403.4
1995	1403.3	1399.6	1401.5

Table 1. The measured gravity difference between the reference (871003) and the point under investigation (871002)

7. Calibrations of the gravimeters. Metrological services.

The gravimeters G-55 and G-600 have been calibrated on the line Metsähovi-Tromsö, Norway. The gravity difference between these stations amounts to 623 mgal and is determined by absolute gravimeters. During this calibration also the absolute stations in Vaasa and Sodankylä and all the first order gravity stations along the line were measured.
We also have established a calibration line for relative gravimeters, to replace Helsinki-Olkkala used since 1959. The new line is called Masala-Vihti and has 6 stations spaced at 10...11 mgal. The total range is 53 mgal with a driving distance of 40 km on good roads. The starting point is the new headquarters of

the Finnish Geodetic Institute, with an exenter outside the building. The end point is in lightweight shed where either indoor or outdoor conditions can be arranged. The 4 intermediate points are outdoors on bedrock. The gravity values at the end points were measured with the JILAg-5 absolute gravimeter in autumn 1997. The line will be used to determine the linear calibration factors of gravimeters employed in regional surveys and geophysical prospecting and to monitor the performance of gravimeters for geodetic work (RUOTSALAINEN et. al).

The superconducting gravimeter has been calibrated using both LCR G-55 gravimeter and JILAg-5 absolute gravimeter. The achieved accuracy is 0.3 %.
Finnish Geodetic Institute is officially involved to national metrology and is the National Standards Laboratory for free fall acceleration.

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Report on the Gravimetry in Japan during the Period from April 1994 to March 1998

NATIONAL REPORT TO THE 2^{ND} JOINT MEETING OF
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AND THE INTERNATIONAL GEOID COMMISSION (IgeC)

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THE NATIONAL COMMITTEE FOR GEODESY OF JAPAN
AND THE GEODETIC SOCIETY OF JAPAN

Report on the Gravimetry in Japan during the Period from April 1994 to March 1998

Foreword

This document is the quadrennial report of gravimetric works made in Japan during the period from April 1994 to March 1998. It is to be submitted to the International Gravity Commission of the International Association of Geodesy at the Joint Meeting with the International Geoid Commission, to be held in Trieste, Italy from September 7 to 12, 1998. A few of works and publications not included in the previous report are also supplemented. It summarizes gravimetric works such as 1) international and domestic gravimetric connections, 2) absolute gravimetry, 3) gravimetry in Antarctica, 4) tidal gravity changes and free oscillations, 5) non-tidal gravity changes, 6) gravity survey in Japan, 7) marine gravimetry, 8) data handling and gravity/geoid maps, 9) gravity data analysis, 10) geoid and theoretical study of gravity field, 11) lunar and planetary gravimetry, 12) superconducting gravimetry, etc. Complete references of the related articles are found in the bibliography.

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Compiled by Hideo Hanada and Yoichi Fukuda

Contents

1. International and Domestic Gravimetric Connections

The Geographical Survey Institute (GSI) completed a new gravity reference of the Japan Gravity Standardization Net 1996 (JGSN96) in cooperation with the National Astronomical Observatory of Mizusawa (NAOM), Nagoya University, and Hokkaido University. The JGSN96 consists of gravity values at 117 nation-wide stations, nine of which are categorized as Fundamental Gravity Stations (FGSs) where absolute gravity measurements were carried out and the rest is chosen from 180 first-order gravity stations, and they are open to public. The values are given in microgal and were estimated by the least squares method from absolute gravity values by FG5 (Micro-g Solutions Inc.) gravimeters at 9 stations and accumulated data of about 14,000 relative gravity connections after the previous reference of the Japan Gravity Standardization Net 1975 (JGSN75) was published. All the data employed were those obtained only by the GSI that takes responsibility for land geodetic references (Yamaguchi et al., 1997; Nakai et al., 1997). The accuracy of the JGSN96 is estimated about 10 10 μgals (1gal=0,01m/s^2), which is one order higher than that of the JGSN75. GSI carried out the first-order gravity survey, which started its second round in 1992, at nine FGSs, 54 first-order gravity stations and 78 bench marks with the LaCoste & Romberg (LCR) model-G gravimeters for the period concerned (Nakal et al., 1997; Yamamoto et al., 1998).

Nakagawa et al. (1995) and Shichi (1995) examined sensitivity characteristics of LCR gravimeters in detail in order to verify the accuracy of the field data of the international gravimetric connection between Japan and China as well as domestic ones in both countries carried out during the period from 1985 to 1986. They concluded that the gravity measurements had been accomplished with an accuracy of a few μgals usually and 5 μgals at the maximum concerning the setting accuracy of the gravimeter throughout the whole period of the investigation.

International gravimetric connections between Japan, Singapore and Indonesia were repeated by Disaster Prevention Research Institute, Kyoto University (DPRI) cooperated with the Earthquake Research Institute, University of Tokyo (ERI) and Bandung Institute of Technology (ITB) in September 1995 and December 1996, for the purpose of increasing reliability of gravity values at gravity stations near Bandung in Java Barat (West Java), especially at DG.0 (national fundamental gravity station of Indonesia) in Bandung. Direct gravimetric connection between Japan and Indonesia was also carried out in January 1995. Scale constants of the gravimeters were revised by comparing the difference between the measured value at the IGSN71 stations in Japan and that in Singapore with the difference between the authorized values. Considering these results and the result obtained in 1993 (Murata et al., 1994), gravity values were determined with an accuracy of 20-30 μgals (Nakamura and Okubo, 1997). Survey Department of Ministry of Law of Singapore helped us very kindly. However there was one serious problem that all gravity stations in Singapore registered in the IGSN71 except only one station (Singapore A) could not keep their original circumstances caused by rebuilding or remodeling.

DPRI and ITB; carried out gravity survey in November 1997 along two survey lines traversing nearly perpendicular to the Lembang fault (10 kn north of Bandung) or the Cimandiri fault (100 km south of Jakarta) to make clear the structure of the faults as the first step. They measured gravity at intervals of 500 m along the 50 km length survey line crossing the Lembang fault and along the 30 km survey line crossing the Cimandiri fault. Positions of all these observation sites were determined by using interferometry GPS.

2. Absolute Gravimetry

The NAOM developed the absolute gravimeter with a rotating vacuum pipe which is capable of automatic operation by rotating a vacuum pipe around a horizontal axis by 180 degrees with an angular velocity high enough to keep the falling object. It obtained absolute gravity values at Esashi Gravity Station for longer than one year and obtained the following results. 1) The absolute gravity data with a standard deviation of about 20 μgals can determine the amplitudes of the tidal gravity variation including the effects of ocean tides with an uncertainty of less than 0.5 percent. The difference between the observed and the theoretical Earth tides agrees with the oceanic gravity tides based on the Schwiderski's model within about 10 percent error. 2) The observed mean gravity values, on the other hand, increase at a rate of about 0.01 μgals/day (3.6 μgals/year). The rate of 3.6 μgals/year is equivalent to crustal subsidence at the rate of about 1mm/year if we assume the height variation only takes part in the gravity change with the free air gradient. 3) The observed gravity change due to the polar motion agrees with the theoretical one based on the 1066A Earth model with an accuracy of about 20 % (Hanada et al., 1995; Hanada and Sato, 1995; Hanada, 1996a; Hanada et al., 1997a, Hanada et al., 1997b). The NAOM investigated causes of systematic errors appeared in absolute gravity measurements and confirmed that the largest systematic error source, which seems to be common for all the absolute gravimeters and can cause the error of as large as 100 μgals, is rotation of a falling object around a horizontal axis induced by difference in time of release of the object from points of support (Hanada et al., 1996).

