ASSOCIATION INTERNATIONALE DE GÉODÉSIE

BUREAU

GRAVIMETRIQUE

INTERNATIONAL

BULLETIN D'INFORMATION

N° 60

Juin 1987

18, avenue Edouard-Belin
31055 TOULOUSE CEDEX
FRANCE

Informations for Contributors

Contributors should follow as closely as possible the rules below :

Manuscripts should be typed (double-spaced) in Prestige-Elite characters (IBM-type), on one side of plain paper 21 cm x 29.7 cm, with a 2 cm margin on the left and right hand sides as well as on the bottom, and with a 3 cm margin at the top (as indicated by the frame drawn on this page).

Title of paper. Titles should be carefully worded to include only key words.

Abstract. The abstract of a paper should be informative rather than descriptive. It is not a table of contents. The abstract should be suitable for separate publication and should include all words useful for indexing. Its length should be limited to one typescript page.

Table of contents. Long papers may include a table of contents following the abstract.

Footnotes. Because footnotes are distracting, they should be avoided as much as possible.

Mathematics. For papers with complicated notation, a list of symbols and their definitions should be provided as an appendix. All characters that are available on standard typewriters should be typed in equations as well as test. Symbols that must be handwritten should be identified by notes in the margin. Ample space (1.9 cm above and below) should be allowed around equations so that type can be marked for the printer. Where an accent or underscore has been used to designate a special type face (e.g., boldface for vectors, script for transforms, sans serif for tensors), the type should be specified by a note in the margin. Bars cannot be set over superscripts or extended over more than one character. Therefore angle brackets are preferable to overbars to denote averages, and superscript symbols (such as *,$'$, and $^{\neq}$) are preferable to accents over characters. Care should be taken to distinguish between the letter O and zero, the letter l and the number one, kappa and k, mu and the letter u, nu and v, eta and n, also subscripts and superscripts should be clearly noted and easily distinguished. Unusual symbols should be avoided.

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

References. A complete and accurate list of references is of major importance in review papers. All listed references should be cited in text. A complete reference to a periodical gives author (s), title of article, name of journal, volume number, initial and final page numbers (or statement "in press"), and year published. A reference to an article in a book, pages cited, publisher, publisher's location, and year published. When a paper presented at a meeting is referenced, the location, dates, and sponsor of the meeting should be given. References to foreign works should indicate whether the original or a translation is cited. Unpublished communications can be referred to in text but should not be listed. Page numbers should be included in reference citations following direct quotations in text. If the same information has been published in more than one place, give the most accessible reference ; e.g. a textbook is preferable to a journal, a journal is preferable to a technical report.

Tables. Tables are numbered serially with Arabic numerals, in the order of their citation in text. Each table should have a title, and each column, including the first, should have a heading. Column headings should be arranged to that their relation to the data is clear.

Footnotes for the tables should appear below the final double rule and should be indicated by a, b, c, etc. Each table should be referred to in the text.

Illustrations. Original drawings of sharply focused glossy prints should be supplied, with two clear Xerox copies of each for the reviewers. Maximum size for figure copy is (25.4 x 40.6 cm). After reduction to printed page size, the smallest lettering or symbol on a figure should not be less than 0.1 cm high ; the largest should not exceed 0.3 cm. All figures should be cited in text and numbered in the order of citation. Figure legends should be submitted together on one or more sheets, not separately with the figures.

Mailing. Typescripts should be packaged in stout padded or stiff containers ; figure copy should be protected with stiff cardboard.

Address :

BUREAU GRAVIMETRIQUE INTERNATIONAL

18, Avenue Edouard Belin

31055 TOULOUSE CEDEX

FRANCE

Phone :

61.27.44.27
61.27.40.72

Telex :

CNEST B 531081 F
or
7400298

BUREAU GRAVIMETRIQUE INTERNATIONAL

Toulouse

BULLETIN D'INFORMATION

Juin 1987

N° 60

Publié pour le Conseil International des
Unions Scientifiques avec l'aide financière
de l'UNESCO
Subvention UNESCO 1986 DG/2.1/414/50

TABLE OF CONTENTS

Bull. d'Inf. n° 60

Pages

PART I : *INTERNAL MATTERS*

PART II : *CONTRIBUTING PAPERS*

PART I

INTERNAL MATTERS

GENERAL INFORMATIONS

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

1. HOW TO OBTAIN THE BULLETIN

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

The Bulletin contains general informations on the community, on the Bureau itself. It informs about the data available, about new data sets, ...

It also contains contributing papers in the field of gravimetry, which are of technical character. More scientifically oriented contributions should better be submitted to appropriate existing journals.

Communications presented at general meetings, workshops, symposia, dealing with gravimetry (e.g. IGC, S.S.G.'s,...) are published in the Bulletin when appropriate - at least by abstract.

Once every four years, a special issue contains (solely) the National Reports as presented at the International Gravity Commission meeting. Other special issues may also appear (once every two years) which contain the full catalogue of the holdings.

About three hundred individuals and institutions presently receive the Bulletin.

You may :

- *either request a given bulletin, by its number (59 have been issued as of Jan. 1 1987, but numbers 2, 16, 18, 19 are out of print),*
- *or subscribe for regularly receiving the two bulletins per year plus the special issues.*

Requests should be sent to :

Mrs. Nicole ROMMENS
CNES/BGI
18, Avenue Edouard Belin
31055 TOULOUSE CEDEX - FRANCE

Bulletins are sent on an exchange basis (free of charge) for individuals, institutions which currently provide informations, data to the Bureau. For other cases, the price of each number is as follows :

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

2. HOW TO REQUEST DATA

2.1. Station Description Diagrams for Reference, Base Stations (including IGSN 71's)

Request them by number, area, country, city name or any combination of these.

When we have no diagram for a given request, but have the knowledge that it exists in another center, we shall in most cases forward the request to this center or/and tell the inquiring person to contact the center.

Do not wait until the last moment (e.g. when you depart for a cruise) for asking us the information you need : station diagrams can reach you by mail only !

2.2. G-Value at Base Stations

Treated as above.

2.3. Mean Anomalies, Mean Geoid Heights, Mean Values of Topography

The geographic area must be specified (polygon). According to the data set required, the request may be forwarded in some cases to the agency which computed the set.

2.4. Gravity Maps

Request them by number (from the catalogue), area, country, type (free-air, Bouguer...), scale, author, or any combination of these.

Whenever available in stock, copies will be sent without charges. If not, two procedures can be used :

- *we can make (poor quality) black and white (or ozalide-type) copies at low cost,*
- *color copies can be made (at high cost) if the user wishes so (after we obtain the authorization of the editor).*

The cost will depend on the map, type of work, size, etc... In both cases, the user will also be asked to send his request to the editor of the map before we proceed to copying.

2.5. Gravity Measurements

They can be requested :

(a) either from the CGDF (Compressed Gravity Data File). The list and format of the informations provided are the following :

CGDF RECORD DESCRIPTION
60 CHARACTERS

Col. 1	Classification code - 0 if not classified
2- 8	B.G.I. source number
9-15	Latitude (unit = 1/10 000 degree)
16-23	Longitude (unit = 1/10 000 degree)
24	Elevation type 1 = Land 2 = Subsurface 3 = Ocean surface 4 = Ocean submerged 5 = Ocean bottom 6 = Lake surface (above sea level) 7 = Lake bottom (above sea level) 8 = Lake bottom (below sea level) 9 = Lake surface (above sea level with lake bottom below sea level) A = Lake surface (below sea level) B = Lake bottom (surface below sea level) C = Ice cap (bottom below sea level) D = Ice cap (bottom above sea level) E = Transfer data given
25-31	Elevation of the station (0.1 M) This field will contain depth of ocean (positive downward) if col. 24 contains 3, 4 or 5.
32-36	Free air anomaly (0.1 mgal)
37-38	Estimation standard deviation free air anomaly (mgal)
39-43	Bouguer anomaly (0.1 mgal) Simple bouguer anomaly with a mean density of 2.67 - No terrain correction.
44-45	Estimation standard deviation bouguer anomaly (mgal)
46	System of numbering for the reference station 1 = IGSN 71 2 = BGI 3 = Country 4 = DMA
47-53	Reference Station
54-56	Country code
57	1 : measurement at sea with no depth given 0 : otherwise

Col. 58 Information about terrain correction
0 = no information
1 = terrain correction exists in the archive file

59 Information about density
0 = no information or 2.67
1 = density ≠ 2.67 given in the archive file

60 Information about isostatic anomaly
0 = no information
1 = information exists but is not stored in the archive file
2 = information exists and is included in the archive file.

(b) or from the Archive file. The list and format of the informations provided are the following :

ARCHIVE FILES
RECORD DESCRIPTION
160 CHARACTERS

Col. 1- 7 B.G.I. Source number

8- 12 Block number
Col. 8-10 = 10 square degree
Col. 11-12 = 1 square degree

13- 19 Latitude (Unit : 1/10 000 degree)

20- 27 Longitude (unit : 1/10 000 degree) (-180 to +180 degree)

28 Accuracy of position
The site of the gravity measurement is defined in a circle of radius R
0 = No information on the accuracy
1 = R <= 20 M (approximately 0'01)
2 = 20 < R <= 100
3 = 100 < R <= 200 (approximately 0'1)
4 = 200 < R <= 500
5 = 500 < R <= 1000
6 = 1000 < R <= 2000 (approximately 1')
7 = 2000 < R <= 5000
8 = 5000 < R
9 ...

29 System of position
0 = unknown
1 = Decca
2 = visual observation
3 = radar
4 = loran A
5 = loran C
6 = omega or VLF
7 = satellite
9 = Solar/stellar (with sextant)

30- 31 *Type of observation*

A minus sign distinguishes the pendulum observations from the gravimeter ones.

0 = current observation of detail or other observation of a 3 rd or 4th order network
1 = observation of a 2nd order national network
2 = observation of a 1st order national network
3 = observation being part of a national calibration line
4 = individual observation at sea
5 = mean observation at sea obtained from a continuous recording
6 = coastal ordinary observation (Harbour, Bay, Sea-side...)
7 = harbour base station

32 *Elevation type*

1 = Land
2 = Subsurface
3 = Ocean surface
4 = Ocean submerged
5 = Ocean bottom
6 = Lake surface (above sea level)
7 = Lake bottom (above sea level)
8 = Lake bottom (below sea level)
9 = Lake surface (above sea level with lake bottom below sea level)
A = Lake surface (below sea level)
B = Lake bottom (surface below sea level)
C = Ice cap (bottom below sea level)
D = Ice cap (bottom above sea level)
E = Transfer data given

33- 39 *Elevation of the station (0.1 M)*

This field will contain depth of ocean (positive downward) if col. 32 contains 3, 4 or 5.

40 *Accuracy of elevation (E)*

0 = unknown
1 = E <= 0.1 M
2 = 1 < E <= 1
3 = 1 < E <= 2
4 = 2 < E <= 5
5 = 5 < E <= 10
6 = 10 < E <= 20
7 = 20 < E <= 50
8 = 50 < E <= 100
9 = E superior to 100 M

41- 42 *Determination of the elevation*

= no information
0 = geometrical levelling (bench mark)
1 = barometrical levelling
2 = trigonometrical levelling
3 = data obtained from topographical map
4 = data directly appreciated from the mean sea level
5 = data measured by the depression of the horizon

(marine)
Type of depth (if Col. 32 contains 3, 4 or 5)
1 = depth obtained with a cable (meters)
2 = manometer depth
4 = corrected acoustic depth (corrected from Mathew's tables, 1939)
5 = acoustic depth without correction obtained with sound speed 1500 M/sec. (or 820 Brasses/sec)
6 = acoustic depth obtained with sound speed 800 Brasses/sec (or 1463 M/sec)
9 = depth interpolated on a magnetic record
10 = depth interpolated on a chart

43- 44 Mathews'zone
When the depth is not corrected depth, this information is necessary.
For example : zone 50 for the eastern Mediterranean Sea

45- 51 Supplemental elevation
Depth of instrument, lake or ice, positive downward from surface

52- 59 Observed gravity (0.01 mgal)

60 Information about gravity
1 = gravity with only instrumental correction
2 = corrected gravity (instrumental and Eotvos correction)
3 = corrected gravity (instrumental, Eotvos and cross-coupling correction)
4 = corrected gravity and compensated by cross-over profiles.

61 Accuracy of gravity (e)
When all systematic corrections have been applied

0 =		E	<=	0.05
1 =	.05	< E	<=	0.1
2 =	0.1	< E	<=	0.5
3 =	0.5	< E	<=	1.
4 =	1.	< E	<=	3.
5 =	3.	< E	<=	5.
6 =	5.	< E	<=	10.
7 =	10.	< E	<=	15.
8 =	15.	< E	<=	20.
9 =	20.	< E		

62 System of numbering for the reference station
This parameter indicates the adopted system for the numbering of the reference station
1 = for numbering adopted by IGSN 71
2 = BGI
3 = Country
4 = DMA

63- 69 Reference station
This station is the base station to which the concerned station is referred

70- 76	*Calibration information (station or base)* This zone will reveal the scale of the gravity network in which the station concerned was observed, and allow us to make the necessary corrections to get an homogeneous system.
77- 81	*Free air anomaly (0.1 mgal)*
82- 86	*Bouguer anomaly (0.1 mgal)* Simple bouguer anomaly with a mean density of 2.67 - No terrain correction.
87- 88	*Estimation standard deviation free air anomaly (mgal)*
89- 90	*Estimation standard deviation bouguer anomaly (mgal)*
91- 92	*Information about terrain correction* Horizontal plate without bullard's term
93- 96	*Density used for terrain correction*
97-100	*Terrain correction (0.1 mgal)* Computed according to the previously mentioned radius (col. 91-92) & density (col. 93-96)
101-103	*Apparatus used for the measurements of G*

Codes for col. 91-92:

- 0 = no topographic correction
- 1 = CT computed for a radius of 5 km (zone H)
- 2 = CT 30 km (zone L)
- 3 = CT 100 km (zone N)
- 4 = CT 167 km (zone 02)
- 11 = CT computed from 1 km to 167 km
- 12 = CT 2.5 167
- 13 = CT 5.2 167

Codes for col. 101-103:

- 0.. pendulum apparatus constructed before 1932
- 1.. recent pendulum apparatus (1930-1960)
- 2.. latest pendulum apparatus (after 1960)
- 3.. gravimeters for ground measurements in which the variations of G are equilibrated or detected using the following methods :
  - 30 = torsion balance (Thyssen...)
  - 31 = elastic rod
  - 32 = bifilar system
- 4.. Metal spring gravimeters for ground measurements
  - 42 = Askania (GS-4-9-11-12), Graf
  - 43 = Gulf, Hoyt (helical spring)
  - 44 = North American
  - 45 = Western
  - 47 = LaCoste-Romberg
  - 48 = LaCoste-Romberg, Model D (microgravimeter)
- 5.. Quartz spring gravimeter for ground measurements
  - 51 = Norgaard
  - 52 = GAE-3
  - 53 = Worden ordinary
  - 54 = Worden (additional thermostat)
  - 55 = Worden world wide

56 = Cak
57 = Canadian gravity meter, sharpe
58 = GAG-2
6.. Gravimeters for underwater measurements (at the bottom of the sea or of a lake)
60 = Gulf
62 = Western
63 = North American
64 = LaCoste-Romberg
7.. Gravimeters for measurements on the sea surface or at small depth (submarines..)
70 = Graf-Askania
72 = LaCoste-Romberg
73 = LaCoste-Romberg (on a platform)
74 = Gal and Gal-F (used in submarines) Gal-M
75 = AMG (USSR)
76 = TSSG (Tokyo Surface Ship Gravity meter)
77 = GSI sea gravity meter

104 Conditions of apparatus used
1 = 1 gravimeter only (no precision)
2 = 2 gravimeters (no precision)
3 = 1 gravimeter only (without cross-coupling correction)
4 = 2 gravimeters (influenced by the cross-coupling effect) with the same orientation
5 = 2 gravimeters (influenced by the cross-coupling effect) in opposition
6 = 1 gravimeter (compensated for the cross-coupling effect)
7 = 1 gravimeter non subject to cross-coupling effect
8 = 3 gravimeters

105 Information about isostatic anomaly
0 = no information
1 = information exists but is not stored in the data bank
2 = information exists and is included in the data bank

106-107 Type of the isostatic anomaly
0.. Pratt-Hayford hypothese
01 = 50 km including indirect effect (Lejay's tables)
02 = 56.9 km
03 = 56.9 km including indirect effect
04 = 80 km including indirect effect
05 = 96 km
06 = 113.7 km
07 = 113.7 km including indirect effect
1.. Airy hypotheses (equality of masses or pressures)
10 = T = 20 km (Heiskanen's tables, 1931)
11 = T = 20 km including indirect effect (Heiskanen's tables 1938 or Lejay's)
12 = T = 30 km (Heiskanen's tables, 1931)
13 = T = 30 km including indirect effect
14 = T = 40 km
15 = T = 40 km including indirect effect
16 = T = 60 km

17 = T = 60 km including indirect effect
6.......
65 = Vening Meinesz hypothesis "modified Bouguer anomaly" (Vening Meinesz, 1948)

108-112 Isostatic anomaly a (0.1 mgal)

113-114 Type of the isostatic anomaly B

115-119 Isostatic anomaly B

120-122 Velocity of the ship (0.1 knot)

123-127 Eotvos correction (0.1 mgal)

128-131 Year of observation

132-133 Month

134-135 Day

136-137 Hour

138-139 Minute

140-145 Numbering of the station (original)

146-148 Country code (B.G.I.)