Hanada (1997) proposed a method of absolute gravity measurement which utilizes a Fabry-Perot interferometer with two retroreflectors and two beam splitters and showed theoretically and experimentally that it has a sensitivity of 10^{-9} in the gravitational acceleration with falling distance of less than only 1 mm.

Suzuki and Hanada (1995) evaluated absolute gravity values obtained by a free rise-and-fall (Sakuma type) absolute gravimeter at Mizusawa in 1981-1985 and found a gravity decrease of about 150 μgals. However this may not be a real gravity change of geophysical origin but may be an apparent one stemming from the difference between the real and the interpolated lengths of the etalon used as the length standard.

The GSI which has three FG5 gravimeters (No. 104, No. 201, No. 203) carried out absolute gravity measurements with one or two FG5 absolute gravimeters at 15 stations; eleven of which were newly occupied: Kumamoto, Hiroshima, Susa, Kanozan, Omaezaki, Kakegawa, Chichijima, Nagaoka, Matsushiro, Airs, and Rikuoka stations: the remains of the stations were existing FGSs, Shintotsugawa, Esashi, Tsukuba, and Kyoto FGSs. Though standard deviation of a single drop for the measurements ranges from 9 to 64 μgals, which depends on micro seismic noises, final results were obtained with statistic errors better than 2 μgals.

The GSI also carried out absolute gravity measurements at three sites in Australia, Mt. Stromlo, Tidbinbilla, and Mt. Pleasant, in cooperation with the Australian Geological Survey Organization (AGSO) and the Australian Land Information Group (AUSLIG) in 1996 under a Japan-Australia Science and Technology Agreement. The absolute gravity values measured by one or two FG5 gravimeters are obtained with standard deviation of a single drop of 10 to 24 μgals. Gravity values at Mt. Stromlo, which is one of the IAGBN(A) stations, measured by three FG5 gravimeters (two GSI's gravimeters: No. 104 and No. 201 and one Australian gravimeter: No. 110) agreed within 3 μgals. Gravity changes due to ocean tide loading were detected at all the stations.

The ERI, the Ocean Research Institute (ORI) and the NAOM carried out an experiment to verify the precision of the FG5 absolute gravimeter through collocation with superconducting gravimeters (SG) for several days at two sites (Okubo et al., 1996). They found 2 to 4 μgals diurnal/semi-diurnal signals in the time series of absolute gravity measurements. The signals agree well with theoretical ocean tide both in amplitude and in phase, demonstrating that FG5's precision is better than 2 μgals. Furthermore we found discrepancy between the FG5 measurements and the SG measurements is 1.3 to 1.5 μgals. These results verify that the FG5 has precision of 1 to 2 μgals.

The GSI carried out absolute gravity measurement at the Supplementary Fundamental Gravity Station (Kyoto C) in Kyoto University, in 1995. At that time, Takemoto et al. (1997) made microtremor observation to examine effects of ground vibrations on absolute gravity measurement. As a result, scattering of measured absolute gravity values is closely correlated to ground vibrations within the frequency range from 3 Hz to 12 Hz, while significant correlation between the averaged gravity value and ground vibrations could not found.

3. Gravimetry in Antarctica

The observation with a superconducting gravimeter (SG) at Syowa Station was commenced in March 22, 1993 by the 34th Japanese Antarctica Research Expedition (JARE). This site is only SG site in Antarctica. The observation is kept mainly by the National Institute of Polar Research (NIPR) and the NAOM with the support of related Japanese Institutes and researchers (Sato et al., 1995). Since then, continuous observation of gravity changes with the SC has been made together with the LCR gravimeter (model-D). Several authors carried out tidal analysis using the TIDE signal data of the SG (Sato et al., 1995; Sato et al., 1996a; Sato et al., 1997a; Sato et al., 1997b; Tamura et al., 1997).

For the short-period gravity tides at Syowa, Sato et al. (1996a) reexamined the tidal factors for diurnal and semidiurnal tides based on the data obtained by the SG during a period of 2 years from 1993 to 1995 using the new global ocean tide models by Matsumoto et al. (1995) to correct for the ocean tide effects. They found that there was a large discrepancy exceeding 10 % in the delta-factor for the semidiurnal tides and concluded that it was mainly caused by their inaccurate estimation of the ocean tide correction as has been pointed out by Ogawa et al. (1991). For the long-period gravity tide, Sato et al. (1997a) analyzed Mf and Mm constituents using the same data of 2 years mentioned above, and compared them with theoretical ones including the ocean tide effects estimated using the five global ocean tide models available at that moment. The averaged ocean tide effects of the five models were

0.433 and 0.244 μgals with the differences between the minimum and the maximum values of 0.104 and 0.033 μgals for Mf and Mm tides, respectively. The estimated Mm phases were nearly 180 degrees through the five models and variation among the models was relatively small compared with that of the Mf phases. These indicate that Mm gravity tide is much closer to an equilibrium tide than the Mf tide. The observed delta-factors corrected for the ocean tide effects were within the ranges of 1.158 - 1.169 for Mf and 1.163 -1.169 for Mm in spite of the scatter of the ocean tide corrections. It is noted that the mean delta-factors of the five models, i.e. 1.162 for Mf and 1.165 for Mm are slightly larger than theoretical values based on the elastic Earth. Sato et al. (1997a) investigated the polar motion effect on gravity observed with the SG at Syowa and obtained the amplitude factor (delta-factor) of 1.198 ± 0.035 and a time lag against to the predicted ones from the IERS (the International Polar Motion Service) data. We need further analysis based on much longer data in order to obtain much concrete value for the time lag.

The GSI conducted the third measurement by an absolute gravimeter in January - February 1995 at Syowa (IAGBN No. 0417) as the 36th JARE (Yamamoto, 1996). In all, four sets of absolute gravity measurements were carried out at Syowa, and four different absolute gravity values were obtained. NIPR held a workshop on January 1996 to discuss the four values, and 982524.327 ± 0.015 mgals was adopted as the absolute gravity value at Syowa (Kaminuma et al., 1997).

4. Tidal Gravity Changes and Free Oscillations

Signals of Earth's free oscillations were recorded by the SC after large earthquake occurrences. Tanaka, Furuno and Nawa (1997) tried to detect combination tones between the Earth tides and the Earth's free oscillations using the long-period seismograms of the Bolivian great deep earthquake on June 9, 1994 recorded by a broad band seismometer and the SG. The results suggested that combination tones between the free oscillations and the semidiurnal tide existed.

From the analyses based on the SG data of 3 years at Syowa, Nawa et al. (1998), for the first time in the world, reported the evidence of incessant excitation of the Earth's free oscillations mainly of the fundamental spheroidal modes in a frequency ranges from 0.3 to 0.5 mHz. The frequency-time spectrogram of this record is striped by more than 30 lines mostly corresponding to the fundamental modes at mgal level parallel to time axis. They compared it with a synthetic spectrogram based on the assumption that only natural earthquakes take part in the free oscillations in order to investigate the cause of the excitation, and suggested the possibility of earthquake origin. Variable motions in the atmosphere and/or oceans are also discussed as one of possible excitation sources of the observed incessant Earth's free oscillations.

Department of Geophysics, Kyoto University continued observation of tidal gravity change using two LCR gravimeters at Shizuoka and Omaezaki in Tokai district, central Japan. Li et al. (1996) investigated the detectabilities of nontidal and tidal gravity changes at both stations. As for the nontidal gravity changes, it is difficult to detect meaningful signals in the order of 1 μgal/year because of large and irregular drifts of gravimeters. They showed that δ-factor fluctuations more than 1% could not be expected before and after earthquakes smaller than M=6.5 at the epicentral distance of 100 km.