149 Flag (internal use)

150-154 Original source number (ex. D.M.A. Code)

155-160 Sequence number

Whenever given, the theoretical gravity (g0), 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 :

$$g0 = 978031.85 * [1 + 0.005278895 * \sin^2 (\varphi) + 0.000023462 * \sin^4 (\varphi)], \text{ mgals}$$

where φ is the geographic latitude.

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

Formulas used in computing free-air and Bouguer anomalies

Elev Type	Situation	Formulas
1	Land Observation	FA = g + 0.3086*H - g0 BO = FA - 0.1119*H
2	Subsurface	FA = g + 0.2238*D2 + 0,3086*(H-D2) BO = FA - 0.1119*H
3	Ocean surface	FA = g - g0 BO = FA + 0.06886*H (H = depth of ocean positive downward from surface)
4	Ocean submerged	FA = g - g0 BO = FA + 0.06886*H (D2 =depth of instrument positive downward) (H = depth of ocean positive downward)
5	Ocean bottom	FA = g + 0.3086*H - g0 BO = FA + 0.06886*D1 (D1 = depth of ocean positive downward)
6	Lake surface (above sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.04191*D1 - 0.1119*(H-D1) (D1 = depth of lake positive downward)
7	Lake bottom (above sea level)	FA = g + 0.08382*D1 + 0.3086*(H-D1) - g0 BO = FA -0.04191*D1 - 0.1119*(H-D1)
8	Lake bottom (below sea level)	FA = g + 0.08382*D1 + 0.3086*H-D1) - g0 BO = FA - 0.04191*D1 - 0.06999*(H-D1)
9	Lake surface (above sea level with bottom below sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.04191*H - 0.06999*(H-D1)
A	Lake surface (below sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.1119*H + 0.06999*D1
B	Lake bottom (surface below sea level)	FA = g + 0.3086*H - 0.2248*D1 - g0 BO = FA - 0.1119*H + 0.06999*D1 (D1 = depth of lake positive downward)
C	Ice cap (bottom below sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.03843*H - 0.07347*(H-D1) (D1 = depth of ice positive downward)
D	Ice cap (bottom above sea level)	FA = g + 0.3086*H - g0 BO = FA - 0.03843*D1 - 0.1119*(H-D1) (D1 = depth of ice)

2.6. Satellite Altimetry Data

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

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

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

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

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

All requests for data must be sent to :

Mr. Daniel LAMY
Bureau Gravimétrique International
18, Av. E. Belin - 31055 Toulouse Cedex - France

In case of a request made by telephone, it should be followed by a confirmation letter, or telex.
Except in particular cases (massive data retrieval, holidays,...) requests are satisfied within one month following the reception of the written confirmation, or information are given concerning the problems encountered.

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

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

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

The costs of the services listed below are a revision of the charging policy established in 1981 in view of the categories of users - mostly contributors of measurements and scientists, and also considering the large amount of support of our host organizations.

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

However, and at the discretion of the Director of B.G.I., some of the services listed below may be provided free of charge upon request, to data contributors, individuals working in universities, such as students, and generally to any person who can contribute to our activities on a data or documentation exchange basis.

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

3.1. Digital Data Retrieval

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

. minimum charge : 100 F.

. maximum number of points : 100 000 ; massive data retrieval will be processed and charged on a case by case basis.

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

. 20° x 20° blocks, as shown on the next pages (maps 1 and 2) : 400 F each set.
. For any specified area (rectangular configurations delimited by meridians and parallels) : 1. F per degree square ; 100 F minimum charge (at any scales, within a maximum plot size of : 90 cm x 180 cm).
. For area inside polygon : same prices as above, counting the area of the minimum rectangle comprising the polygon.

3.3. Data Screening

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

. 5 F/100 points to be screened
. 100 F minimum charge.

3.4. Gridding

(interpolation at regular intervals Δ in longitude and Δ′ in latitude - in decimal degrees) :

. $\frac{10\ F}{\Delta\Delta'}$ per degree square

. minimum charge : 150 F

. maximum area : 40° x 40°.

3.5. Contour Maps of Bouguer or Free-Air Anomalies

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

$\frac{10.\ F}{\Delta}$ per degree square, plus the cost of gridding (see 3.4) after agreement on grid stepsizes. (at any scale, within a maximum map size of : 90 cm x 180 cm).

. 250 F minimum charge

. maximum area : 40° x 40°.

3.6. Computation of Mean Gravity Anomalies

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

. minimum charge : 150 F

. maximum area : 40° x 40°.

3.7. Gravity Maps

3.7.1. Catalogue of all gravity maps :

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

3.7.2. Maps

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

- Special maps :

<u>Mean altitude maps</u>

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

Maps of gravity anomalies

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

World maps of anomalies (with text)

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

Charts of recent sea gravity tracks and surveys (1:36 000 000)

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

Miscellaneous

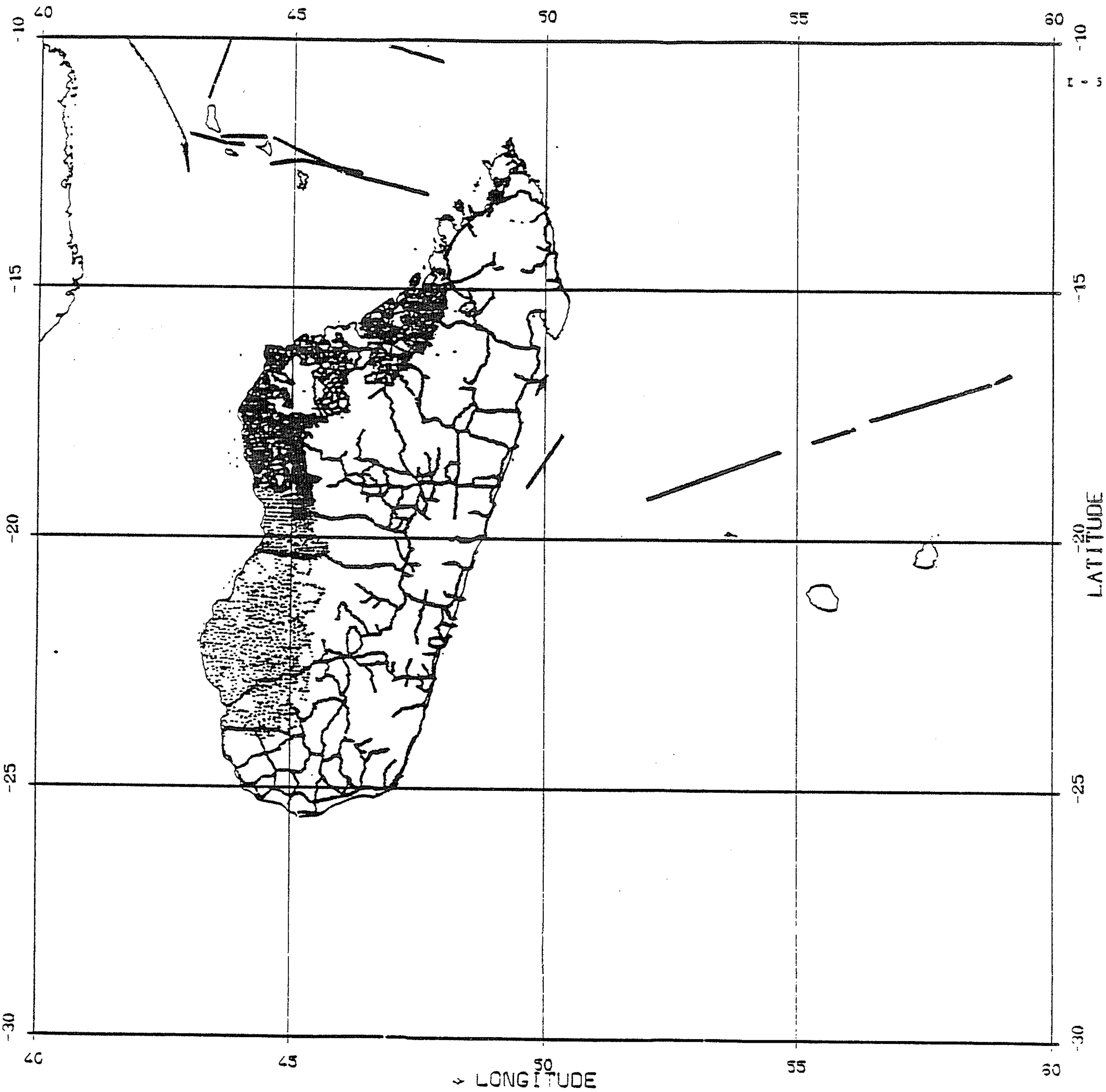
CATALOGUE OF ALL GRAVITY MAPS (listing)	1985	200 French Francs
THE UNIFICATION OF THE GRAVITY NETS OF AFRICA (t. 182)	1979	150 French Francs

- *Black and white copy of maps : 100 F per copy*

- *Colour copy : price according to specifications of request.*

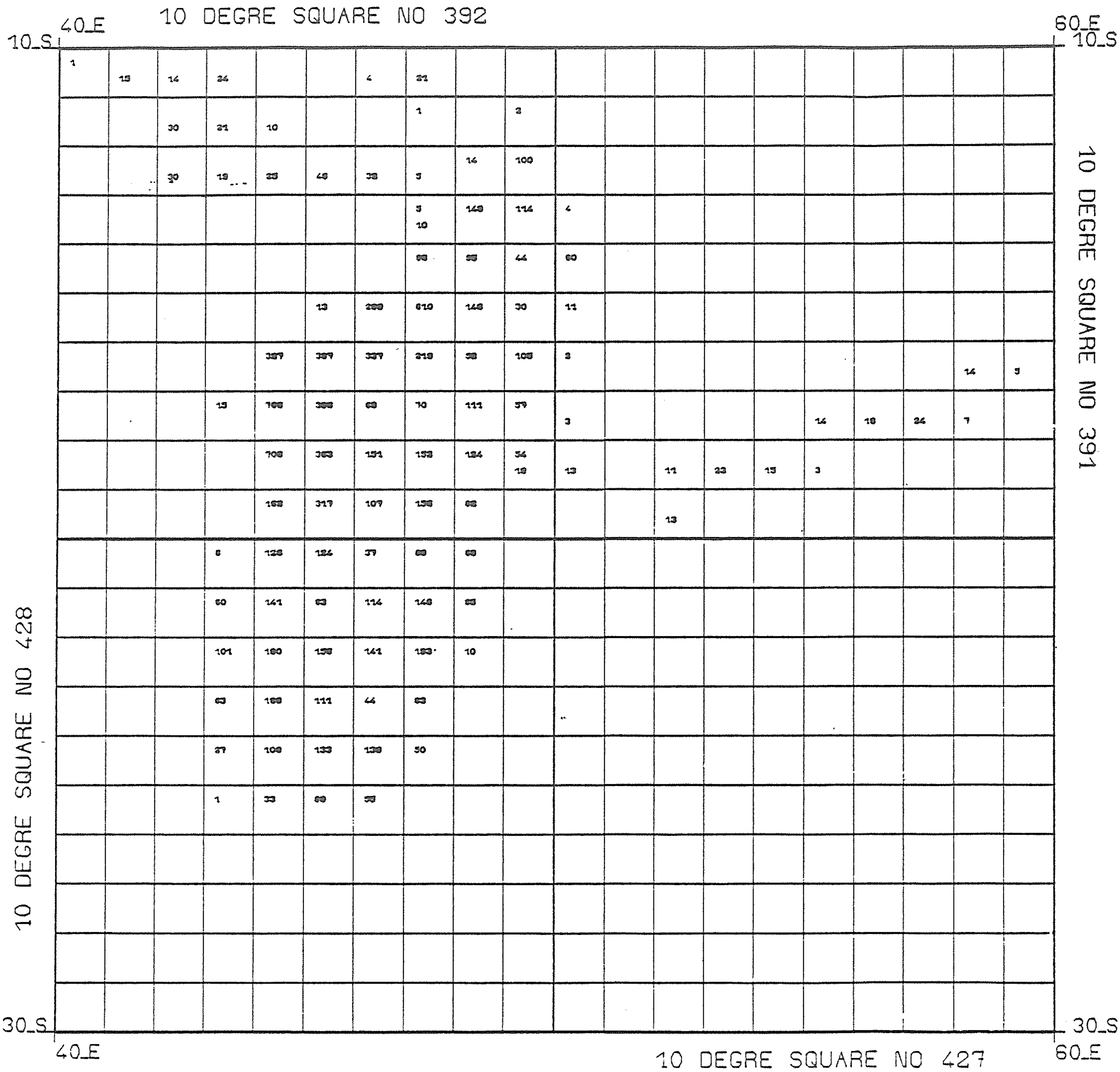
Mailing charges will be added for air-mail parcels
(when "Air-Mail" is requested)

Map 1. Example of data coverage plot



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

REPRESENTATION OF EARTH AND SEA GRAVIMETRIC STATIONS



4. PROVIDING DATA TO B.G.I.

4.1. Essential Quantities and Information for Gravity Data Submission

1. Position of the site :

- *latitude, longitude (to the best possible accuracy),*

- *elevation or depth :*
  - *. for land data : elevation of the site (on the physical surface of the Earth)**
  - *. for water stations : water depth.*

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

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

---

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

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

4.2. Optional Information

The information listed below would be useful, if available. However, none of this information is mandatory.

. *Instrumental accuracy :*

- *identify gravimeter (s) used in the survey. Give manufacturer, model, and serial number, calibration factor (s) used, and method of determinating the calibration factor (s).*

- *give estimate of the accuracy of measured (observed) gravity. Explain how accuracy value was determined.*

. *Positioning accuracy :*

- *identify method used to determine the position of each gravity measurement site.*

- *estimate accuracy of gravity station positions. Explain how estimate was obtained.*

- *identify the method used to determine the elevation of each gravity measurement site.*

- *estimate accuracy of elevation. Explain how estimate was obtained. Provide supplementary information, for elevation with respect to the Earth´s surface or for water depth, when appropriate.*

. *Miscellaneous information :*

- *general description of the survey.*

- *date of survey ; organization and/or party conducting survey.*

- *if appropriate : name of ship, identification of cruise.*

- *if possible, Eötvös correction for marine data.*

. *Terrain correction :*

Please provide brief description of method used, specify : radius of area included in computation, rock density factor used and whether or not Bullard´s term (curvature correction) has been applied.

. *Isostatic gravity :*

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

. *Description of geological setting of each site.*

4.3. Formats

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

The contributor may use, if he wishes so, the BGI Official Data Exchange Format established by BRGM in 1976 : "Progress Report for the Creation of a Worldwide Gravimetric Data Bank", published in BGI Bull. Info. n° 39, and recalled in Bulletin n° 50 (pages 112-113).

If magnetic tapes are used, contributors are kindly asked to use 1600 b.p.i. unlabeled tapes (if possible), with no password, and formated records of possibly fixed length and a fixed blocksize, too. Tapes are returned whenever specified, as soon as they are copied.

PART II

CONTRIBUTING PAPERS

GRAVIMETRIC RESEARCH CARRIED OUT WITHIN THE FRAME OF INTERNATIONAL COOPERATION OF COUNTRIES MEMBERS OF SUB-COMMISSION 7 "EAST EUROPE AND SOVIET UNION" IN 1983-1986

by

Yu.D. Boulanger

1. Non-tidal gravity changes in time were studied of both global and local nature.

1.1. Every 2-3 years repeated absolute gravity determinations are made for the study of global changes with the help of the absolute GABL gravimeter at points Moscow (Ledovo) and Novosibirsk (USSR), Warsaw (Poland), Potsdam (GDR), Pecni (Czechoslovakia), Budapest (Hungary), Sofia (Bulgaria).

1.2. Regional research is carried out at three sites :

- in GDR along the East-West line. Repeated observations are made systematically every year with participation of specialists from Hungary, Czechoslovakia and GDR. The changes, correlating with the geotectonic structure of the region, are obtained.

- in the area of the town of Vidin, by a group of Bulgarian and Soviet specialists, a test area was set up for the study of the possible gravity field changes caused by the changes in the water level of the Danube during the floods and low water periods. Four cycles of measurements were accomplished : two during high water level and two during low water level. A reliable correlation is obtained between the changes in the gravity value and the water level in the river.

- gravity changes with time were studied on the Carpathian geodynamic test area.

2. A standard test area was established for calibration of relative gravimeters using absolute determinations made by the GABL gravimeter in Warsaw, Potsdam, Pecni, Budapest, and Sofia. In 1987 this test area shall be amplified by a site in Bucharest. The accuracy of the scale of the test area has the relative error of about 5×10^{-6}.

3. At sites in Potsdam, Moscow, and Budapest a study was made of the non-linearity of the gravity field near the pillars on which the highly accurate gravity determinations are obtained.

   As the result of the experiments, the vertical gradient anomalies were recorded reaching 200 mcgal/m and the horizontal gradients exceeding 40 mcgal/m.

RAPPORT SUR LES ACTIVITES DE RECHERCHE DU B.R.G.M. EN GRAVIMETRIE POUR L'ANNEE 1986

by

R. Millon

*** Techniques gravimétriques de haute précision**

Une campagne de mesures du gradient vertical (350 mesures) a été faite sur le pilier A3 de Sèvres avec 3 gravimètres. Elle a abouti à proposer une nouvelle valeur (288 µgal/m) un peu supérieure (15 µgal/m) à celle de 1977.

Référence : Rapport B.R.G.M. 86 DT 028 GPH, M. Ogier et R. Millon : Déterminations statistiques du gradient vertical de la pesanteur sur le pilier A3 de Sèvres.

*** Banque de données gravimétriques**

La mise en banque de données des mesures gravimétriques entreprise au cours des années précédentes s'est poursuivie en 1986 et a porté essentiellement sur d'anciennes missions concernant le Nord de la France pour lesquelles le système de référence (Nord de Guerre) a dû être converti.

Références : Rapport B.R.G.M. 86 GPH 79, C. Mennechet - Vérification et correction de données gravimétriques (codes miniers 87 D et E ; 97 K, L, M et N ; 2074). Mise au point d'une procédure de travail.

Rapport B.R.G.M. 86 GPH 026, M. Ogier et F.X. Vaillant : Vérification de la banque de données gravimétriques françaises en date du 1/4/86.

*** Interprétations**

- Supervision de travail de thèses ou D.E.A. sur la gravimétrie :

  . de l'Aquitaine (F. Marchal)
  . de la Marche (Melle Lemaire)

- Interprétation gravimétrique de l'Albigeois pour la synthèse Pyrénées (Melle Sauron).

Calcul des effets de la croûte inférieure et du Moho pour des contrastes de densité variables latéralement (déduits des vitesses publiées). Etude des effets topographiques régionaux (N. Debeglia). Référence : Rapport B.R.G.M. 86 DT 014 GPH).

F O U R   Y E A R S   E X P E R I E N C E
W I T H   K S S 3 0   S E A G R A V I M E T E R

by

Bosko D. Loncarevic

Geological Survey of Canada

Bedford Institute of Oceanography

DARTMOUTH, N.S., Canada B2Y 4A2

A B S T R A C T

Since July 1981, we have used a KSS30 Seagravimeter on 13 cruises on 6 different ships. On ships over 2000t displacement, with winds under 30 kts, the repeatability of readings is better than 2 mGal after applying a drift correction (usually less than 0.1 mGal/day) and compensating for a filter delay. Comparisons with other instruments showed (i) An agreement of +/- 0.05 mGal RMS between two KSS30s; (ii) LaCoste and Romberg SL1 had a lower standard deviation on crossovers; (iii) KSS30 has the same or better accuracy as a bottom gravimeter; and (iv) New platform design (KT31) improves the standard deviation by a factor of two.

Presented at 12th Meetiing, International Gravity Commission, 22-26 September, 1986. Toulouse, France.

1. INTRODUCTION.

A new seagravimeter system was acquired by the Geological Survey of Canada (GSC) in July 1981. The system was immediately installed on CSS DAWSON and taken to sea for acceptance trials. The accuracy specified in the contract could not be demonstrated on that cruise and the final acceptance was withheld pending certain equipment improvements and further sea trials.

This report describes improvements in system performance as the result of evaluations on 13 cruises on a variety of ships over a four year period (see TABLE 1). The overall improvement of performance was a result of close cooperation between GSC and the equipment manufacturers leading to numerous hardware modifications and software changes (Loncarevic, 1986).

The instrumental development by the manufacturers, coupled with the development of operational procedures by GSC, resulted in an improved instrument. Under favourable conditions of accurate navigation, calm to moderate sea, and a ship with stable motion characteristics, the new instrument is capable of measurement accuracy of better than 1 mGal. Measurement of gravity at sea to this accuracy under less favourable conditions remains an elusive goal.

2. ACQUISITION OF A NEW SEA GRAVIMETER.

Sea gravity measurements have been conducted on Canadian Research ships since 1963. In the first fifteen years of that program several million observations were acquired using ASKANIA

Gss2 and LaCoste&Romberg seagravimeters. An analysis of this large data bank showed a number of problems with the observations due to unexpected errors, occasional large drifts, unexplained jumps ('tares') and unreliable calibration factors. Gss2 represented the late 1950's technology and by late 1970's was obsolete so that obtaining spare parts and maintenance was becomming increasingly more difficult.

A decision was reached therefore to replace Gss2 with a new instrument bearing in mind the following criteria.

1. Accuracy of better than 1.0 mGal on crossovers under most favourable conditions.

2. Readout precision of 0.05 mGal or better.

3. Stable and predictable drift of less than 2 mGal per month.

4. Reasonable accuracy (2 - 3 mGal) under vertical accelerations of 30 - 50,000 mGal (so that measurements could be made from smaller ships).

5. Adjustable filtering to allow for quick response during turning maneuvers (so that measurements could be made in ice infested waters).

6. Up-to-date digital technology including interfacing to other shipboard computers.

7. Transportability and ease of installation on different ships.

8. Well designed operator interface to allow easy monitoring and control.

9. Purchase price, reliability of supplier and

prospects for continuing improvements.

After an examination of the available equipment and discussions with manufacturers, a decision was made in the summer of 1980 to purchase a KSS30 seagravimeter from Bodenseewerk Geosystem GmbH, Ueberlingen, F. R. Germany (Sensor serial number 012). This was the first production unit to be delivered by the company.

3. EVALUATION AND SEA TRIALS.

The following account is a chronological description of cruises on which important aspects of equipment performance were evaluated. (Each cruise is identified by the ship's name, year and cruise number). On each one of these cruises a new aspect of equipment operation was discovered which resulted in improved performance. The account illustrates the need for continuing efforts in instrument development in order to make the highest accuracy gravity measurements.

3.1. DAWSON 81 - 037.

This was a short, two day cruise designed as a part of the acceptance trials. The evaluation was carried out on the Halifax Gravity Test Range (Goodacre, 1964). The old ASKANIA Gss2 seagravimeter was mounted next to the KSS30 platform and the readings of both instruments were compared to the reference gravity stations established by a bottom gravimeter. The navigation utilised an Integrtadted navigation system developed at the Bedford Institute of Oceanography - BIONAV (Grant, 1977;

Grant and Wells, 1984). BIONAV uses LORAN-C radio positioning network in range-range mode with a local atomic clock reference. The correction for clock offset is obtained from Transit satellite passes.

Interfacing of navigation to KSS30 system was difficult at first because the navigation computer could not be easily programmed to provide a formatted input to the gravimeter computer. The problem was solved during the cruise by inserting an HP85 desktop computer to reformat the data. BIONAV output new navigation information once every 10 seconds while the KSS30 requires input once every second. The ZE30 computer of the KSS30 system was re-programmed to cope with the slower rate of navigational updates but under those conditions the turn compensation could not be tested.

Although the test was conducted under ideal conditions of glassy calm sea, the gravimeter trace appeared more rugged than one would expect, caused by a somewhat erratic performance of the platform due to the 10 seconds step-wise input of navigation. There was also some ambiguity about the polarity of correction signals applied to the platform. At the end of the cruise an electrical instability of the gyro erection loop caused oscillations of the platform and the circuit had to be re-designed after the cruise. The importance of proper balancing of the sensor within its gimbals mounting was also recognized.

At the begining of the cruise the calibration factor was in error because the thumbwheel switches were set to 0.8937 instead of the correct value of 0.7937. This error manifested itself in discrepancies on opposite courses and the switches were reset half-way through the cruise.

An example of results from the cruise is shown in Fig. 1. It is seen that there is an offset between the two gravimeters due to different filtering constants. The general agreement between the two gravimeters and the reference gravity stations was encouraging. The repeatability of KSS30 observations was within 2 mGal and the agreement with reference stations was within 3 mGal.

3.2 LADY HAMMOND 81 - 060

This cruise was in late November during the worst time of the year for storms in Atlantic Canada. The main effort was testing of the platform and a number of measurements were made to gather data on the platform performance. As a result, it was discovered that a cross-coupling effect could be present if an error existed between the orientation of the gyro and gimbal axes. A new method of gyro mounting was designed to insure the accurate orientation within 2 seconds of arc.

It was also discovered that friction in platform bearings could seriously affect the platform under high horizontal accelerations. New circuits were designed to compensate for this friction. These design changes were implemented by the manufacturers in 1982 and greatly improved the performance of the platform.

3.3 QUEST 82 - 050

By the time this cruise sailed it was known that there were problems with the platform but the ship schedule could not be changed. The cruise therefore concentrated on the development of software for direct communication between the gravimeter and the navigation computer (BIONAV), on measurements of acceleration spectra under different sea conditions, and on design of a data logging system.

The effect of seiches was observed for the first time while making harbour observations prior to sailing. Seiches are standing waves observed in an enclosed body of water. They are caused by a passage of weather fronts, changing barometric pressure or gusty winds. The effect is illustrated in Fig. 2 with the data collected on a later cruise. Considering these disturbances and the effect of sea and earth tides, it was concluded that for a good harbour connection with an accuracy of 0.1 mGal, observations should be taken over a period of at least 36 hours (Loncarevic, 1982).

3.4 BAFFIN 82 - 039

Three gravimeters operated on this cruise under the "worst case" operating conditions. Two LaCoste and Romberg seagravimeters (SL1 and S56) were installed in the gravity lab in the centre of the ship while KSS30 was installed in the after lab near the stern of the ship and one deck above the sea level. Because the instruments were so far apart they experienced different acceleration environements and direct quantitative comparision of performance was not feasable.

Records of all three gravimeters over a 4 hour period are shown in Fig. 3. The records show that all three instruments agreed within a 1 mGal envelope. Close inspection of the records shows that KSS30 response was delayed relative to the L&R instruments. This was due to filter delay in KSS30. Although L&R had a longer time constant, its filter was designed so that it had a zero phase shift (LaCoste, 1983; Valliant, 1983).

The close correspondence of 'noise' recorded in all three instruments suggests a common cause. The ship was steaming at 6 kts with the wind on the port beam. Under these conditions, short term changes in the Eotvos effect are likely but could not be corrected for by the available navigational information.

During this cruise the KSS30 platform was inadvertantly left operating in the 'gyro erection Mode 2'. In this mode, turn maneuvering and earth rate compensations are disabled. When navigation input is not smooth, this is a better setting however, it was discovered that the Eotvos correction was not applied to the computed output. This was corrected by software revisions.

3.5 MAXWELL 83 - 004

On the basis of previous cruises and laboratory tests, a tentative conclusion was reached that the KSS30 seagravimeter was capable of meeting the manufacturers specifications of 0.2 to 0.3 mGal accuracy under good weather conditions, provided that adequately accurate navigational information could be supplied at the input to the gravimeter. It was therefore decided to carry out a further trial under carefully controlled conditions in Mahone Bay, N.S., a large protected bay about 100 km south of Halifax (Loncarevic and Woodside, 1984).

Mahone Bay was chosen for this trial because it is used by the Canadian Hydrographic Service as a proving ground for new navigational systems. Good geodetic control exists around the bay and the ship used (CSS MAXWELL, 270t displacement) has worked in the area so that its Captain was familiar with the problems of navigating along straight lines amongst the islands and shoals of the bay. Using a small ship had two further advantages: i) it is easier to navigate a small ship into a tight corner thus allowing us to extend our lines; and ii) we wanted to test the gravimeter on a small ship where the whole spectrum of accelerations and vibrations is shifted towards the higher frequencies.

The primary navigational aid for this cruise was a SYLEDIS system with three shore beacons and a mobile master on the ship. The system had a proven positional accuracy of 1 - 2 m and could calculate velocity and course at approximatly 2 second intervals. Two other aids were evaluated: an interface to digitize the ships gyro compas and an electro-magnetic (EM) log which could give a continuous output of two components of ships speed through the water. Both the gyrocompass and the EM log were interfaced to the KSS30 and provided speed and ship's head information in real time at one second intervals.

A large number of repeat lines run in the bay clearly identified two problems that must be overcome before high accuracy measurements of gravity at sea are possible. The first problem is the need to eliminate phase delay from the filter response. It was evident from this cruise that the data from the same lines run on opposite courses could not be compared directly because of the delay which was a function of the horizontal gradient of gravity and the ship's speed. The second problem was the exact conning of the ship along predetermined lines. In spite of the excellent positioning with Syledis, and numerous visual marks (Islands and marker buoys) it was virtually impossible to run exactly the same lines as can be seen from Fig. 4. Where the tracks corresponded exasctly, the agreement was everywhere within 1 mGal and the standard deviation was 0.26 mGal. (See dashed and dotted tracks in Fig. 4). Where the track departed from the intended line (see solid track in Fig. 4) the measured gravity also deviates from the mean value.

3.6 HUDSON 83 - 017

Two identical KSS30 systems with sensors S/N 012 and S/N 016 operated side-by-side during this cruise over a 28 day period. The instruments were installed in the gravity laboratory and the weather was generally good with calm seas.

The difference between the two meters for the duration of the cruise is shown in Fig. 5. It can be seen that there was a gradual and monotonous increase in the difference between the beginning and the end of the cruise due to a differential drift rate between two instruments (S/N 016 was a brand new instrument). It can be seen also that there is a correlation between the variations in gravity (lower profile) and variations in difference. This suggested an error in calibration of one of the instruments. After applying a 1.8 mGal/28 days correction for drift, and a 0.36% calibration factor correction the overall agreement between the two gravimeters was on the average within an envelope of 0.2 mGal while on straight course.

A detailed comparision of the outputs of two gravimeters over one hour period while travelling on course 090^{o} at 10 kts is shown in Fig. 6. The lower profiles are the raw gravity readings of the two instruments. At the scale of this plot (one vertical division = 2 mGal) almost everywhere the two instruments agree within the thickness of the pen line. The centre, random looking profile is the difference with the scale magnified by a factor of 10 (i.e. one vertical division = 0.2 mGal). The top (dotted) profile is the Eotvos correction constant everywher within +/- 0.5 mGal except near 184/0112 hours where there was a slight adjustment in speed resulting in a 2 mGal 'quasi' anomaly recorded by both meters. Near the end of the profile is a real gravity anomaly of about -9 mGal magnitude with a local gradient of almost 1 mGal/min. The anomaly is recorded by both meters with the same response within +/- 0.1 mGal.

A comparision of straight tracks from a small, carefully controlled grid survey showed an agreement between the meters with standard deviation of 0.056 mGal.

3.7 BAFFIN 84 - 044

During the five weeks of comparison between KSS30 and the LaCoste and Romberg SL1 seagravimeters in the area between Cape

Breton, N.S. and Newfoundland, we experienced a full range of operating conditions: from a flat calm sea to winds exceeding 50 knots, and from smooth gravity field to areas with large gradients over the continental shelf edge.

The layout of the survey with lines 10 n.m. apart and check lines at right angles 20 n.m. apart gave us 82 crossovers where the repeat readings of each instrument could be compared (Macnab et al., 1985). After correcting for positive drift and a delay response of two minutes, the KSS30 crossover errors had a standard deviation of 1.47 mGal. For SL1, the standard deviation is 0.87 mGal using the same crossovers. The histogram of crossover errors is shown in Fig. 7.

The layout of the survey was such that there were four orthogonal track directions. The mean differences between the readings of two instruments in four directions are shown in Table 2 and Fig. 8. There appeared to be a directional bias due to a heading error of one of the gyro platforms. This is the only time that a heading error was detected on either instrument and the observation remains unexplained.

As the accelerations experienced by a ship increase, the gravimeter records become noisier but it is difficult to establish a quantitaive relationship between the two. The simplest parameter to measure at sea is the wind speed and direction. These are regularly recorded by the bridge, at least once per watch (every four hours). These wind speeds are plotted as the lower profile in Fig. 9. The top profile is the standard deviation of the difference between the readings of two instruments averaged over 8 hour periods.

Although the correlation between the two curves is not perfect, the standard deviation increases substantially whenever the wind speed exceeded 25 kts. This occurred for over 29% of the time. Similarly, the standard deviation of the difference exceeded 1 mGal for about 32% of the time, usually following a period of strong winds. The standard Deviation exceeded 1 mGal for the last six days of the cruise indicating a considerable deterioration of weather after 14 November.

The increasing discrepancy between the readings of the instruments with increasing accelerations is attributed to less effective filtering of the KSS30 (an observation at variance with cruise BAFFIN 82-039, see earlier). SL1 had a symmetrical 60-point weighted filter with no phase delay and an effective time constant of 600 seconds. A numerical filter was designed to post-process KSS30 data to eliminate the phase delay and to apply the same degree of filtering as for SL1. The results are shown in Fig. 10, a. and b. This figure shows the SL1 (upper profile) and KSS 30 (lower profile) records displaced by 5 mGal from a KSS30 record passed through the new filter (middle). Data in Fig. 10.a. were recorded on a relatively calm day while those in Fig. 10.b. were from a stormy day. We see that the new filter is much more effective and produces a smoother record than either of the original profiles. Of course, one can always produce any degree of smoothing desired, provided a long enough sequence of data is available for filtering. In the process, the real anomalies will be smoothed out and some of the desired information will be lost.

To assess the improvement that the new filter may give us, the eight-hour standard deviation of the differences between two instruments were recalculated using post-processed data for the KSS30 with the filter constant of 600 seconds. The result is shown in Fig. 9 as the middle profile. The average standard deviation for the whole cruise is substantially reduced and the most dramatic improvement is on stormy days when the new filter decreases standard deviation by a half or more. The standard deviation for over 30,000 differences for the duration of the cruise drops from 1.34 mGal for data recorded on board ship to 1.02 mGal after post-processing of KSS30 data.

3.8 QUEST 85 - 139

The previous cruise (BAFFIN 84-044) had demonstrated that the performance of KSS30 was comparable, but somewhat inferior to that of SL1. Since the former is believed to have a better sensor, it was concluded that the discrepancy must be due to a defective or ineffective KT30 platform. This last evaluation was therefore organized to compare KT30 and the new KT31 platforms (Loncarevic et al., 1986).

The KT30 platform, delivered with the KSS30 system followed the design of the old ANSCHUETZ platform used with Gss2 gravimeters. In that design, the roll axis (i.e. axis parallel to the longitudinal axis of the ship) is supported at one end only. The instrument is cantilevered from this support point so that the bearing experiences a torque moment. In spite of special design and strengthening of this bearing, it is a vulnerable component. The adjustment of the bearing is critical and it can easily be damaged.