5. Non-tidal Gravity Changes

5.1 Gravity Changes Associated with Crustal Deformation and Seismic and Volcanic Activity

Gravity changes before a coming great earthquake in a seismic risk region of Tokai District have been monitored with both absolute and relative gravimeters, according to a national project of earthquake prediction. Relative field gravity measurements in the district have been repeated since 1981, as a joint research of the NAOM, Nagoya University and Kyoto University. More than 6 gravimeters have occupied about 40 stations, most of them are bench marks distributed in 60 km x 70 km area, every June for taking a possible seasonal gravity variation into consideration. The gravimeters have been the LCR model-G and D meters, and the Scintrex CG3M and the ZLS LAND meters are also employed for recent years. The accuracy is estimated to be a few microgals for all the stations every year. In the southern part of the district, gravity changes according to the Bouguer gradient have been found in the earlier stage. Namely, at the southern end of Omaezaki, the relative gravity increase of 1 μgal/year is consistent with the relative height change of 5 mm/year. The 1998 gravity measurements has revealed that the same tendency has still continued (National Astronomical Observatory Mizusawa et al., 1998).

In order to clarify possible secular/annual changes in gravity, the GSI and the ERI have been collaboratively conducting absolute gravity measurements at Omaezaki and Kakegawa with their respective FG5 absolute gravimeters since 1996. The GSI has already carried out the absolute gravity measurements eleven times at Omaezaki and expected the detection of a secular change of gravity there. This can be associated with the subsidence at Omaezaki observed by spirit leveling, due to the subduction of the Philippine Sea Plate.

The ERI carried out absolute gravity measurements at Omaezaki, Tokai, Japan where the great Tokai earthquake has long been anticipated. They compared their results in 1995 and in 1996 with previous results by the GSI in 1987 and by the NAOM in 1992 (Okubo, Yoshida and Araya, 1997). They found regional gravity decrease during an interseismic period at the subduction plate boundary where the land is steadily subsiding. This paradoxical finding poses a challenging problem on the subduction dynamics at converging plate boundaries.

The Hydrographic Department of Japan (JHD) carried out gravity surveys at volcanic islands of the Izu-Ogasawara arc in 1995 and 1997 in order to detect a vertical crustal movement (Hydrographic Department, 1996a, 1997a, 1998a).

Department of Geophysics, Kyoto University carried out precise gravity measurements, repeatedly, in the southeastern part of Shikoku District, in order to detect the secular change of gravity. The gravity changes obtained were not correlated with the vertical movements obtained from leveling surveys which were performed during the almost corresponding period (Higashi and Kusumoto, 1996). Kyoto University repeated precise equi-gravity measurement since 1964 at a few year intervals in the Kii Peninsula including Kinki District and south of the peninsula for detecting the precursor of a coming large Nankaido earthquake, and Nakamura (1995) did not find clear increase of gravity there.

Ehara et al. (1995) carried out gravity monitoring during four and a half years at the geothermal zone in the central Kyushu, Japan and they could show the relational model between incoming and outgoing of underground mass. Nishijima et al. (1997) could find out gravity change related to the production of geothermal material in and around geothermal power plant area. They could avoid the effect of shallow ground water level change by using the method of multivariate regression analysis between precipitation and gravity change near the area. Hashimoto et al. (1996) repeated gravity measurement around Kuju volcano in the central part of Kyushu at a few week intervals after the eruption in October 1995. Though they could not find a distinguishable gravity change at the foot of the volcano, the gravity change amounted to 80 μgals near the crater. There were a characteristic pattern of the gravity change in the volcanic active process, that is, a quick increase of gravity soon after the eruption and a following gradual decrease. The decrease rate of mass of the volcano can be estimated as several tens of thousands tons per day from the observed gravity change.

5.2 Gravity Changes Associated with Groundwater Level

Beppu Geothermal Research Laboratory (BGRL), Kyoto University has been conducting precise gravity measurements since 1993 to detect gravity changes associated with groundwater variations in Beppu geothermal area (Fukuda et al., 1996). BGRL carried out supplementary leveling surveys in 1996-1997 (Fukuda et al, 1997b), and also carried out absolute gravity measurements in cooperation with ERI in 1995 and 1997, respectively. The results obtained so far show that the major parts of the gravity changes (about 60 %) are well explained by the groundwater level changes, while the other part needs further investigations.

Laboratory of Geothermics, Kyushu University carried out repeated gravity measurements at the four geothermal Fields (Hatchobaru, Takigami, Yamagawa and Oguni) and the erupting volcano (Kuju volcano) in Kyushu, Southwestern Japan in order to monitor the underground geothermal fluid flow systems. Characteristic common features of gravity change were detected at both geothermal fields and the erupting volcano (Ehara et al., 1995b; Tagomori et al., 1996; Ehara et al, 1997, 1998). In the production zones or near the active craters, gravity decreased rapidly just after the commencement of production of geothermal fluid or phreatic eruption and then rather rapidly increased. After that, gravity decreased gradually and became stable. In the reinjection zones, gravity increased a little just after the commencement of reinjection of wasted geothermal fluid and after that, the gravity did not change so much. Such a pattern of gravity change shows that the underground fluid flow is reaching a new hydrological equilibrium state after the commencement of production-reinjection of geothermal fluid or phreatic eruption.

5.3 Gravity Changes Associated with Sea Level Variation

Fukuda and Sato (1997) calculated gravity effects of sea level variations at 18 superconducting gravimeter (SG) sites over the world using satellite altimeter data. They also mapped the gravity effects on continental region and then employed Empirical Orthogonal Function (EOF) analysis to examine the details of the effects (Fukuda and Sato, 1998). Although the annual mode of the global variation (the lst mode) is dominant, this mode is mainly due to thermal expansion of sea water. As far as the gravity changes are concerned, the 2nd and the 3rd modes likely play more important role.

6. Gravity Survey in Japan

6.1 General

OYO Corporation (OYO) has established new gravity stations that amounts to 19,685 during the years from April, 1994 through March, 1998, that is, 1,075 for 1994, 5,104 for 1995, 6,488 for 1996 and 7,018 for 1997. Among the 19,685 stations, about 6,500 stations are for fault surveys carried out after the 1995 Hyogo-ken Nanbu Earthquake. Most of the remaining stations of about 13,000 are for various engineering problems such as disaster prevention, finding sink holes in karstic area, measuring depth to very shallow basement structure or building foundation, finding cavities in banking structure, etc. Nozaki et al. (1993) carried out gravity survey at 556 stations and determined 2-layered 3-dimensional gravity basement structure in the central part of the Mexico Basin, where severe damages were caused by the 1985 Michoacan Earthquake. Integrating the results by Nozaki et al. (1993) and those of the existing seismic reflection surveys, the Japan Building Disaster Prevention Association and Japan International Cooperation Agency (1996) have conducted re-analysis of gravity data to construct a more reliable 3-layered 3-dimensional basement structure in the central part of the Mexico Basin.

OYO (1995) has carried out basic feasibility study of geophysical methods including microgravity survey method (Takahashi et al., 1997). Detectability of microgravity anomalies arising from the anomalous density distribution in sedimentary layers (typically shallower than several hundred meters), which is deformed by fault movement, has been tested at the Nojima Fault, using 312 gravity data in the 1350 m x 2500 m survey area, and using subsequently selected 109 data in the 180 m x 70 m area. Gravity surveys have so far been conducted in a variety of geophysical survey applications for large scale subsurface investigations, such as geodetical, geophysical, volcanological and disaster prevention researches, exploration for resources as petroleum, minerals, and so on. In this sort of gravity survey, let's say an ordinary gravity survey, all of the field planning and data processing are based on the gravity measurements of the order of 1 mgal or 0. 1 mgals.