The new KT31 platform is of a radically different design. The sensor is mounted inside a double ring gimbal support with bearings in both axes supported at both ends. A smaller gyro used with KT31 can be mounted on the inner gimbals so that the displacement of the reference direction from the gyro housing is always small and the erection loop drives this difference to zero. The KT31 design is better, and it is evident that this platform can be made more accurate with less effort.

A detailed comparision of the performance of the two gravimeters is shown in FIG. 11. The upper plot (Fig. 11.a) shows a 'good' line; two instruments agree with each other well, within a fraction of a milligal, along the whole length of the profile. The raw gravity is smooth, indicating small horizontal accelerations and a smooth progress of the ship through the water without sudden course alterations or speed changes. The two Eotvos corrected gravity traces (profiles 3 and 4) follow each other and are smooth everywhere except for as small 'bump' just north of 43^{o}22N (caused by a spike in navigation).

The lower plot (Fig. 11.b) is an example of a 'poor' line; the agreement between the two instruments is not very good. There is an overall DC shift of the KSS30 so that its readings are almost 2 mGal lower everywhere. Even more disturbing are the negative 'bumps', the largest of which (just south of 43^{o}32N) exceeds 5 mGal.

These lines were a part of a set of 5 N-S and 4 E-W lines run on the Halifax Gravity Test Range. The mean difference at 20 crossovers (after tidal correction) was 0.42 mGal for KSS31 and 0.80 mGal for KSS30 gravimeters. The standard deviation was 0.288 and 0.535 mGal respectivly. The results indicate a factor of two improvement in accuracy of the KSS31 system.

During the first part of the cruise the ship sailed over 800 km due south of Halifax. After five days in the working area, the ship sailed back to Halifax thus covering a large range of gravity. The difference of the two gravimeters over this latitude range is shown in Fig. 12

The lower profile in this figure shows the Raw gravity which recorded almost 800 mGal gravity change due to latitude. The upper profile shows shows the difference bewteen the two systems (note change in scale) It is clear that there is a correlation between the two profiles thus indicating again that one of the instrument calibration factors was in error.

4. CONCLUSIONS

The experience of the evaluation of the KSS30 seagravimeter has confirmed our belief that the main obstacle to good gravity measurements at sea continues to be inadequate navigation. A SYLEDIS type of radio navaid can be used for a small survey with the distance to the farthest shore beacon of less then 100 km. The high cost and limited range make this useful only for special applications.

GPS NAVSTAR is still an unknown quantity since the announced policy calls for reduced accuracy when the system becomes fully operational in 1989 or 1990. While the positional accuracy of GPS will be more then adequate for gravity measurements, it is not clear that it will provide sufficiently accurate measurement of east-west velocity which is necessary for calculation of the Eotvos correction. Smooth, continuous, real time velocity information is essential and the only system that can provide it is an inertial navigator. We have not had an opportunity to evaluate such equipment but the experiments with the EM-log demonstrated the advantages of continuous velocity input.

One of the original objectives specified during the acquisition of the seagravimeter was the ability to cope with higher ambient accelerations than the old Gss2 and thus be able to operate on smaller ships. It is not clear that this objective has been acheived. It remains true that the quality of gravity measurements at sea is inversely proportional to the magnitude of the ambient accelerations. The more stable the measuring platform (i.e. bigger the ship) the better the measurements.

The original platform design of the KSS30 system was unsound with the cantilever arrangement guaranteed to cause problems with the platform bearings. The new platform, described above under QUEST 85 - 139 cruise, is far superior and should greatly improve future gravity measurements.

Other possible improvements are in data processing and sensor drift. The dedicated, special purpose computer (ZE 30) restricts the development of software and thus limits experimentation which could lead to improvements in system performance. There are now powerful (and cheap) off-the-shelf general purpose computers (for example Hewlett Packard Series 200) which could be used in place of ZE30. The optimum digital filtering should be further investigated using zero-phase shift criteria. Such a filter should be incorporated in the system software, and this could be easily done if a standard computer was used in place of the ZE30.

The drift of the sensor is small and appears predictable over short periods. Over a long period it seems less predictable since the drift of our sensor had changed sign after the first two years of operation. The effect on long term drift of transport of the clamped instrument, of long periods without thermostatic control and of clamping and unclamping of the instrument at sea, should be further investigated.

The calibration of the sensors needs careful evaluation by each individual user. It is clear that in at least two cases, the calibration factors were in error. Eliminating these errors is important in order to make measurements made with different instruments comparable. It is equally important for accurate application of the Eotvos correction as otherwise there will be a bias (dependent on velocity) between measurements made on easterly and westerly courses.

5. ACKNOWLEDGMENTS.

Special thanks are due to my technical assistant, Michael Hughes who has lived with sea gravimeters for over twenty years and who was the key participant in every one of the cruises discussed in this report. I am also indebted for assistance, advice and support to John Woodside, Ron Macnab, Keith Manchester, Charlotte Keen and Everett Coldwell. Constructive relations with the Instrument manufacturers and their representatives Wielant Gauthier and Ingo Himmler have helped the project. We appreciate the help from the BIO Navigation experts, Mike Eaton and Steve Grant and numerous Ship Masters and officers who responded to our demands for constant Eotvos correction. This contribution is a part of GSC Project 810031.

REFERENCES

Goodacre, A.K., 1964. A shipborne Gravimeter Testing Range near Halifax, Nova Scotia; JOURNAL OF GEOPHYSICAL RESEARCH, 69, p. 1-9.

Grant, S.T., 1977. A user-developed integrated navigation system; in PROCEEDINGS, International Congress of Surveyors, Stockholm, V. 15, p. 99-113.

Grant, S.T. and Wells, D.E., 1984. Interactions among Integrated Navigation Components. MARINE GEODESY, 7, p. 153-170.

LaCoste, L., 1983. LaCoste and Romberg straight-line gravity meter. GEOPHYSICS, 48, p. 606-610.

Loncarevic, B.D., 1982. First evaluation of a new digital sea gravimeter (KSS30) (Abs.); in Abstracts, Annual Meeting of the Canadian Geophysical Union/Canadian Exploration Geophysical Society (9th: York University, Toronto), p.26.

Loncarevic, B.D., 1986. Four Years Experience with KSS30 Seagravimeter (Abs.); EOS, V. 67, No. 16, p. 261.

Loncarevic, B.D., Hughes, M.D., and Himmler, I., 1986. Evaluation of sea gravimeters: Comparison of Bodenseewerk KSS30 and KSS31 systems; in CURRENT RESEARCH, Part B, Geological Survey of Canada, Paper 86-1B, p. 85-96.

Loncarevic, B.D., and Woodside, J.M., 1984. Coastal Geophysics: Gravity measurements in Mahone Bay, N.S. with a shipborne seagravimeter. (Abs.); in Joint programme with abstracts, Annual Congress, Canadian Meteorological and Oceanographic Society (18th: Dalhousie University, Halifax, N.S.) and Annual Meeting , Candaian Geophysical Union (11th: Dalhousie University, Halifax, N.S.), p. 120.

Macnab, R., Loncarevic, B.D., Cooper, R.V., Girouard, P.R., Hughes, M.D., and Shouzhi, F., 1985. A regional marine multiparameter survey south of Newfoundland; in CURRENT RESEARCH, Geological Survey of Canada, Paper 85-1B, p. 325-332.

Valliant, H.D., 1983. Field trials with the LaCoste and Romberg straight-line gravimeter; GEOPHYSICS, 46, p. 40-44.

FIGURE CAPTIONS

Fig. 1 Comparison between KSS30 (solid line), Gss2 (Dashed) and bottom (crosses) gravimeters. ETV is the Eotvos-corrected gravity in mGal with an arbitrary origin. The two uppermost profiles are the Eotvos correction calculated from gyro and log readings (high frequency) and averaged through the navigation computer. The two lowest profiles are the two components of acceleration.

Fig. 2 KSS30 readings in harbour with a portion of the record expanded to show regular oscillations of the trace due to seiches. The X-axis is in hours of the day.

Fig. 3 Records of KSS30 and two LaCoste & Romberg gravimeters over a four hour period. Note that all three gravimeters show the same 'noise' characteristics. KSS30 (solid line) has a phase delay of 2-3 minutes relative to the other two instruments.

Fig. 4 Three repeat E - W lines in Mahone Bay. The lower set of lines shows the ship's tracks in plan. The small variations of the gravity profiles (upper set) of less then 0.5 mGal amplitude are believed to be real gravity anomalies. The X-axis is in decimal degrees of longitude. Note that at Longitude 64.14^{o}W where all tracks coincide, all three gravity profiles also have the same value.

Fig. 5 Difference of readings of two KSS30 seagravimeters over a 28 day period (upper profile, one vertical division = one mGal) compared to raw gravity (lower profile, one vertical div. = 100 mGal). Note a relative drift between instruments of 1.8 mGal and a correlation between the value of gravity and magnitude of difference.

Fig. 6 Comparision of two KSS30 gravimeters (lower profiles) over one hour period (one vertical division = 2 mGal). Centre profile is the difference plotted on expanded vertical scale (one vertical division = 0.2 mGal). Upper most profile (dotted) is the relative variations of Eotvos correction.

Fig. 7 Histogram of crossover error of KSS30 (dashed) and SL1 (solid) gravimeters.

Fig. 8 Mean difference of KSS30 and SL1 gravimeters on four principal courses. This course dependence is probably caused by a gyro platform heading error, but the error could not be identified nor has this effect been observed on other comparisons.

Fig. 9 Comparison of wind speed (lower curve) and standard deviation of differences between SL1 and KSS30 seagravimeters (averaged over 8 hour periods) Upper curve is standard deviation form shipboard records. Middle curve is standard deviation after post-processing of KSS30 readings (see text).

Fig. 10 Comparison of SL1 (upper profile) and KSS30 (lower profile) with post processed KSS30 readings (middle profile). (a) Record on a calm day; (b) record on a stormy day.

Fig. 11. Detailed comparison of KSS30 and KSS31 gravimeters on a. Line 7 North and b. Line 2 South. The six profiles in this figure are from top to bottom: 1, Ship's velocity (0 - 15 kt vertical scale) and 2, ship's course (vertical scale: 240 - 30^{o} in a., 60 - 210^{o} in b.) from BIONAV; 3, KSS31 corrected for Eotvos effect (dashed); 4, KSS30 corrected for Eotvos effect; 5, Raw gravity for KSS30 (this profile is displaced down by 5 mGal so as not to interfere with the two corrected profiles above it); and 6, The difference between corrected readings of KSS31-KSS30 (Note: For difference profiles in a. the Y-axis origin is -10 mGal; in b. the origin is 0 mGal).

Fig. 12 Raw gravity value (lower profile) recorded during cruise QUEST 85-139 (see text). Upper profile is the difference between KSS30 and KSS31 gravimeters which shows a correlation with gravity change due to an error in calibration factor of one of the instruments.

TABLE I

Cruise Designation	Ship	Length (m)	Displacement (t)	Dates	Comments
81 - 037	DAWSON	64.5	1940	2 Feb - 12 Feb	Acceptance Trial. Comp. KSS30, Gss2 and Bottom Grav.
81 - 038	DAWSON	64.5	1940	6 Aug - 29 Sep	Trip to Greenland. Verific'n of calibration factor.
81 - 060	L.HAMMOND	58.5	437	19 Nov - 28 Nov	Platform development.
82 - 050	QUEST	77	2400	2 Feb - 12 Feb	Comp. KSS30-Gss2. Navigation interface and logging.
82 - 014	HUDSON	90.4	4773	25 May - 10 Jun	
82 - 010	BAFFIN	87	4907	23 Jun - 16 Jul	Test of HiFix
82 - 039	BAFFIN	87	4907	19 Nov - 22 Dec	Comp. KSS30-SL1-S56
83 - 004	MAXWELL	35	270	15 Apr - 2 May	Inshore Geophys. SYLEDIS Nav.
83 - 017	HUDSON	90.4	4773	7 Jun - 5 Jul	Comp. two KSS30's
83 - 035	BAFFIN	87	4907	3 Nov - 30 Nov	First Routine survey
84 - 030	HUDSON	90.4	4773	27 Jul - 26 Aug	ODP site surveys. First CIGAL Development
84 - 044	BAFFIN	87	4907	19 Oct - 26 Nov	Comp. KSS30-SL1.
85 - 139	QUEST	77	2400	20 Nov - 3 Dec	Comp. KSS30-KSS31.

TABLE II

Track Direction	NW	NE	SW	SE
Mean Difference	1.08	0.22	-0.80	-0.05
Number of Obs.	9	15	10	13

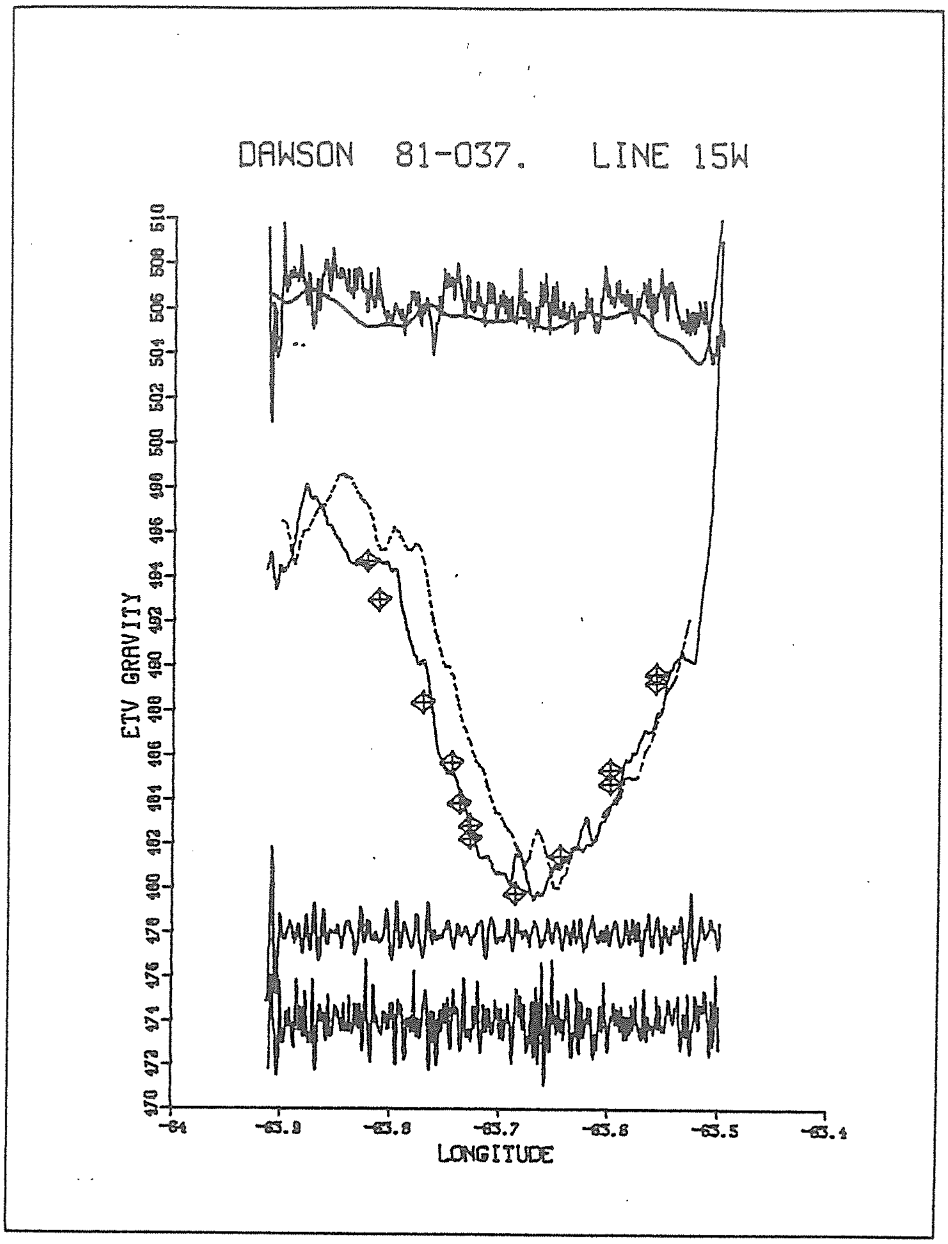
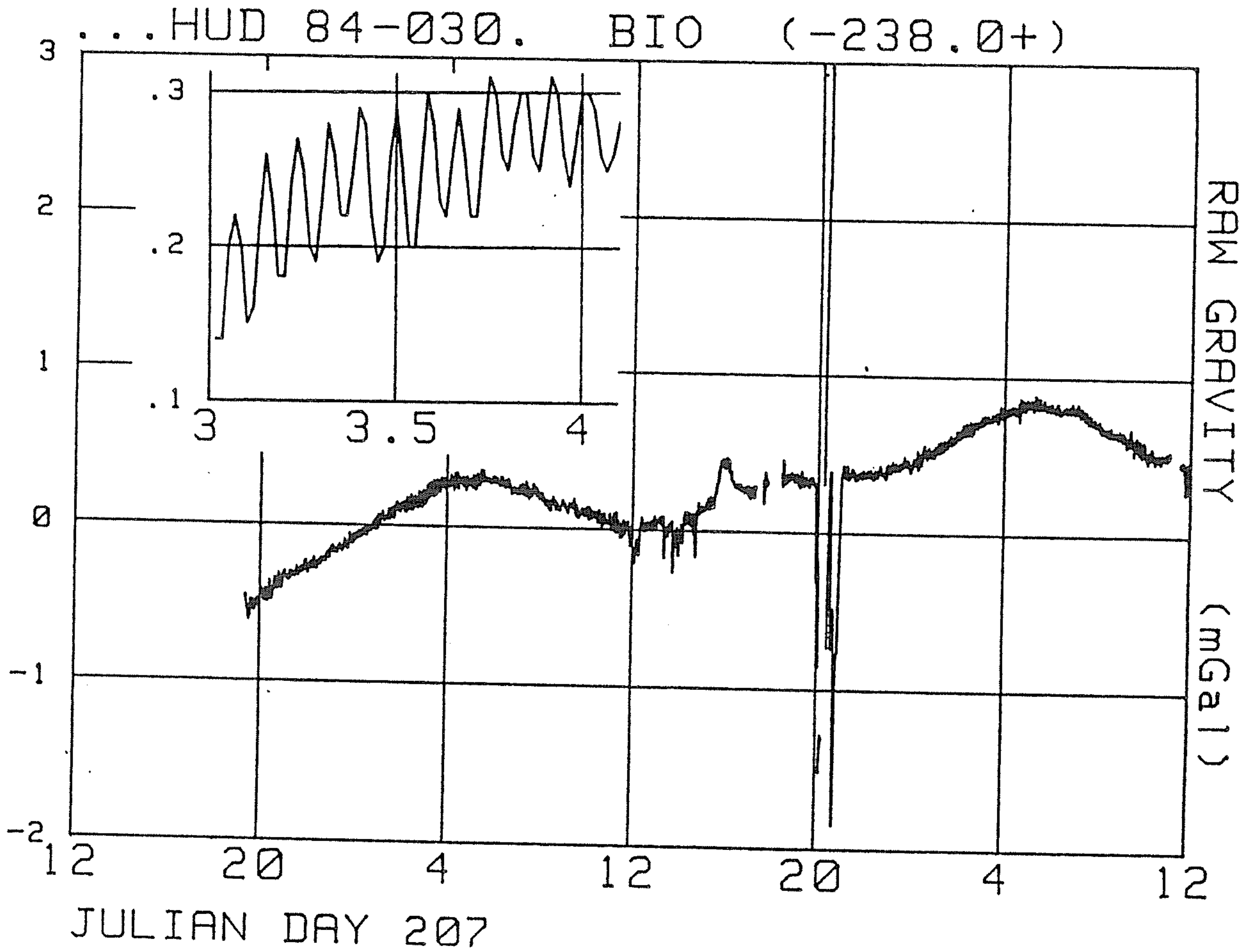