On the other hand, as the portability, stability, and accuracy of modern gravimeters, such as the LCR and the Scintrex CG-3M meters, have increased, microgravity survey; which is based on microgal-order gravity measurements, has come to be used in various scientific and engineering fields. From the view-points of microgravity survey, Nozaki and Kanemori (1996) presented some typical examples for detecting micro-folding/faulting in deformed sedimentary layers shallower than 50 m deep, stalactite caves or sink holes in karstic areas, etc. Nozaki (1997) discussed the differences between the microgravity survey and the ordinary gravity survey, and showed the expected structure scale detectable by microgravity anomaly is to be of the order of 1 m; accordingly, the typical spacing of gravity stations will be about 1 m. Such examples of microgravity survey are for detecting very shallow artificial objects as buried remains, abandoned mine shafts, buried slags in reclaimed land, etc., as well as natural density anomalies in very shallow sedimentary layers down to several tens meters.

Nagoya University has been conducting a gravity survey in southwestern Japan since 1978. During the period concerned, about 14,000 of new data are added to its gravity database, which now stores about 40,000 gravity data. Areas covered were southeastern Kyushu, seismic source region of the 1995 Hyogo-Ken Nanbu Earthquake, Toyama Plain and its vicinity in Hokuriku District, the Yoro Mountains and the Nobi Plain in Tokai District and so on. By performing total revision on all gravity data collected from more than 20 of other organizations, Nagoya University has compiled a gravity database, which covers southwestern Japan very densely with about 110,000 points of high precision gravity data.

Nawa et al. (1997) proposed a new inversion method based on the Bayesian approach to obtain the lateral density variation of the terrain above sea level. They applied the method to southwest Japan by using 45,000 gravity data.

Gravity Research Group in Southwest Japan created a precise gravity anomaly map in southwest Japan with more than 80,000 gravity data. This map reveals an excellent correlation between tectonic boundaries or known faults and Bouguer anomaly distributions. Yamamoto and Shield (1994) found in this map that there are many abrupt changes of gravity anomalies which do not correspond to any known surface boundaries or geologic structures and suggest that these changes indicate the existence of hidden faults or tectonic boundaries.

6.2 Hokkaido Area

Hokkaido University carried out gravity surveys and established more than 1000 stations in the eastern Hokkaido area in 1996-1997. The new Bouguer gravity map reveals many features and suggests that the thickness of surface deposits appears to be greater than 1.5 km assuming a density contrast of 1.0 g/cm^3. In the southern part of the Hidaka Mountains, located in the middle Hokkaido, Hokkaido University has made extensive gravity surveys together with vibro-seismic reflection and magnetotelluric surveys during 1994-1997 to improve the gravity coverage and to detect the inclined structures of the Hidaka. Main Thrusts (HMT) beneath the Hidaka Mountains (Arita et al., 1998). Gravity measurements were made along the three routes across the Hidaka Mountains and their surroundings and Hokkaido University established more than 1000 new stations. Vibro-seismic results show us the clear reflection zone in the HMT which is inclined eastward and continues at least at a depth of 12 km, assuming the P-wave velocity of 6 km/s. Arita et al. (1998) inverted gravity data together with the results from seismic data and obtained a best fit model as a preliminary crustal structure across the Hidaka Mountains. Synthetic gravity shows a good agreement with the observed gravity along the three profiles across the Hidaka Mountains.

The Geological Survey of Japan (GSJ) has conducted gravity surveys in order to prove the brief feature of gravity anomalies in Hokkaido area at about 5,500 stations during the period from 1992 to 1997.

6.3 Honshu Area

The GSJ published the 2,500 gravity data of the Kitakami Mountains obtained during the period from 1989 to 1992 (Morijiri et al., 1995). The New Energy Development Organization (NEDO) conducted gravity surveys for research and development of geothermal resources in Kakkonda geothermal area, Iwate Prefecture, with 362 gravity data, and locations and heights of stations were determined by differential GPS. For the purpose of covering the region where gravity data are scarce, the GSJ has obtained about 2,500 gravity data until March 1998 in a part of Kinki and Kyushu District.

OYO Tohoku Branch Office conducted a gravity survey for the purpose of exploiting a new hot spring near Sendai City, Miyagi Prefecture. Total number of gravity stations amounted to 259 in the 13 km x 13 km survey area (Ministry of Construction Tohoku Regional Construction Bureau, 1996).

OYO Tokyo Branch Office analyzed the existing Bouguer anomaly data (grid data provided by GSJ) over a 93 km x 95 km area of southern Kanto District, the central portion of which the Tachikawa Fault locates, and conducted a new gravity survey at 1,524 stations in the 51 cm x 20 km area crossing over the southeastern extension of outcrop of the Tachikawa Fault (Yokohama City Office, 1997). After the 1995 Hyogo-ken Nanbu Earthquake, many active fault surveys, which are financially supported by the Science and Technology Agency, have been carried out in Japan to evaluate the fault activities and to investigate the faulting experiences. In the course of such surveys, the Tokyo Branch Office has analyzed the existing Bouguer anomaly data, provided by Nagoya University and the GSI, over a 90 km x 70 km area around the Fujikawa Fault System, Shizuoka, Japan, and carried out a detailed gravity survey at 680 stations in the 4 km x 7 km rectangular area (Geological Survey of Japan, 1996a).

It is commonly thought that Mt. Fuji has no isostatic: root because the contour lines of Bouguer anomalies are not disturbed over Mt. Fuji. Shizuoka University (Tanaka and Satomura, 1995) carried out gravity measurements in the area around Mt. Fuji, and made a new Bouguer anomaly map and an isostatic anomaly map, in order to reconsider whether the Mt. Fuji has an isostatic root or not. There is no clear difference in the contour shapes between the two anomaly maps. This result shows that undisturbance of contour lines of the Bouguer anomaly at Mt. Fuji is not a necessary condition for non-achievement of isostasy. Shizuoka University carried out gravity measurements and compiled the gravity data in Tokai District in the central part of Honshu Island, Japan. Satomura (1995) discussed some tectonic aspects there such as land collisions by the plate motions, faulting and seismic disaster, from the gravity data.

A gravity survey across the Median Tectonic Line (MTL) was conducted together with seismic reflection and refraction, and magnetotelluric surveys, (Ito et al., 1996a, b). The MTL, with a length of more 1000 km is the most significant fault in Japan. Gravity was measured at intervals of 125 m with 13.5 km length. More than 200 density models were tested based on the structural frame derived from the seismic reflection results. Their results confirm that the MTL dips northward at about 30 to 40 degrees from the surface to about 5 km depth, where it becomes listric. This fault geometry more reasonably explains the reactivation history of the MTL; the motion has occurred on a listric-type fault in so-called oblique or lateral ramp manner.

Kanazawa et al. (1997) made gravity survey near the MTL in the area in Kinki District where geological structure of the MTL is complicated. They surveyed at the interval of 200-300 m in and around the MTL and of 500 m-2 km in the surrounding area. Bouguer anomaly map shows high and low anomaly zones parallel to the MTL. In the western part of the area, the position of high gravity anomaly zone is north side of the MTL. On the contrary it is south side of the MTL in the eastern part of the area. We can get an important information to study the structure of the MTL.

OYO Hokushin'etsu Branch Office analyzed the existing Bouguer anomaly data (grid data provided by the GSJ) over a 115 km x 96 km area around Toyama Prefecture, and carried out a detailed gravity survey at 656 stations in 6 km x 14 km area which includes the Kurehayama Fault and the Kurehayama Hill (Toyama Prefectural Office, 1997). OYO Chubu Branch Office analyzed the existing Bouguer anomaly data, provided by Nagoya University and the GSI, over a 50 km x 70 km area, including a part of the MTL, and conducted a detailed gravity survey at 503 stations in the selected 5.0 km x 12.5 km area around Ise City (Mie Prefectural Office, 1998).

Hagita et al. (1997) revealed some prominent subsurface structure of the Himi and the Isurugi Faults, Toyama Prefecture, Hokuriku District. Unlike the Isurugi active fault that characterizes the western boundary of the Toyama Plain, the Himi Fault shows neither clear topographic lineaments nor large fault zones. The Himi Fault does not seem to be an active fault but is likely to have finished its main activity before the Pliocene. Kunitomo and Shichi (1995) analyzed subsurface structures of the boundary faults developing in the western and southern margins of the Kofu Basin, Yamanashi Prefecture, central Japan.

OYO Kansai Branch Office carried out a detailed gravity survey in the eastern part of Kyoto City and its peripheral mountainous area, where the Hanaore Fault runs through (Geological Survey of Japan, 1996b). In the survey, 615 stations are newly occupied in the 4.7 km x 3.7 km area.

The Department of Geophysics, Kyoto University carried out a test gravity survey to detect the detailed structure of an active fault in Kyoto Prefecture. The intervals of the gravity points were set less than 50 m and the obtained gravity data were carefully analyzed (Iwano et al, 1998). The result of the gravity survey showed a good agreement with the seismic reflection survey conducted separately.

Inoue et al. (1995, 1997), Ryoki and Nakagawa (1995, 1997) and Ryoki (1997) tried to make clear the basement structure of Osaka Sedimentary Basin, inferred from gravity anomaly in many methods. They pointed out that it is useful to take off the effect of large-scale structure such as the Philippine Sea slab in advance before the calculation of local underground structure of this area, and that decrease in apparent density contrast between sediment and bedrock layers affected by fluctuation of depth level of the boundary is not negligible, even in the case that the effect of inhomogeneous mass distribution of the sediment layer takes main part. They estimated the depth of bedrock using the methods of density measurement of care samples from boreholes for a hot spring, seismic reflection survey, geological survey and so on. The revised Bouguer anomaly map showed clearly steeper gradient of gravity anomaly in the seismic source area than that outside of the area. This is the first map for us to recognize the existence of active faults realistically by using the physical observation around this area, although it is described previously in geological or topographical point of view. The Koyo Fault which runs in Ashiya and Nishinomiya City is not considered to be a seismogenic fault from a seismological point of view, but damaged zones caused by the earthquake distribute complexly around the fault. Jido et al. (1997) and Akamatsu et al. (1998) discussed the bedrock structure around the Koyo Fault referring the observation results of the aftershocks, the microseisms, the seismic reflection survey and the dense gravity survey in and around the area. They made clear that the eastern part of the bedrock at the boundary of the Koyo Fault subside by 700-800 m. DPRI and Nagoya University and the GSJ are now carrying out dense gravity survey not only in Awaji Island nor near Kobe but around Osaka Bay (Osaka Basin) to estimate the bedrock structure comprehensively in the area.

Concerning the Hyogoken Nanbu Earthquake, a precise gravity survey on land was carried out in 1995 and the number of data amounted to about 1,800 points (Murata et al., 1996; Makino et al., 1996). A sea bottom gravity survey was carried out in Osaka Bay and the eastern part of the Harima-Nada open sea, and 408 gravity data was obtained (Komazawa et al., 1996).

The ERI and Nagoya University carried out dense gravity measurements with the Fast Static GPS positioning along five survey lines across the Rokko Fault system (Kobayashi et al, 1996a, 1997a). They calculated the Bouguer anomaly to estimate the underground structure relevant to the 1995 Hyogoken Nanbu Earthquake (M=7.2, Jan.17, 1995). They applied the two-dimensional Talwani's method to the modeling, assuming that the density structure is similar for all the five survey lines. All the Bouguer anomaly profiles are characterized by flat areas on the Rokko Mountains and Kobe Plain, with steep gradient between them. The gradient is most likely due to the fault scarps between the Rokko granite and the sedimentary layer of the Osaka and Kobe groups. It also indicates that the faults are vertical or reverse ones, at least just below their surface traces. This finding is consistent with the tectonic background of the Rokko Mountains that have upheaved under the east-west compression in the Quaternary. Moreover, they found the southwestward extension of the Koyo Fault underneath the sedimentary layer. The extension runs on the edge of the earthquake disaster zone. They inferred that the thickness of the sedimentary layer is 1-2 km near the sea, decreasing gradually toward the mountain side. The wedge-like structure and the hidden fault under the Kobe Plain may have served as a focusing lens of seismic rays during the earthquake.

Shichi et al. (1995) made dense gravity survey at several hundreds meters in the northern part of Awaji Island where the Nojima Fault appeared on the ground surface when the Hyogo-ken Nanbu Earthquake occurred and in the western part of Kobe City. Shichi et al. (1996) extended survey area from Awaji Island to Nishinomiya City (east of Kobe City) and to northern part of Kobe City. Surveyed area covered perfectly the area of the earthquake source. Shichi and Aoki (1995) analyzed subsurface structure of the seismic source region of the Hyogo-Ken Nanbu Earthquake inferred from gravity anomaly, and explained the occurrence of belt-like zonal distribution of the seismic intensity 7 (in Japan meteorological Agency scale).

OYO Chugoku Branch Office carried out gravity data analysis for the purpose of exploiting a new hot spring in Matsue City, in which 500 gravity data provided by Shimane University and Nagoya University were used (Matsue City Office, 1994). The Chugoku Branch Office carried out gravity basement survey for re-utilization of abandoned field of salt-pan (Kinkai Salt Producing Corporation, 1995). Three hundred and ninety-seven stations were established in 2.6 km x 3.7 km survey area, where the Geological basement consisting of granite and Mesozoic sand stone and shale is overburdened by Diluvium and Alluvial deposits. The Chugoku Branch Office analyzed the existing gravity data (grid data provided by the GSJ) over a 40 km x 60 km axes around Yamaguchi Prefecture, and carried out detailed gravity surveys in two selected sites along the Kikukawa Fault; the one is Utanogawa site, where 349 stations are occupied in the 2.0 km x 3.4 km area, the other is Shimohogi site, where 166 stations are occupied in the 200 m x 600 m area (Yamaguchi Prefectural Office, 1997).

DPRI carried out dense gravity measurement with cooperation with Tottori university in and around the Yamasaki active fault which ranges from ESE (near west boundary of Kobe) to WNW (near the junction of Tottori, Okayama and Hyogo Prefectures, West Honshu Island). Many kinds of observations such as seismic, geodetic, geochemical, geomagnetic and so on are now carrying out near the fault.

Shimane University carried out gravity measurements in the western Chugoku and the central Kyushu Districts. Including the data measured in 1993, more than 5,000 points of gravity data are stored in its gravity database. By analyzing gravity anomalies in the surrounding areas of Mts. Sanbe and Daisen, Komuro et al. (1996) and Komuro et al. (1997) revealed the basement structures of respective volcanic regions.