DAWSON 81-037. LINE 15W
ETV GRAVITY
LONGITUDE
-64
-63.9
-63.8
-63.7
-63.6
-63.5
-63.4

Figure 1



...HUD 84-030. BIO (-238.0+)
3
2
1
0
-1
-2
.3
.2
.1
3
3.5
4
RAW GRAVITY (mGal)
12
20
4
12
20
4
12
JULIAN DAY 207

Figure 2

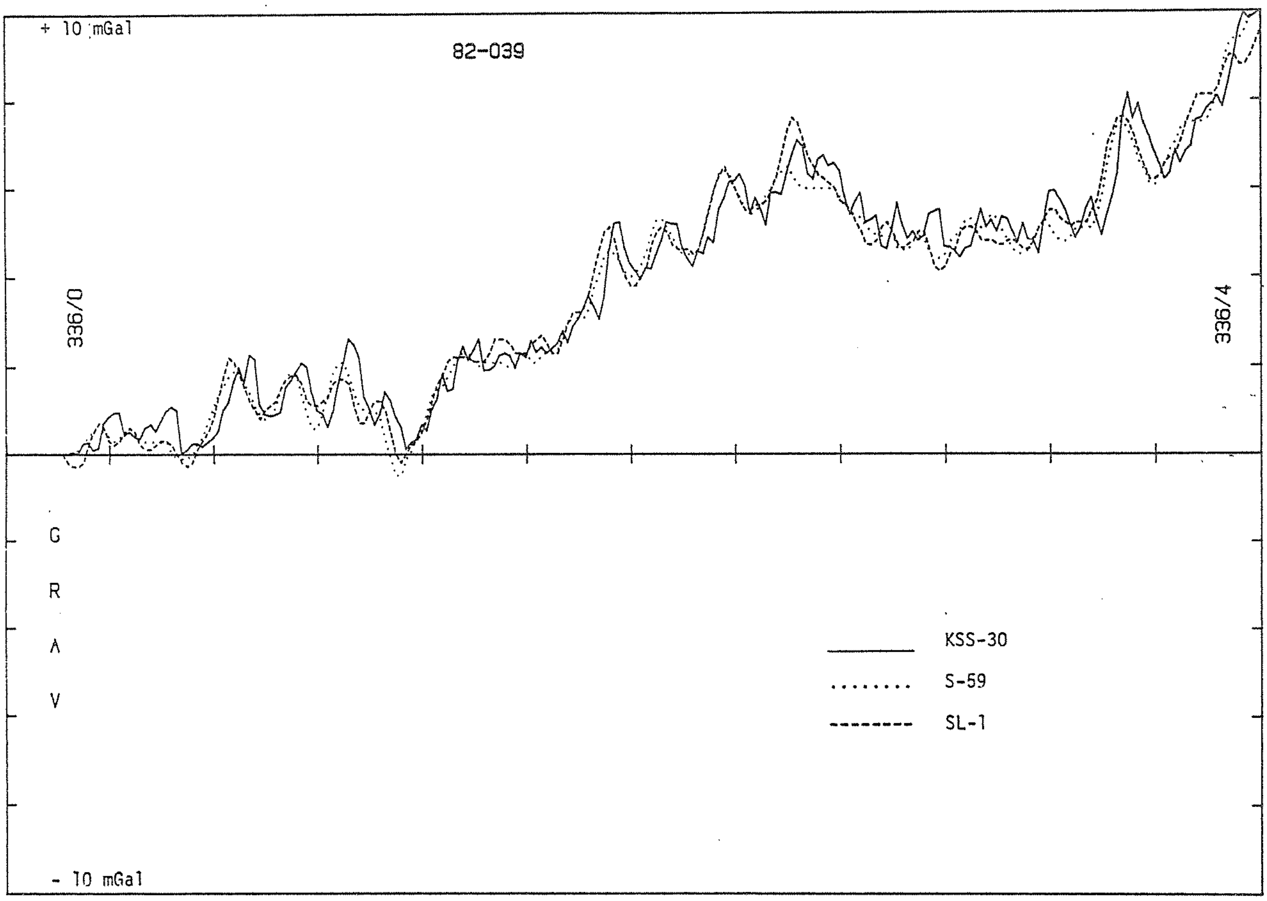
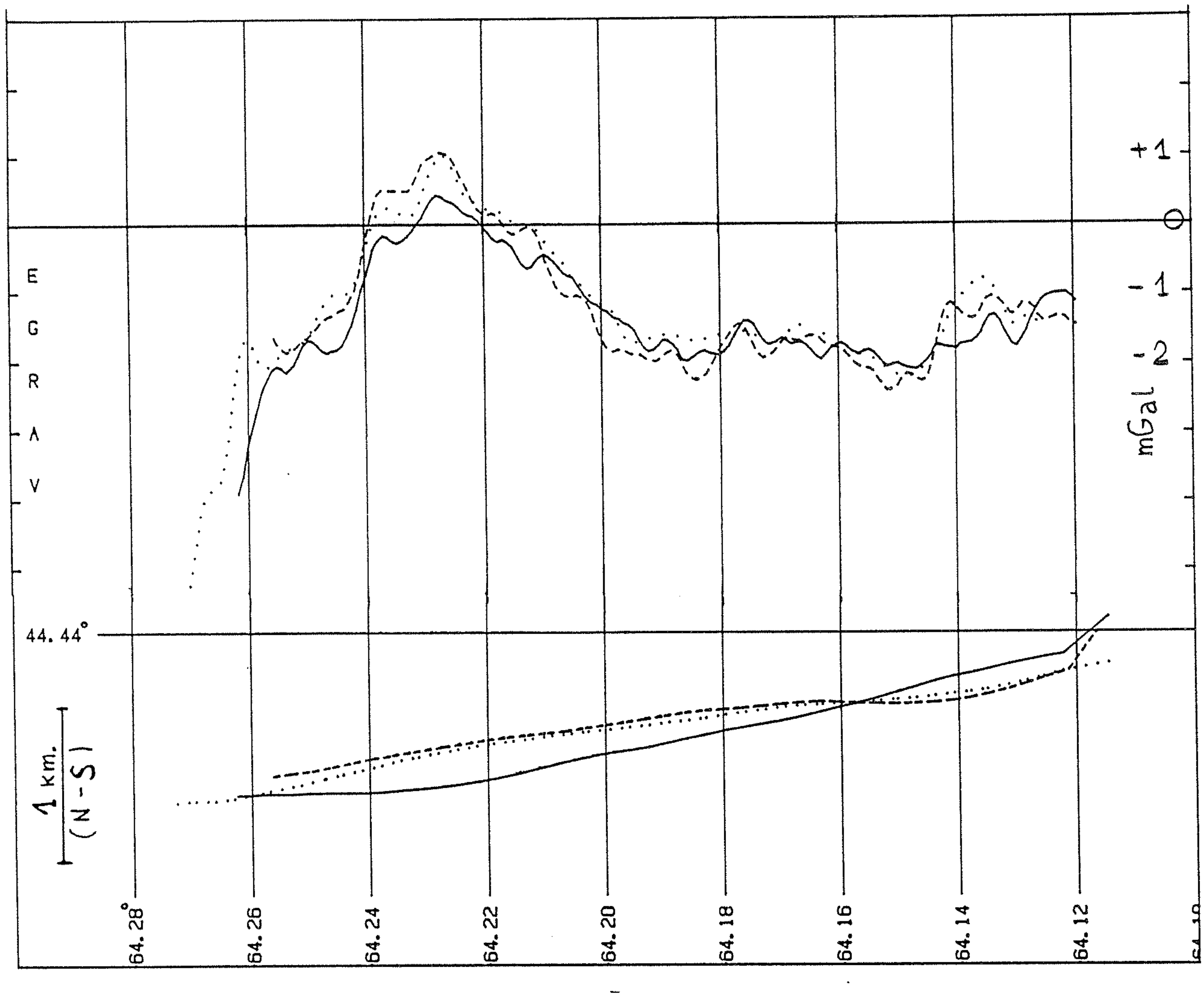


Figure 3



E
G
R
A
V
+1
0
-1
-2
mGal
44.44°
1 km.
(N-S)
64.28°
64.26
64.24
64.22
64.20
64.18
64.16
64.14
64.12

Figure 4

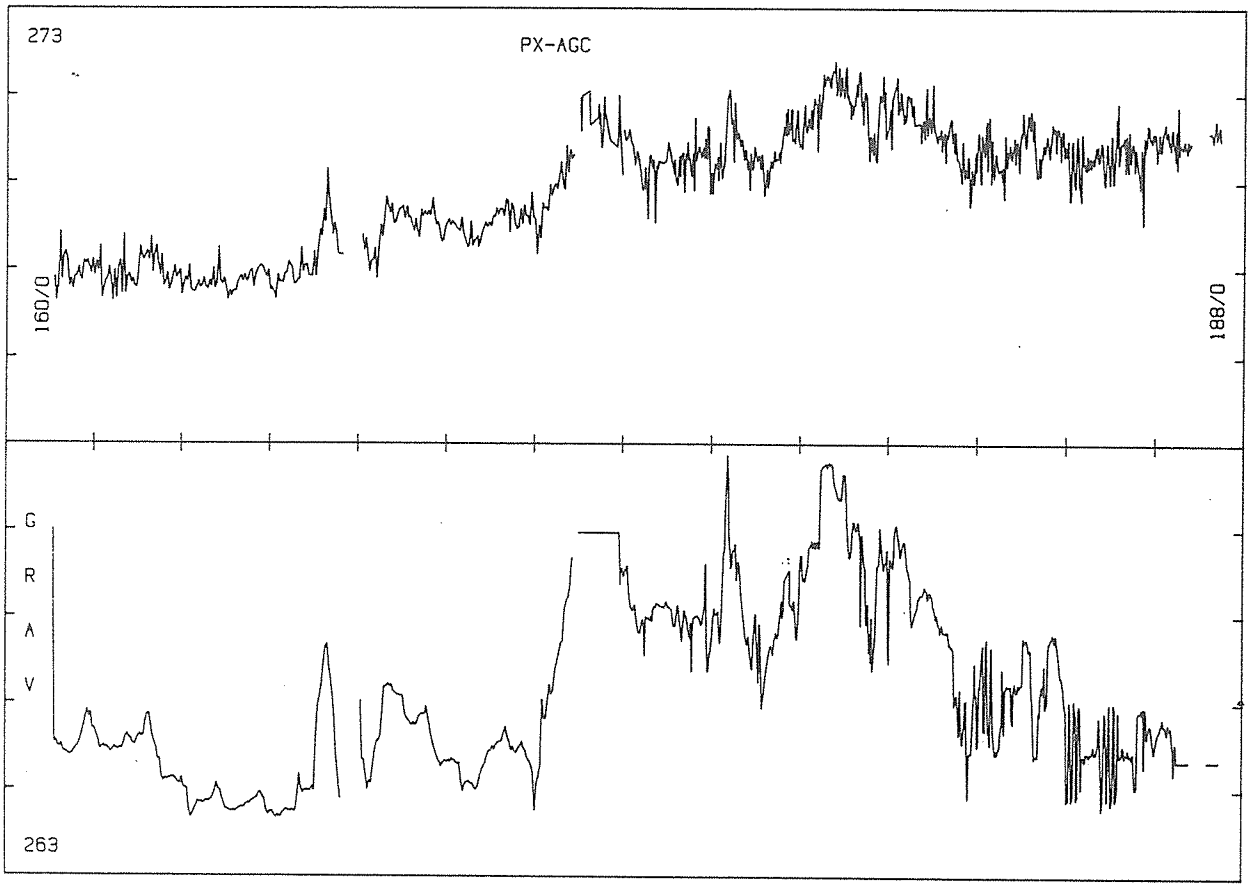


Figure 5

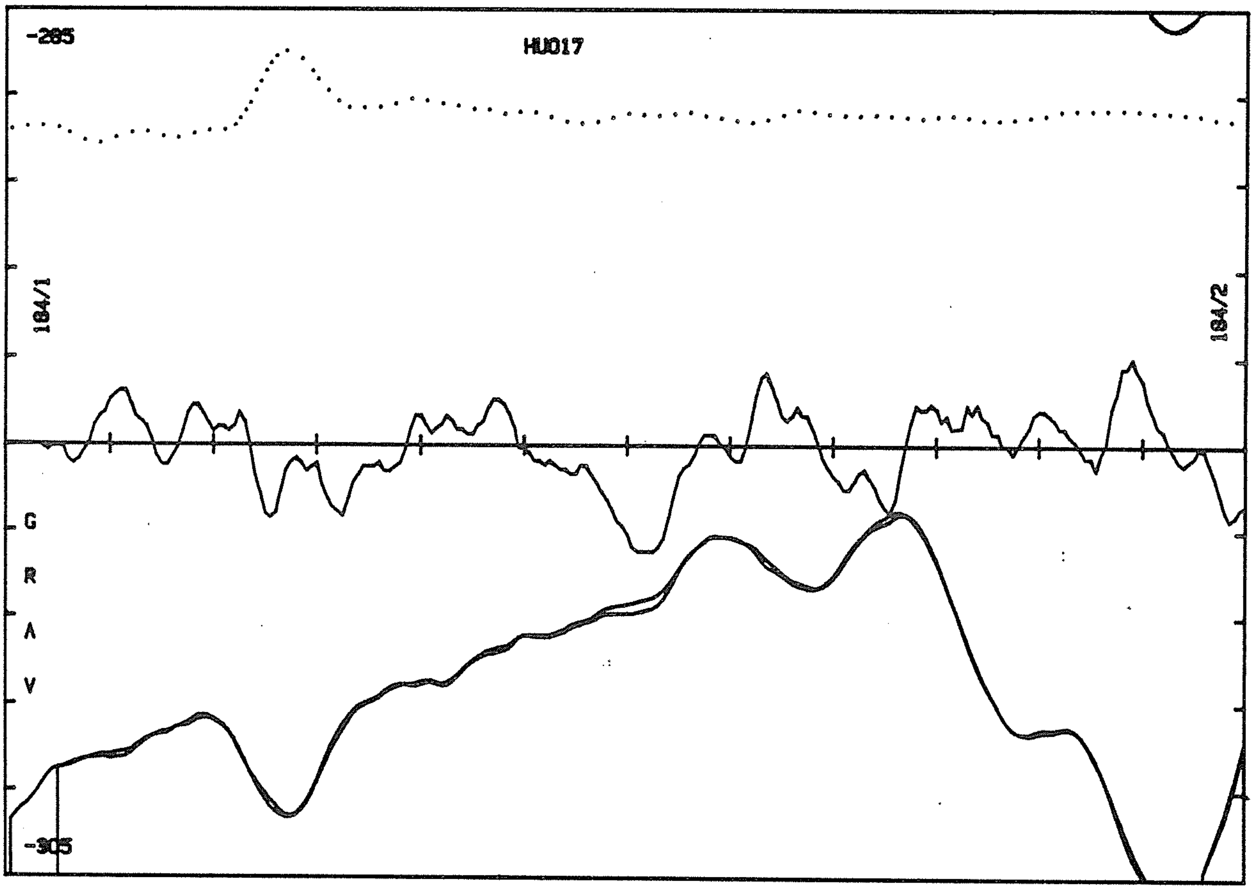
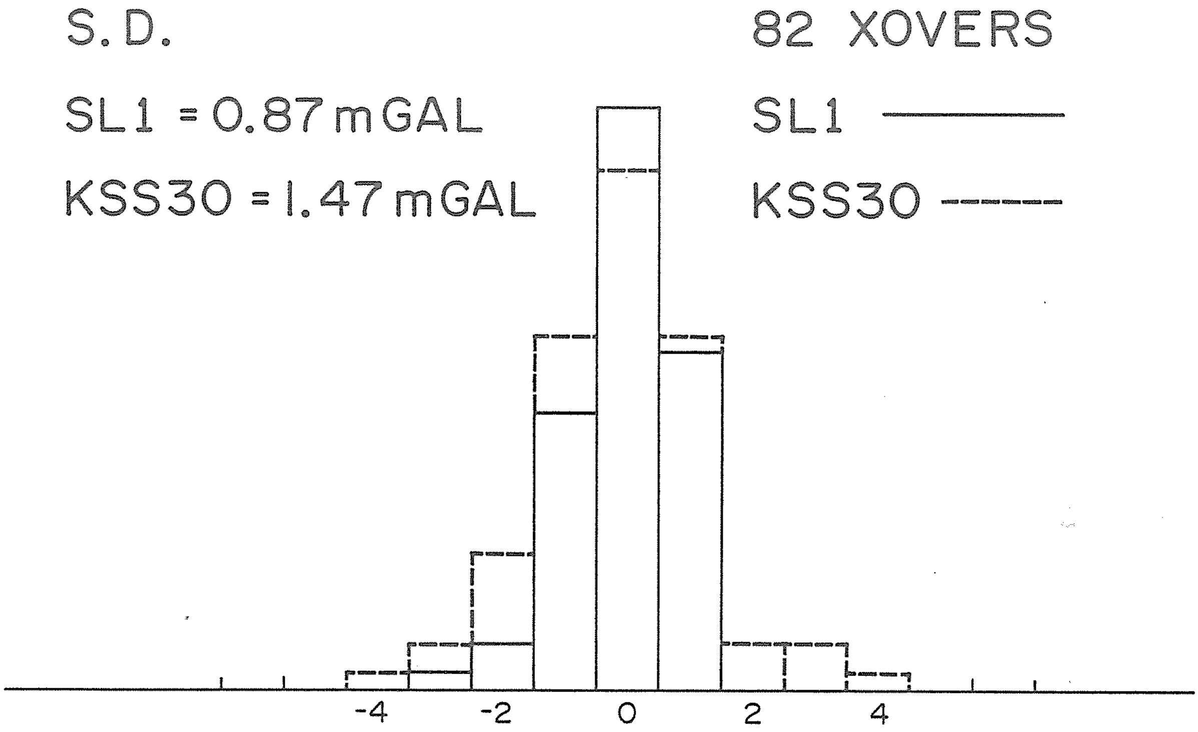


Figure 6



PUB 2.71" ↔ B. LONCAMRE 26 APR/85 VG/K 616-049-0250

Figure 7

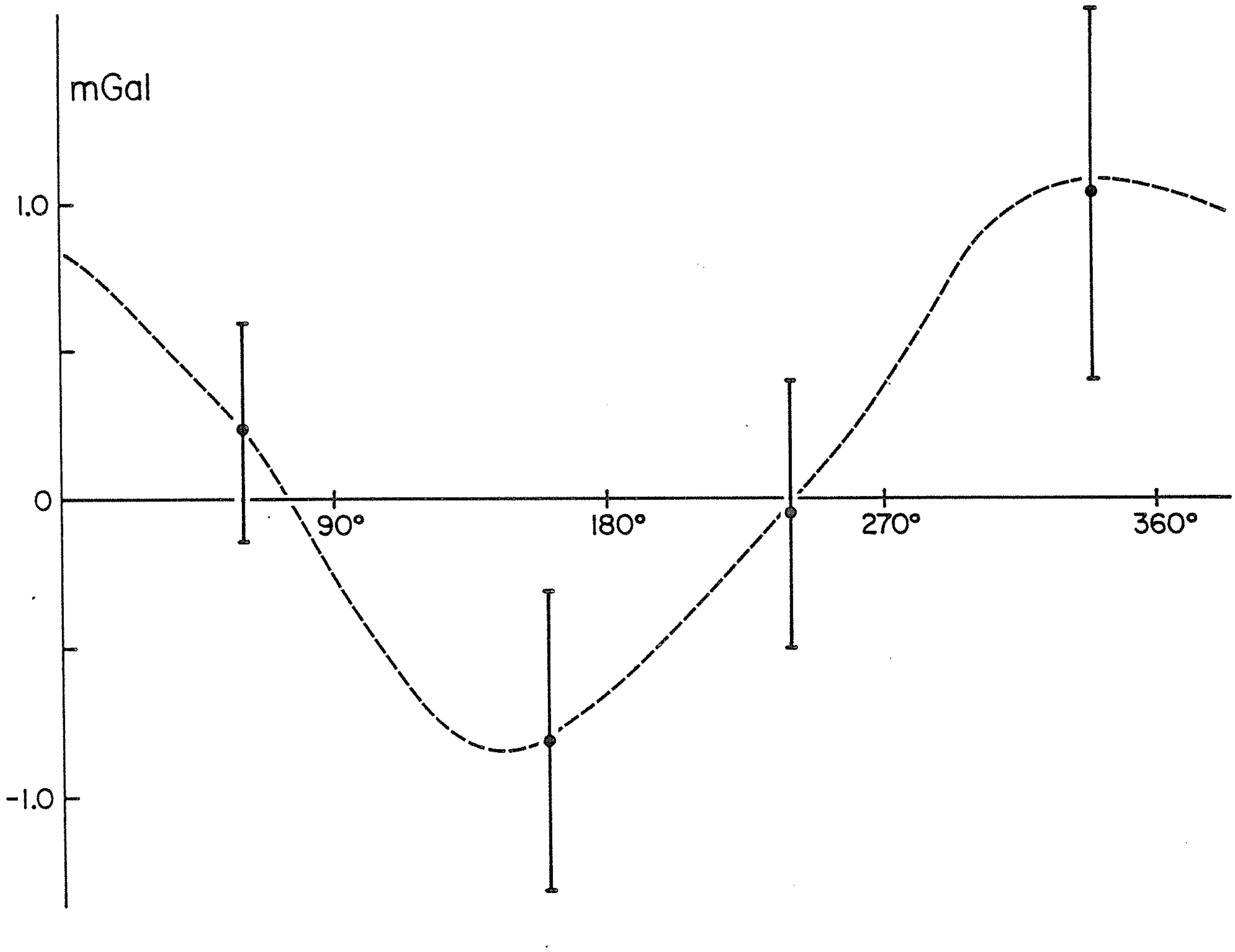
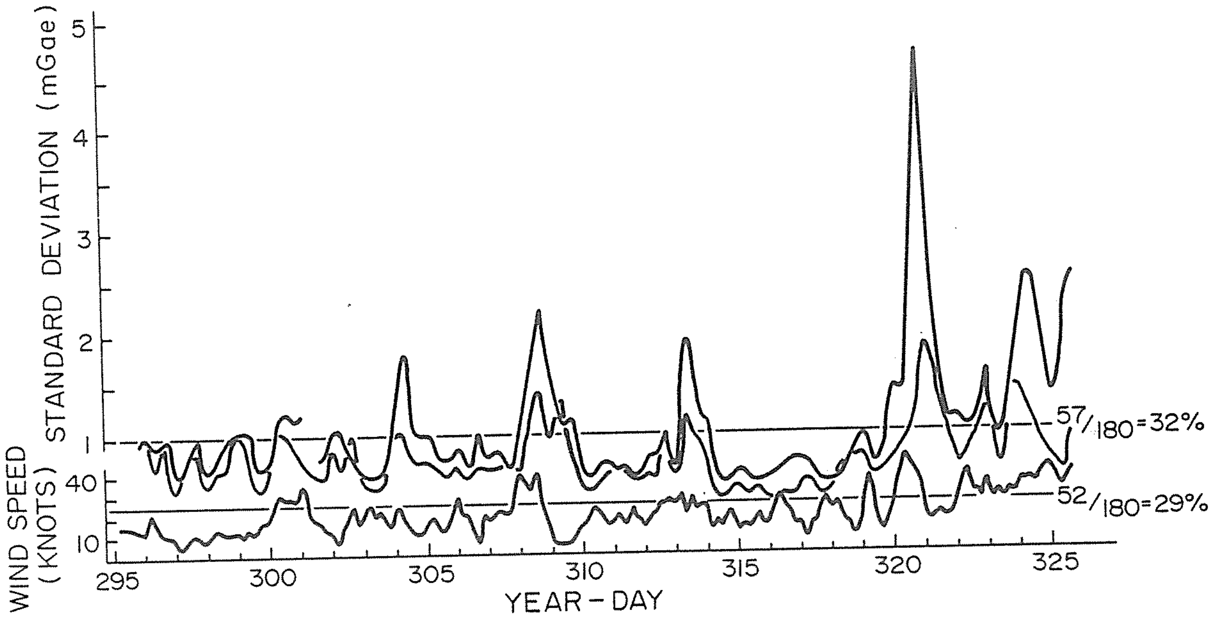