6.4 Shikoku and Kyushu Area

For a search of hot springs and geothermal resources, the GSJ conducted gravity surveys in Tanegashima with about 600 gravity stations, and in Hirado City, Nagasaki Prefecture, with about 350 stations.

OYO Kyushu Branch Office analyzed the existing Bouguer anomaly distribution (grid data provided by the GSJ) over a 71 km x 84 km area covering whole Fukuoka Prefecture, and conducted two detailed gravity surveys; one is for the Minou Fault at 342 stations in 8.5 km x 7.5 km axes, the other is for the Kego Fault at 267 stations in the 6.6 km x 4.3 km area (Fukuoka Prefectural Office, 1997). The Kyushu Branch Office analyzed the existing Bouguer anomaly data (grid data provided by the GSJ) over an 85 km x 73 km area, which covers most Kagoshima Prefecture, and subsequently conducted gravity surveys along three profile lines with total number of stations 137. These observed gravity anomaly profiles are compared with the calculated ones due to geological models (Kagoshima Prefectural Office, 1998).

A dense gravity survey was carried out around the summit craters of the Kirishima volcanoes by using the Scintrex CG-3M gravimeter together with the GPS positioning. Subsurface structures relevant to the Kakuto, the Kobayashi and the Anraku calderas were inferred from the precise Bouguer anomaly data (Kobayashi et al., 1995a; Kobayashi et al., 1995b; Kobayashi et al., 1996b). Kobayashi et al. (1997a, b) discussed the relation between gravity features and the tectonics of southern Kyushu District.

BGRL carried out a test gravity survey to detect the detailed structures of an active fault in Beppu area, Northeast Kyushu (Fukuda et al., 1994; Fukuda et al., 1995). Because of the small density contrast and large regional gravity gradient, the fault structure was hardly detected.

Nishida and Katsura (1998) and Katsura and Nishida (1998) carried out gravity survey in the northern part of Kyushu Island, where the Fukuchiyama Fault and the Kokurahigashi Fault range north and south. They find out difference of 2 km in elevation, in case of the maximum, along the Fukuchiyama Fault inferred from gravity anomalies of the field. And they find that fault zone estimated from the gravity survey is fitted better to the geological boundary than to the topographical lineament zone. Along the Kokurahigashi Fault, the northern part of the fault has a different feature in the elevation opposite to the other part of the same fault. They surveyed at 500 m distance in the 15 km (EW) x 10 km (NS) area and at lesser dense of distribution of observation points out side of the area (25 km x 25 km).

Ehime University conducted a gravity survey in and around Shikoku and Kyushu, and obtained gravity data at 543 stations since 1994. Based on the data, Ohno et al. (1994) found out and analyzed a significant negative anomaly belt in the western Seto Inland Sea.

7. Marine Gravimetry

The GSJ has been conducted marine gravity surveys since 1974 using the survey vessel "Hakurei-maru." The vessel is equipped with the LaCoste & Romberg straight-line sea gravimeter, SL-2. The cruises during the period from 1994 through 1997 are listed in Table 1. Gravity surveys were conducted as a part of the Geological mapping program of the continental margin around the Japanese Islands. Free-air and Bouguer anomaly maps have been published as appendices of "Marine Geology Map Series" at a scale of 1:200,000 (Geological Survey of Japan, 1995, 1996c, 1996d, 1998).

Table 1. Cruises for marine gravimetry by the GSJ during the period from 1994 to 1997

Cruise ID	Cruise Period	Survey Area
GH94	Jun. - Jul. 1994	West of Oshima Peninsula (southwest of Hokkaido)
CH95	Jun. - Jul. 1995	Off Shakotan Peninsula (west of Hokkaido)
GH96	Jun. - Jul. 1996	Around Ishikari Bay (west of Hokkaido)
GH97	Apr. - May 1997	Off Tokai district

The JHD carried out marine gravity surveys using two survey vessels " Meiyo" (550 gross tons) and "Takuyo" (2,600 gross tons) during the period from 1994 to 1998. These vessels are equipped with the sea gravimeter Bodenseewerk KSS-30. The cruises from April 1994 through March 1998 are listed in Tables 2 and 3 (Hydrographic Department, 1997b, 1997c, 1998b, 1998c).

Table 2. Cruises of "Meiyo" for sea gravity surveys conducted by the JHD during the period from April 1994 to March 1998

Cruise Period	Survey Area
Apr. 1994	Japan Trench
May 1994	Offing Akita Yamagata
Feb. 1995	Akasi Kaikyo and Osaka Wan
Apr. 1995	Isikaxi Wan
Aug. 1995	Ise Wan
Jan. 1996	Offing Tosa Wan
May 1996	Suruga Wan
Jul. 1996	Offing Rumoi Okusiri
Sep. 1996	Offing Kusiro
Dec. 1996	Offing Hatizyo

Apr. 1997	Thmogasima
Aug. 1997	Offing Rumoi

Table 3. Cruises of "Takuyo" for sea gravity surveys conducted by the JHD during the period from April 1994 to March 1998

Cruise Period		Survey Area
Apr. - May	1994	Oki-no-Tori Sima
Jul.	1994	Eastern part of Daito Ridge
Aug. - Sep.	1994	Western part of Oki-no-Tori Sima
Oct. - Nov.	1994	Oki-no-Tori Sima
Nov. - Dec.	1994	Western part of Oki-no-Tori Sima
Jan.	1995	Southwestern part of Oki-no-Tori Sima
Apr. - May	1995	Southeastern part of Oki-no-Tori Sima
May - Jun.	1995	Minami-Koho Seamount
Sep.	1995	Southeastern part of Oki-no-Tori Sims,
Oct. - Nov.	1995	Oki-no-Tori Sims.
Nov. - Dec.	1995	Oki-no-Tori Sima
Jan.	1996	Oki-no-Tori Sima
Mar.	1996	Southern part of Oki-no-Tori Sima
Apr. - May	1996	Southern part of Oki-Daito Sima
May - Jun.	1996	Okinawa Trough
Jun. - Jul.	1996	Okinawa Trough
Aug. - Sep.	1996	Okinawa Trough
Nov. - Dec.	1996	Southern part of Oki-Daito Sims,
Jan.	1997	Southwestern part of Oki-Daito Ridge
Mar.	1997	Southwestern part of Oki-no-Tori Sima
Apr. - May	1997	Southern part of Okinawa
Jun.	1997	Southwestern part of Oki-Daito Ridge
Jul. - Aug.	1997	Southern part of Miyako Sima
Oct.	1997	Southern part of Okinawa
Nov. - Dec.	1997	Southern part of Okinawa
Feb. - Mar.	1998	Western part of Minami-Tori Sima

8. Data Handling and Gravity/Geoid Maps

The GSJ published a detailed complete Bouguer anomaly map of Abukuma District, Kitakami District, Oshima District, Tomakomai District and Sapporo District from about 60,000 data as part of the gravity mapping program of the Japanese Islands (Makino et al., 1995; Komazawa et al., 1996b: Hiroshima et al., 1997; Hiroshima et al., 1998; Komazawa et al., 1998).

The GSI published a geoid model in and around Japan in 1998 as one of its digital data series, "Digital Data 5 km Grid (Geoidal Height)" stored in a 1.44 MB floppy disk. The data is widely available to GPS surveyors and anyone else.