Figure 8



PUB 3.28" ↔ B. LONCANIRÈ : 25 APRIL /85 VG / IC

2/5-049-0250

Figure 9

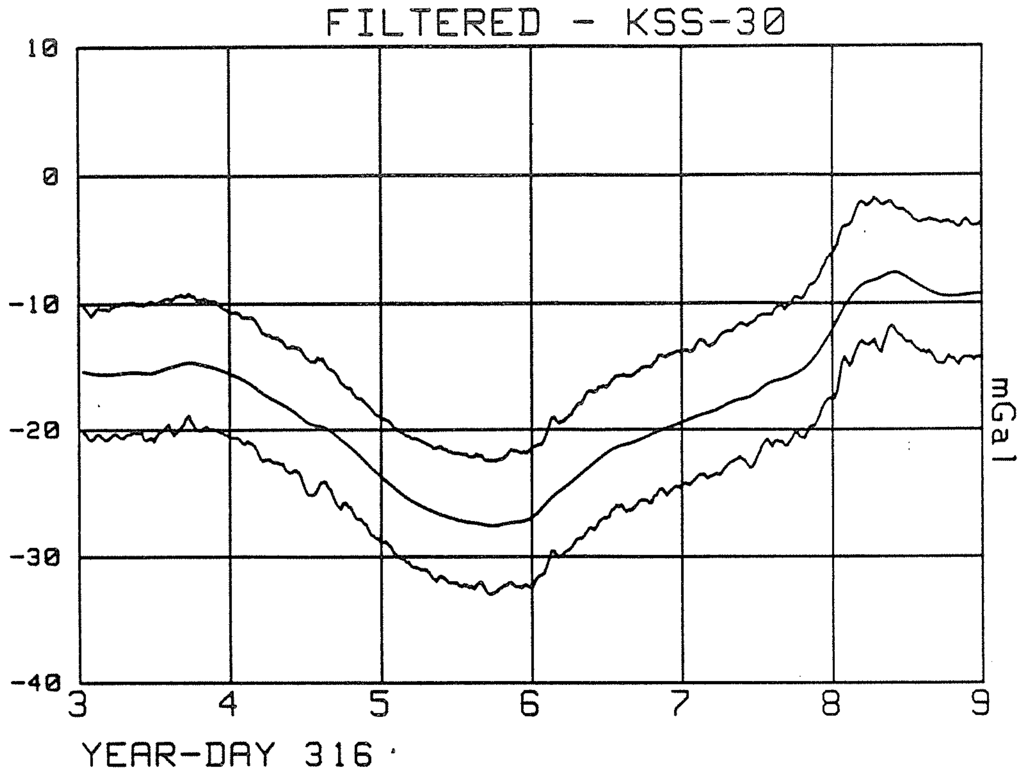


Figure 10a

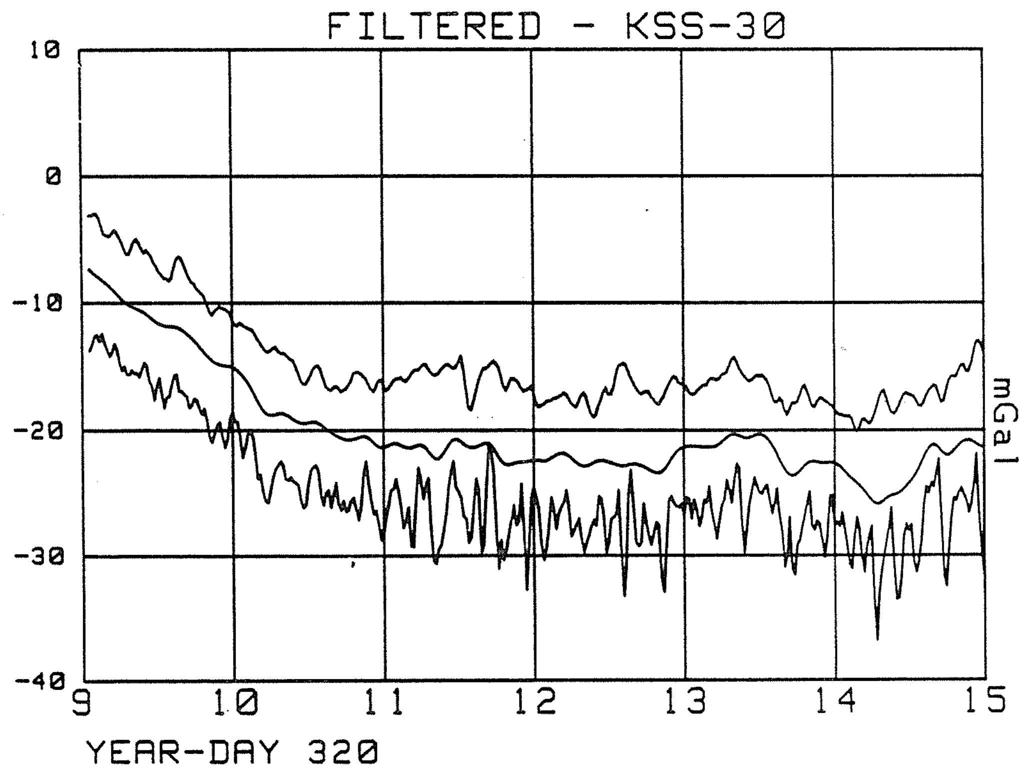


Figure 10b

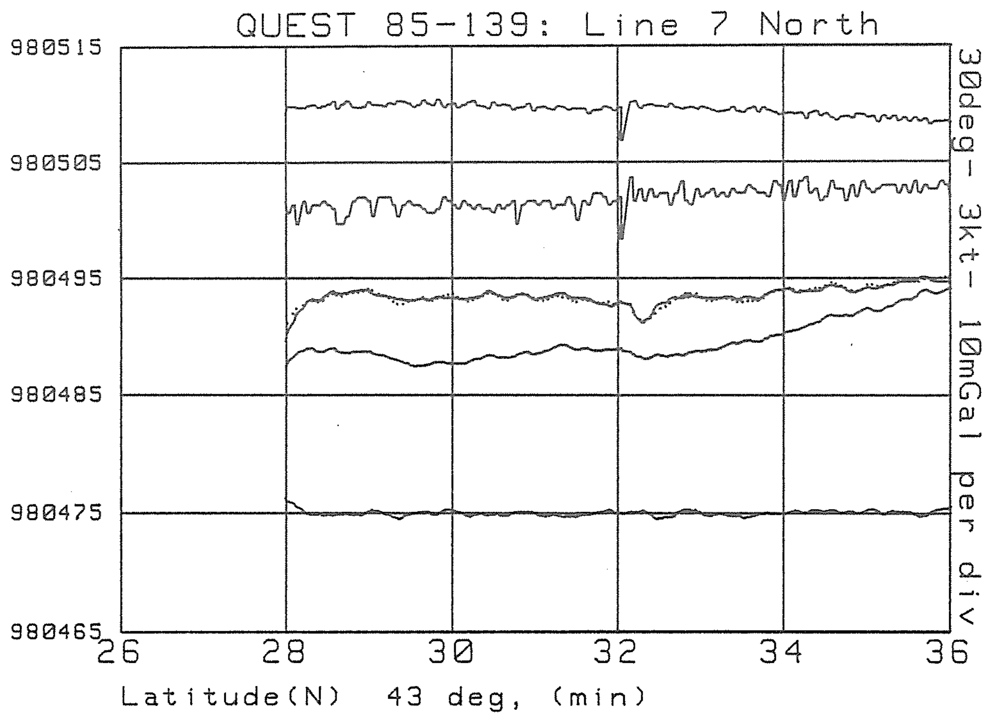


Figure 11a

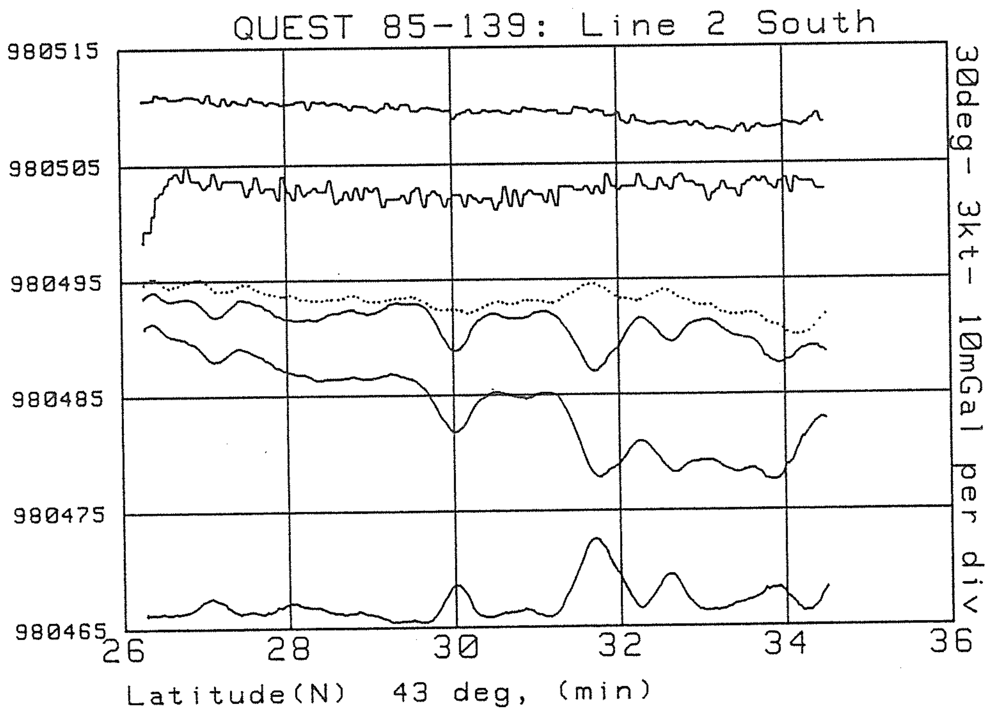
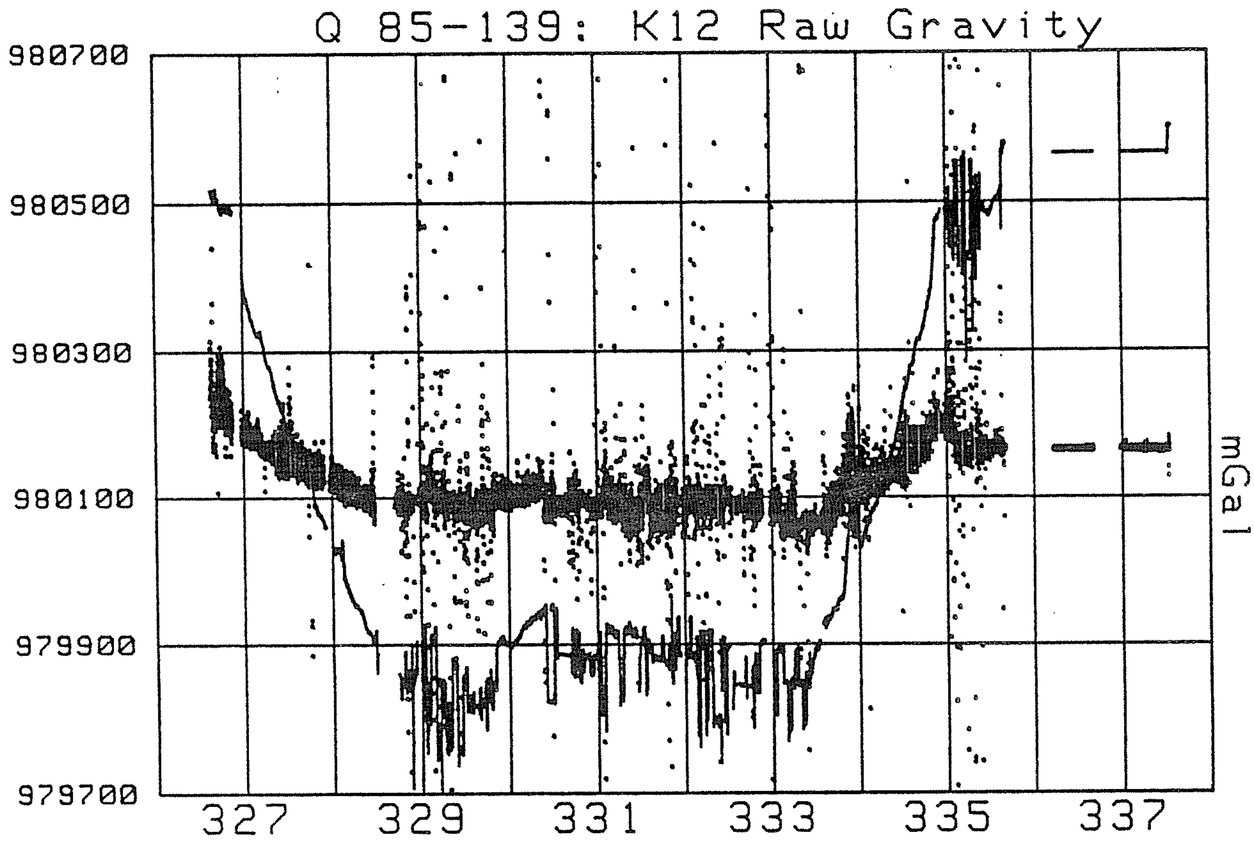


Figure 11b



Q 85-139: K12 Raw Gravity
980700
980500
980300
980100
979900
979700
327
329
331
333
335
337
mGal

Figure 12

The Swiss gravimetric calibration line from Interlaken to Jungfraujoch (Switzerland)[1]

E. Klingelé and H.-G. Kahle[2]

SUMMARY

Supported by the Swiss Geodetic Commission and in agreement with the resolutions set by the International Association of Geodesy (IAG), a gravimetric calibration line from Interlaken to Jungfraujoch was set up in autumn 1980. This line, comprising 7 main stations, allows a more economical calibration of (relative) field gravimeters. Absolute measurements were carried out earlier at the two extreme stations, Interlaken and Jungfraujoch (3500 m), and therefore their gravity values are known. The total difference in gravity between Interlaken and Jungfraujoch is 604.7 mgal and the analysis of the results shows that the correspondence between the relative and absolute values of g are better than 50 µgal (1 µgal = $10^{-8}ms^{-2}$).

1) Institut für Geodäsie und Photogrammetrie, ETH-Hönggerberg, CH-8093 Zürich, Separata Nr. 120

2) Institut für Geodäsie und Photogrammetrie, ETH-Hönggerberg, CH-8093 Zürich

INTRODUCTION

A gravity calibration line Interlaken-Jungfraujoch was set up in agreement with IAG resolutions. The aim was to permit a fast calibration "in sections" of relative gravimeters. This line comprises 7 primary stations which define 6 sections of partial calibration. The absolute gravity values in Interlaken and on Jungfraujoch were measured in 1979 and are therefore known. Thus a detailed study of the gravimeter's calibration factor is made possible. The attention should be drawn to the fact that this line, of which the total difference in gravity reaches 604.7 mgal (1 mgal = $10^{-5}ms^{-2}$), is meant to help the calibration of gravity instruments. In most cases the seven stations have 2 to 3 tie points, the objective being to preserve the value of g in case of environmental modifications. Each station was chosen for its accessibility (by car or train), reducing the carrying of the instruments by hand to a minimum. It is thus possible to measure each section with several gravimeters simultaneously. The 7 stations are: Grindelwald, Alpiglen, Kleine Scheidegg, Eigergletscher, Eigerwand and Jungfraujoch.

Since areas beyond Grindelwald have to be travelled through by mountain train, it is necessary to allow 10 days for measurements to obtain 6 cycles per section, a number which guarantees a good measurement quality. In order to obtain the same difference in gravity as measured between Interlaken and Jungfraujoch it would - in theory - be necessary to move along the same meridian for at least 750 km. The advantage of this calibration line is obvious in terms of time and cost savings.

INSTRUMENTATION

For establishment of the line, the following equipment was used:

2 LaCOSTE & ROMBERG gravity meters, models G317 and G 514, with a reading precision of $\pm 1.10^{-7}ms^{-2}$; a LaCOSTE & ROMBERG gravity meter D (microgal gravity meter) with a precision of ten times above that of the G models, i.e. $\pm$ $1.10^{-8}ms^{-2}$; 2 thermometers at 1/10° C and, finally, a THOMMEN barometer, type 3B4.

At each station, 2 operators measured gravity, temperature and barometric pressure independently. The data were processed by computer immediately after the measuring campaign.

CORRECTION OF THE INSTRUMENTAL DRIFT

Four stations A, B, C and D are measured in the order A-B-C-D-C-B-A. Three cycles of measurement are obtained which give the following experimental drifts :

I. Measures A-B-C-D-B-A

$$d_I = \frac{V_{A2} - V_{A1}}{T_{A2} - T_{A1}}$$ drift valid for the stations B-C-D-C-B

II. Measures B-C-D-C-B

$$d_{II} = \frac{V_{B2} - V_{B1}}{T_{B2} - T_{B1}}$$ drift valid for the stations C-D-C

III. Measures C-D-C

$$d_{III} = \frac{V_{C2} - V_{C1}}{T_{C2} - T_{C1}}$$ drift valid for the station D.

The prefix V indicates the value for g, measured and corrected with the help of tidal variations, and T stands for the measuring time.
The drift rates obtained during the 1980 measuring campaign and for the three gravimeters G317, G514 and D16 are shown as histograms in figure 1.

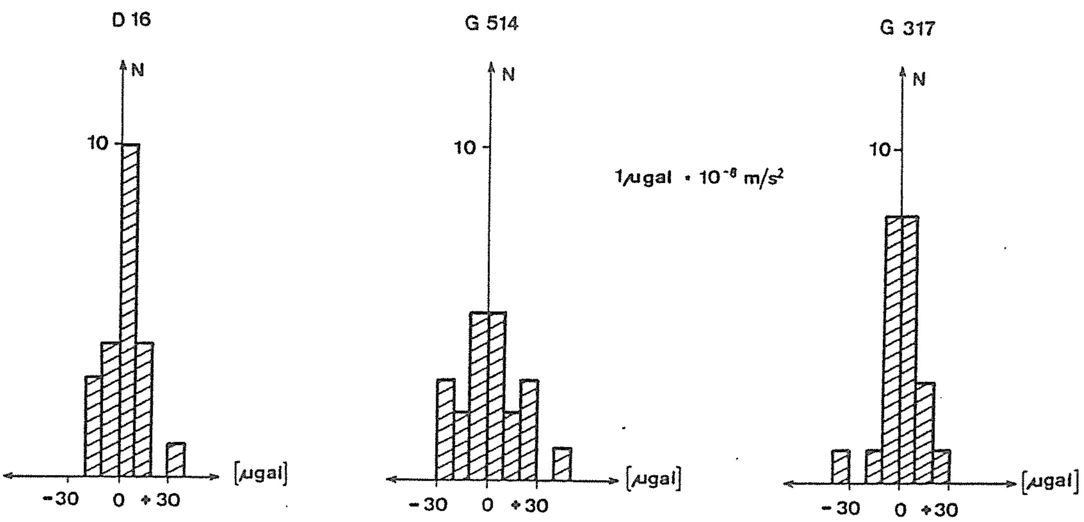


Figure 1: Histograms showing the working drifts of the 3 gravimeters used for the 1980 measuring campaign.

EFFECTS OF ATMOSPHERIC PRESSURE VARIATIONS

There are 3 aspects regarding the influence of atmospheric pressure changes.
Firstly, the beam of the gravimeter can be influenced by atmospheric pressure changes, if the casing is not perfectly waterproof. This influence is negligible for modern gravimeters. The second effect is caused by the gravitational attraction of the layers of air and the third effect (of opposite sign) is due to the distortion of the earth's crust, caused by these variations.

In the case of the Interlaken-Jungfraujoch calibration line, only the second effect was taken into consideration. For this, the values of g (corrected for tidal changes) were re-corrected by $-0.4274 \cdot 10^{-8} ms^{-2}$ per mbar of atmospheric pressure change. These variations were calculated in relation to the mean value obtained during the measuring campaign for the respective station.

The following table (1) shows the atmospheric pressure changes obtained during the 1980 campaign, considered during one cycle and for one station.

ΔP [mbar]:	0.0	0.5	1.0	1.5	2.0	2.5	3.0
N:	10	5	4	0	1	1	1

Table 1: Table of values of the barometric pressure changes within one cycle and for one station.

This table shows clearly the value of the maximum correction applied ($-1.26 \cdot 10^{-8} ms^{-2}$) and this for one measurement only. Consequently, no distortions remain in the results due to atmospheric pressure changes.

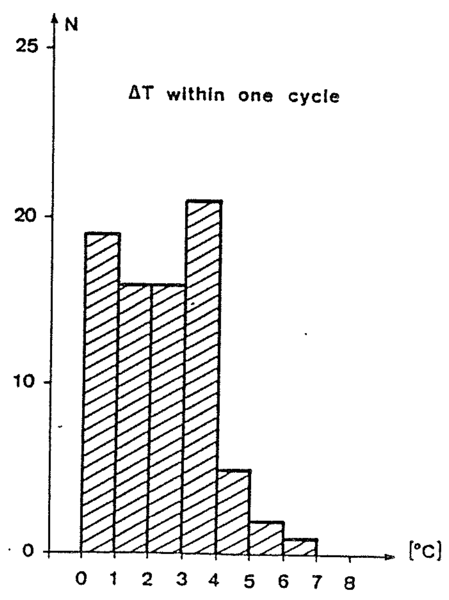


Figure 2:

Histogram of the temperature differences measured within one cycle.

EFFECTS OF EXTERIOR TEMPERATURE VARIATIONS

The highly sophisticated heating and insulation system (thermostating) protects modern gravimeters' measuring systems from exterior temperature and its changes, but not the bubble level which controls the equilibrium of the beam in a horizontal position. The gravimeters are extremely sensitive to thermal shocks; for example in winter, if a heated vehicle passes a measuring station set up outside, the gravimeter will react. It is possible to study the effects of thermal shock on sensitive instruments and thus develop definitions for temperature corrections. But the determination of these effects is long and tedious, and good accuracy cannot be guaranteed. That is why we decided to avoid such shocks and work during periods with low temperature changes (in autumn) and keep the gravimeter at outside temperatures (unheated car and open windows while driving). The biggest differences measured during our 1980 campaign were of 6-7° C and, in most cases, lower than 5° C (see figure 2). Thus it appeared to be unecessary to apply temperature corrections for these measurements.

RESULTS

Table 2 shows the results of the measurements obtained during this first measuring campaign. The column "number of cycles" gives only the number of measurements taken between 2 return trips to one station per gravimeter and for the total of all measurements.

Segment	Nr. of loops	LCR D16		LCR G514		LCR G317		Average of all instruments	
		ΔG	σ	ΔG	σ	ΔG	σ	ΔG	σ
Interlaken S1-Grindelwald	3/9	115.476	0.016	115.530	0.021	115.449	0.010	115.507	0.037
Grindelwald-Alpiglen	5/15	106.043	0.010	106.077	0.015	106.075	0.011	106.065	0.020
Alpiglen-Kleine Scheidegg	5/15	79.053	0.018	79.100	0.009	79.079	0.015	79.078	0.024
Alpiglen-Eigergletscher	1/3	140.625	-	140.706	-	140.590	-	140.640	0.060
Kleine Scheidegg-Eigergletscher	3/9	61.576	0.021	61.622	0.020	61.562	0.031	61.589	0.030
Kleine Scheidegg-Eigergletscher S1	3/9	61.011	0.027	61.072	0.043	61.044	0.044	61.042	0.043
Eigergletscher-Eigergletscher S1	3/3	0.579	0.004	-	-	-	-	0.579	0.004
Eigergletscher-Eigerwand	1/3	149.669	-	149.690	-	149.672	-	149.677	0.011
Eigergletscher S1-Eigerwand	3/9	150.275	0.062	150.272	0.056	150.273	0.018	150.274	0.043
Kleine Scheidegg-Eigerwand	3/9	211.240	0.012	211.340	0.042	211.288	0.031	211.289	0.051
Eigerwand-Jungfraujoch S1	3/9	92.285	0.041	92.271	0.032	92.283	0.003	92.280	0.026

Table 2: Summary of the average results per station. g and the standard deviation (σ) are given in milligal (1 mgal = $10^{-5}ms^{-2}$). Number of cycles (per gravimeter/for all the gravimeters.

Figure 3 shows a schematic layout of the stations including mean differences, standard deviations and closing errors for the central network. In order to keep the sketch tidy, the differences are given in mgal. Each difference and standard deviations will therefore be multiplied by this coefficient in order to obtain values which conform to the International System of Units (ISU).

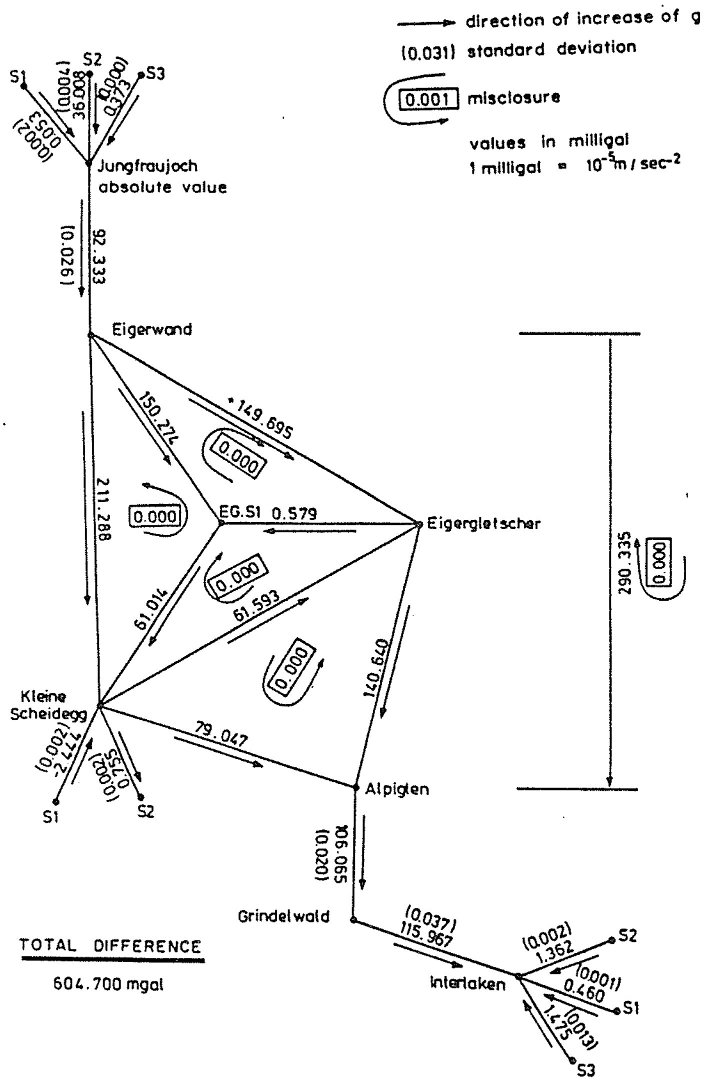


Figure 3:

Spatial distribution of the gravity differences on the calibration line Interlaken-Jungfraujoch.