Four maps of free-air gravity anomalies are published in the series of the basic map of the Sea (map Nos. 6603G, 6722G, 6725G, 6726G) by the JHD. The maps 6722G, 6725G and 6726G, which cover vast area of southern waters of Japan, were produced by compiling gravity data obtained in series of continental shelf surveys by the survey vessel "Takuyo". Ueda (1996) compiled gravity and magnetic anomaly maps covering the Izu-Ogasawara arc from the marine gravity and magnetic surveys by the JHD. A basement magnetic map was obtained by applying the three-dimensional inversion method. Characteristic features of the crust of the Izu-Ogasawara were discussed from the viewpoint of the magnetic, gravity and topographic features.

Since the declassification of the Geosat Geodetic Mission (Geosat/GM), cross-track resolution of satellite altimeter profiles has improved remarkably.

To utilize the high-density satellite altimetry profiles, Terada and Fukuda (1997a, b) tried to use the raw 10 Hz sampling of the GEOSAT/GM data, They carried out some tests in the Southern Ocean and the Antarctic margin and showed that more detailed structures could be retrieved from the 10 Hz sampling data. Using TOPEX/Poseidon altimeter data, Terada et al. (1998) performed a test to investigate whether the 10 Hz sampling data contain geophysically meaningful information or not. The results showed that the 10 Hz sampling data enough contained geophysical meaning in the areas of low oceanographic variations.

9. Gravity Data Analysis

A quantitative gravimetric analysis in and around Aso Caldera in western Japan was conducted and the basement structure was estimated (Komazawa, 1995). It is obvious that the Caldera is formed not only by single depression but multiple depressions and is classified into piston-cylinder type caldera (Valles type) in consideration of its circular steep gradients of basement. A method for estimation of surficial rock densities was also shown. An improved method for two-dimensional gravity analysis by using logarithmic functions was proposed, which can be applied to a shallow and/or a deep basement structure (Makino, 1997).

Doi (1997) estimated a load Green's function for gravity by an inversion method employing gravity changes induced by atmospheric pressure loading. He introduced a theoretically estimated load Green's function as a priori data for calculating a minimum variance solution and the function within 4° from Kyoto was estimated using the data observed by the superconducting gravimeter at Kyoto University. By employing the observationally estimated load Green's function, the atmospheric effects on gravity were corrected more precisely.

Kusumoto et al. (1996) presented a new detailed Bouguer anomaly map for the eastern part of the Beppu Shimabara Graben and a three-dimensional subsurface structure in the region. The obtained structure showed that the eastern part of the Beppu-Shimabara Graben is more likely to be composed of a group of small basins rather than a part of the large graben across central Kyushu. To explain the formation and the tectonic history of these small basins, Kusumoto et al. (1997a, b) carried out a numerical modeling using a simple dislocation model. The result showed that the tectonic basins in and around Beppu Bay were pull-apart basins formed by right-lateral motions of one pair of the active faults. The restoration modeling is useful not only to reveal the tectonic history but also to find a caldera structure. There remains a gravity low in the Beppu Bay area, the low which could not be restored by the modeling. With some Geological evidences, Kusumoto et al. (1998) concluded that the gravity low is caused by a buried caldera.

10. Geoid and Theoretical Study of Gravity Field

Kuroishi (1995) determined the precise gravimetric geoid of Japan, JGEOID93, in 3' x 3' meshes complete to degree and order 360, using the spherical 2-D FFT method with surface gravity data of about 38,000 on the land and about 480,000 on the sea, referring to the OSU91A geopotential model. An iterative algorithm for coordinate conversion from the Tokyo datum to the geocentric frame and a simultaneous adjustment method for crossover errors in ship gravity data were newly developed, and data refinement procedures were improved significantly (Kuroishi et al., 1994). Comparisons with GPS observations on five local networks consisting of bench marks show that the geoid model has an accuracy better than 10 cm. in wavelength shorter than 15 arc degrees and that there exist systematic discrepancies approximated by a tilted plane of 2~4 ppm down in the east, suggesting long wavelength errors. Application of the JGEOID93 to combined adjustment with GPS and terrestrial survey was studied by Nakane and Kuroishi (1995, 1996a-c, 1997). The accuracy of the orthometric height determined from GPS data is estimated to be a few centimeters for small areas if the geoid including the tilt error correction is used, and then the geoid and the GPS data are satisfactory to yield the orthometric heights in local survey.

The GSI developed a height conversion model from the ellipsoidal height measured by GPS to the practical height for fundamental and public surveys in Japan. For this purpose, the GSI carried out nation-wide GPS observations on about 900 first-order bench marks. The GPS/leveling geoid obtained is completely independent of the gravimetric geoid (JGEOID93) and is considered to be more accurate in longer wavelength. Thus Mikuda et al. (1997a) estimated the correction values to the gravimetric geoid in order to compare with the GPS/leveling geoid. The final result showed that the rms difference between the GPS/Leveling geoid and the gravimetric geoid after the correction is better than 7 cm in all survey areas. Further improvement of Japanese geoid has been under way at the GSI. As an initial approach, performance of a newer geopotential model, EGM96 as the reference model is evaluated over Japan (Kuroishi, 1998). Comparisons with GPS/leveling geoidal heights reveal that the EGM96 geoid holds superiority in short wavelength resolution to OSU91A over wide areas in Japan, but no substantial improvement comes out in smaller areas covered by surface gravity data even if the reference model is replaced.

Okubo (1995) discussed the gravity and its potential changes for three types of dislocation model: 1) a point dislocation in a homogeneous half-space, 2) faulting on a finite rectangular plane in a homogeneous half-space, and 3) faulting in a spherically symmetric earth. He presented analytic formulas of the gravity and potential changes for the first two cases, and presented a series expression for the third case. They enable us to evaluate coseismic changes in surface gravity and geoid height. Sun Wenke and Okubo (1998) presented numerical formulation for computing elastic deformations caused by a dislocation on a finite plane in a spherically symmetric earth. It is based on their previous work for a point dislocation. The formulation enables them to compute the displacement, potential and gravity changes due to an earthquake modeled as spatially distributed dislocations. As an application of the finite-fault dislocation theory, they made a case study of the theoretical and observed gravity changes. The computed results are in excellent agreement with the observed gravity changes during the earthquake. The gravity changes in the near field can reach some hundred microgals which can be easily detected by any modern gravimeter. In a far field it is still significantly large: $|\delta g| > 10$ μgals within the epicentral distance $\theta < 6°$, $|\delta g| > 1$ μgal within $\theta < 16^{\circ\circ}$, $|\delta g| > 0.1$ μgals within $\theta < 40°$, and $|\delta g| > 0.01$ μgals globally. They also calculated the geoid height changes caused by the 1964 Alaska Earthquake and by its variation. They found that the great earthquake should have caused the geoid height as large as 1.5 cm.

Sengoku and Ganeko (1994) estimated mean sea surface height and its variation from ERS-1 altimeter data from 1992 to 1993. The variability of the sea surface height clearly shows the strong ocean currents such as the Kuroshio. They found good correlation between the sea level anomaly obtained from altimetry and the Kuroshio path estimated from oceanographic observations.

The JHD continued satellite laser ranging (SLR) observation of remote sensing satellites and geodetic satellites at the Simosato Hydrographic Observatory (Hydrographic Department, 1996b, 1997d, 1998d). The SLR observation of altimeter satellites contributes to precise orbit determination which is indispensably important for altimetry. Kubo-oka (1998) estimated the impact of the SLR tracking at Simosato to TOPEX/Poseidon (T/P) orbit determination. The result suggests that the effect of the Simosato SLR data appears not only above Japan but also on the whole orbit of T/P.

Yamamoto et al. (1994) determined geoid undulation differences using GPS/leveling survey in the southwestern part of Japan. The precision of the GPS/leveling geoid differences determined was estimated to be about 11 cm in which the precision of the ellipsoidal height difference measured by employing GPS, that of the orthometric height difference measured by leveling and others were included. Yamamoto (1994) investigated the geoid undulation differences by employing both GPS/leveling survey and surface gravity data in the southwestern part of Japan. The geoid differences were evaluated only from gravity data with the FFT method, and the geoid differences evaluated were then compared with the GPS/leveling ones.

The result showed the geoid differences were evaluated with a precision of 10~15 cm in this area.

Kagoshima University determined precise geoidal height in and around Sakurajima volcano by using GPS observations at the geodetic control points, and detected spatial pattern of the geoidal undulation which coincides with volcanic depression in and around the crater and agrees with the profile of volcanic underground structure determined from gravity anomaly. The GPS observations also detected two positive undulations in the E-W direction on the outer sides of the depression which are considered to be produced by the formations of Kagoshima graben and Sakurajima volcano in the tectonic field of the E-W compression and N-S elongation (Saishoji et al., 1994; Tanaka et al., 1995; Tanaka et al., 1996; Tanaka, 1997a; Tanaka et al., 1997; Tanaka, 1997b).

11. Lunar and Planetary Gravimetry

The NAOM et al. are pursuing the project RISE (Research In SElenodesy) which measures angular distances between a radio transmitter on a lunar orbiter, that on the Moon, and quasars by differential VLBI together with a laser altimeter and a relay satellite. This project is under SELenological and ENgineering Explorer (SELENE) Project which is Japanese lunar program by the Institute of Space and Astronautical Science (ISAS) and National Space Development Agency of Japan (NASDA), and is to be launched in 2003. It can measure amplitudes of the physical librations and gravitational harmonic coefficients of the Moon with an accuracy one or two orders higher than before (Araki et al., 1996a; Araki et al., 1996b; Hanada, 1996b; Hanada et al., 1996b; Heki et al., 1996; Kawano et al., 1996; Araki et al., 1997; Hanada. et al., 1997c).

Ooe and Hanada (1995a, 1995b) investigated the feasibility of measurement of the mass and the gravity fields of the asteroid NEREUS by using a small gravimeter and by differential VLBI, and concluded that the latter has the advantage of measuring wider axes of the NEREUS although the former method is more feasible than the latter.

In the asteroidal mission MUSES-C by the ISAS, the spacecraft is planned to approach and touch down on the surface of an asteroid to collect samples there. The spacecraft falls freely on it's way to the surface in order to measure gravity and mass of the asteroid. By using LIDAR which is laser ranging instrument for navigation, data of range measurement during free fall (~2 km → ~ 0.1 km in altitude) are obtained at 1 Hz. Gravity and mass of the asteroid are inverted from the data. The goal of our measurement is to determine the asteroid's mass of 1% error. But perfect free fall of spacecraft is rather difficult because of the necessity of spacecraft maneuvering for it's safety touch down. It should be examined that mass inversion of the asteroid is possible or not when velocity disturbance is introduced to the free fall ranging data (Araki et al., 1996b).

Yatabe (1996) derived an expression of the residual gravity field, which consists of the tidal force, the centrifugal force and others, by using the equation of geodesic deviation in general relativity. Applying the expression to the Goddard Lunar Gravity Model 2 (GLGM-2) and the Goddard Lunar Topographic Model 2B (GLTM-2B), Yatabe (1998) found that there is a correlation between the ratio of the residual gravity and the lunar shapes.

12. Superconducting Gravimetry

As a six-years program, GGP (Global Geodynamics Project) has started on July 1, 1997. This is a project with a global network of Superconducting Gravimeter (SG), and the main goal of the project is to acquire the data which are obtained from simultaneous, continuous and high-resolution observations carried out at a number of international SG sites. Japanese GGP group is developing a global SG network, which is called 'GGP Japan-Network', and a sub center of this network is established at the ORI to collect and archive the data of GGP Japan-Network. The network consists of 6 stations; they are, from the north, Esashi station of the NAOM, Matsushiro site of the ORI, Kyoto site of Kyoto University, Bandung site in Indonesia, Canberra site in Australia and Syowa station of the NIPR. An important characteristics of the GOP Japan-Network is in its distribution of the sites on the Earth. The most of the GOP sites of other countries are located in a narrow latitude zone in the northern hemisphere. GOP Japan-Network improves the defect in the distribution of the GOP sites. This is important for the study of the latitude dependency on the Earth's free oscillations and the Earth tides, as well as for global stacking of the data in search for such weak signals as the core gravity modes (Sato et al., 1998).

Imanishi et al. (1996) measured the mechanical responses of the two SGs respectively installed at Esashi and Matsushiro. The characteristics is well approximated by the motion of a proof mass described by a second-order differential equation for a damped oscillation. Their measurement suggested the eigen frequency of 0.20 Hz to 0.24 Hz and the damping constant of 3.0 to 3.5 for the SO, respectively. In order to determine the scale factor of the SO, Sato et al. (1996b) carried out a comparison measurement with FG5 #109 of the ERI for five days in May, 1996 at Esashi. As the results, they showed; 1) the scale factor of the SO previously obtained from the comparison with the LCR gravimeters agrees with that obtained from the absolute values within about 0.2 % and 2) the scale factor from FG5 #109 also agrees with that estimated by FG5 #102 of NOAA (National Oceanographic and Atmospheric Administration of the USA) in 1993 at Esashi within 0.17 %. These comparison results suggest that it is sufficiently possible to calibrate the SO using such an absolute gravimeter as FG5 with the accuracy better than 1 %.

Fukuda and Sato (1997) estimated the gravity effect of sea level variation at the SO sites in the world based on the sea surface height data estimated from ERS-1 and TOPEX/Poseidon altimeter data.

Their results suggest that 1) the gravity effects vary in peak-to-peak amplitudes from 1.5 to 4 μgals according to the site position, and they have a same dominant frequency in variations, i.e. 1 cycle/year but different phases, 2) they also discuss the effect of the ocean variability on the observed polar motion effect of gravity, and suggested the SO observations have a potential to detect not the thermal expansion of the sea water but the mass changes which could not be observed by the satellite altimetry.

Continuous observations of gravity changes have been carried out employing two superconducting gravimeters (SGs; model TT-70, #008 and #009) at Kyoto University since 1988. Mukai et al. (1995c) investigated the effect of room temperature changes on precise gravity observation with the SGs. They clarified that the effect of the room temperature changes on gravity observation can be ignored in the period band shorter than a few days, even if the air conditioner is not used. Higashi (1995, 1996) clarified the instrumental differences between the two SGs comparing the data obtained under similar observation conditions, and confirmed that the SO had high sensitivity and long-term stability for the detection of the long period tides, the free core resonance and the gravity changes due to the polar motion, even in the observation site where the city noises are fairly large. Mukai et al. (1995a, 1995b) estimated atmospheric effects on gravity observations at Kyoto by using meteorological data sets. About 90 % of the atmospheric effects were attributed to local atmospheric variations within 50 km of the station. The remaining effects owing to the air mass outside this zone were of the regional air mass around Kyoto. Comparing the SO data, the residuals showed gravity changes of a few microgals, a part of which might be caused by sources such as variations of the ground water level around the station.

On December 1994, the Aso Volcanological Laboratory of Kyoto University (AVL) installed the SO at the 30 m depth tunnel, which was located about 1 km from the active crater of Aso Volcano, for the purpose of detecting the gravity changes with the volcanic activity. No change of gravity has been observed until now, because Aso Volcano has been continuing to be quiet since 1993. The AVL also has repeated the precise measurements of gravity survey along the climbing road from the foot to the active crater with the precise leveling.

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