Figure 4 shows quite clearly that, as the measured mgal value diminishes, the differences obtained by the three gravimeters verge on a unique value to within a few microgals ($10^{-8}ms^{-2}$).

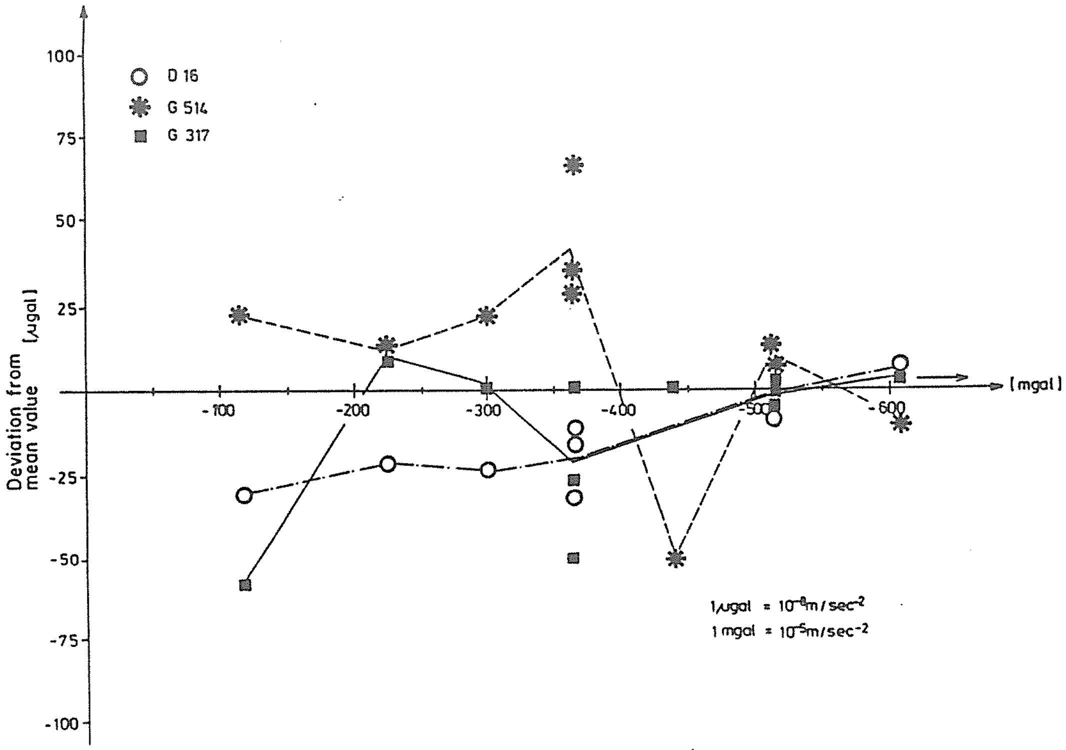


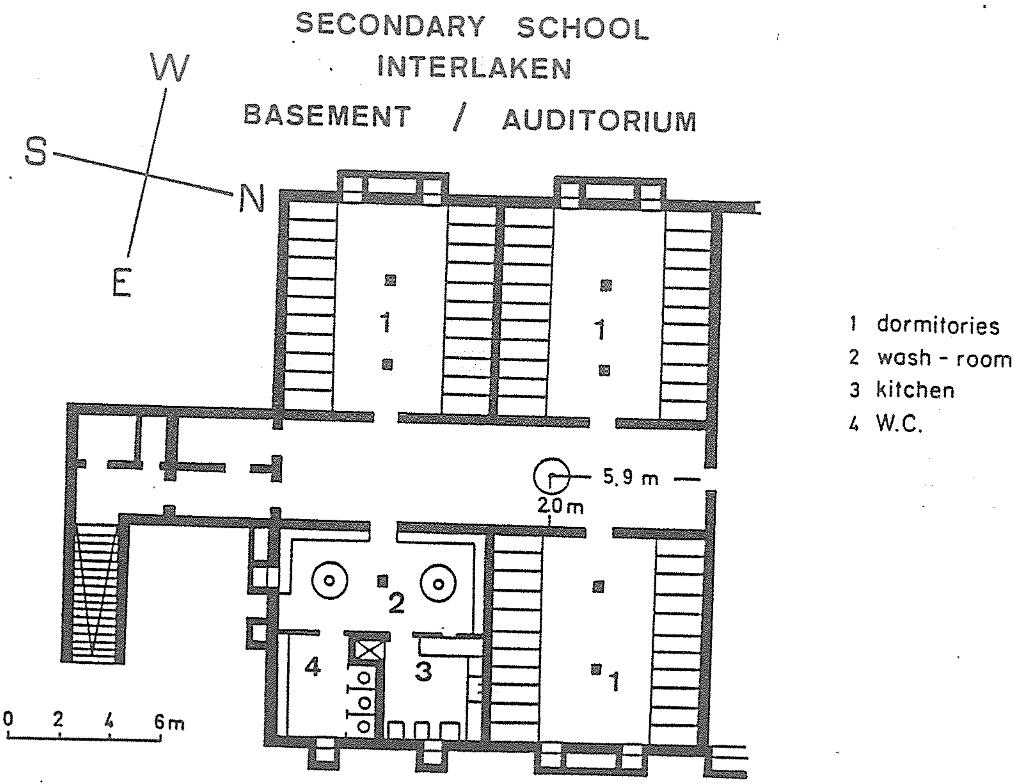
Figure 4: Deviations from the mean values as measured by each gravimeter as a function of the value read.

It should be emphasised that these results and the calibration factors in general are of high quality: The gravity difference between Interlaken and Jungfraujoch is 604,757 mgal (obtained by absolute measurements) (s = 0,038) and 604,700 mgal (s = 0,049) (after adjustment of the central network) for the first measuring campaign carried out with gravimeters.

APPENDIX

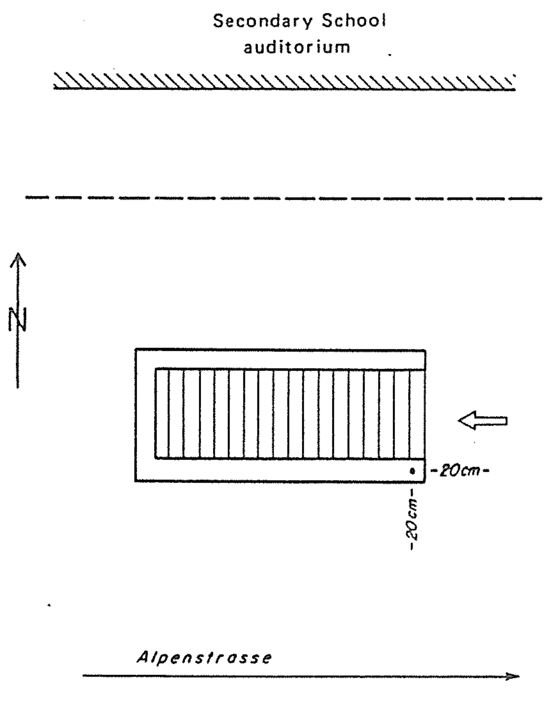
Station locations

INTERLAKEN (1)



VP 1 Interlaken

Gravimeter: Rivet on wall, to the left of entrance to civil defense facilities

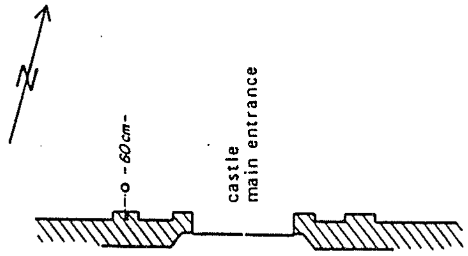


Landeskarte der Schweiz 1 : 25000
(sheet) no. 1208, Beatenberg
632440 / 170510

INTERLAKEN (2)

VP 2 Interlaken

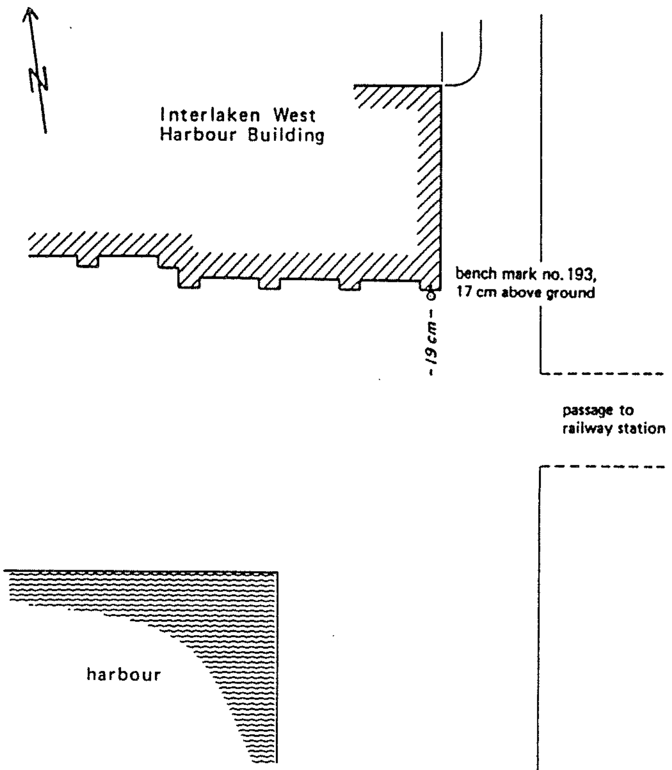
Gravimeter: 60 cm in front of levelling bench mark 289 A
on pedestal to the right of castle main
entrance (district authorities).
Level of gravimeter: 28 cm below bench mark



Landeskarte der Schweiz 1 : 25000
(sheet) no. 1208, Beatenberg
632520 / 170740

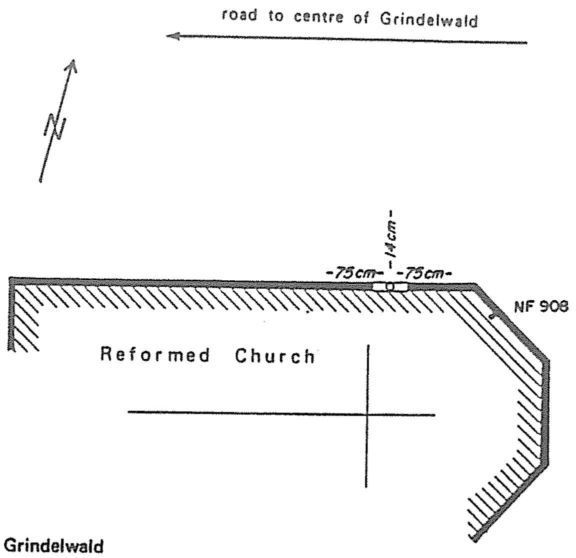
VP 3 Interlaken

Gravimeter: on levelling disk,
19 cm in front of levelling bench mark no. 193



Landeskarte der Schweiz 1 : 25000
(sheet) no. 1208, Beatenberg
631550 / 170290

GRINDELWALD



Grindelwald

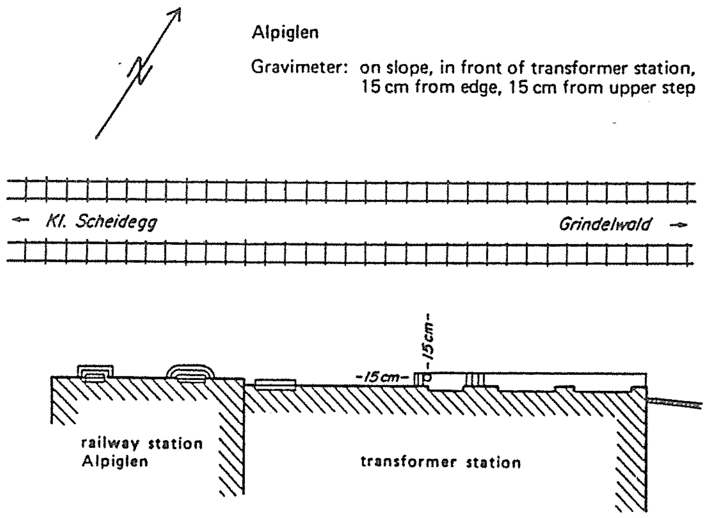
Gravimeter: Centre of threshold
of northern side entrance

Landeskarte der Schweiz 1 : 25000
(sheet) no. 1229, Grindelwald
646510 / 163920

ALPIGLEN

Alpiglen

Gravimeter: on slope, in front of transformer station,
15 cm from edge, 15 cm from upper step



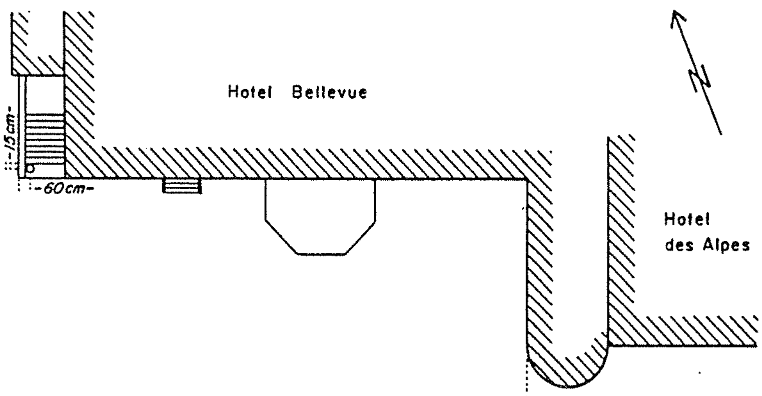
Landeskarte der Schweiz 1 : 25000
(sheet) no. 1229, Grindelwald
643160 / 161130

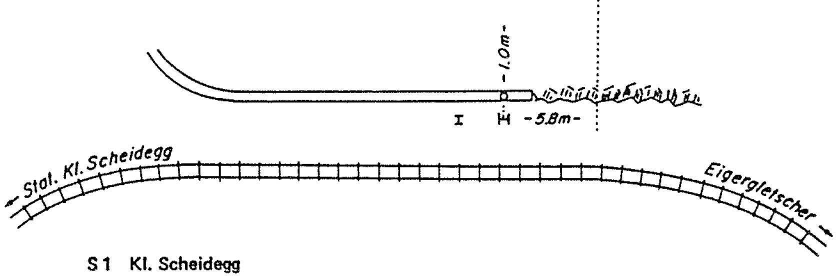
KLEINE SCHEIDEGG

Kleine Scheidegg

Gravimeter: on top granite slab,
60 cm from outer edge,
15 cm from top step

Landeskarte der Schweiz 1 : 25000
(sheet) no. 1229, Grindelwald
640100 / 159470



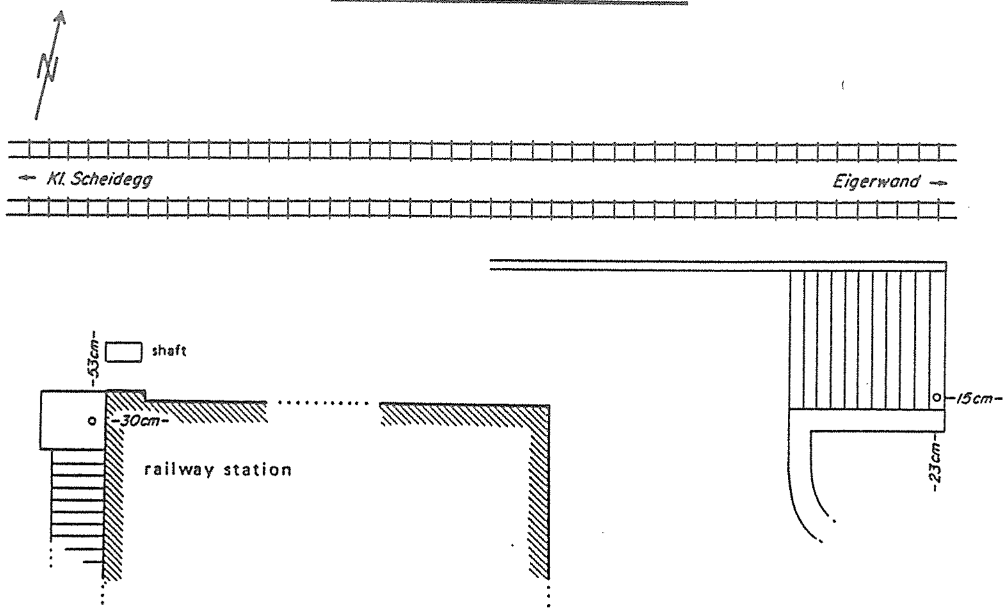


S 1 Kl. Scheidegg

Gravimeter: centre of wall,
opposite electric pylon

Landeskarte der Schweiz 1 : 25000
(sheet) no. 1229, Grindelwald
640100 / 159410

EIGERGLETSCHER



S 1 Eigergletscher

Gravimeter: on granite slab of western stair, 30 cm from wall of building, 53 cm from front of building

Landeskarte der Schweiz 1 : 25000
(sheet) no. 1229, Grindelwald
641070 / 158300

Eigergletscher station

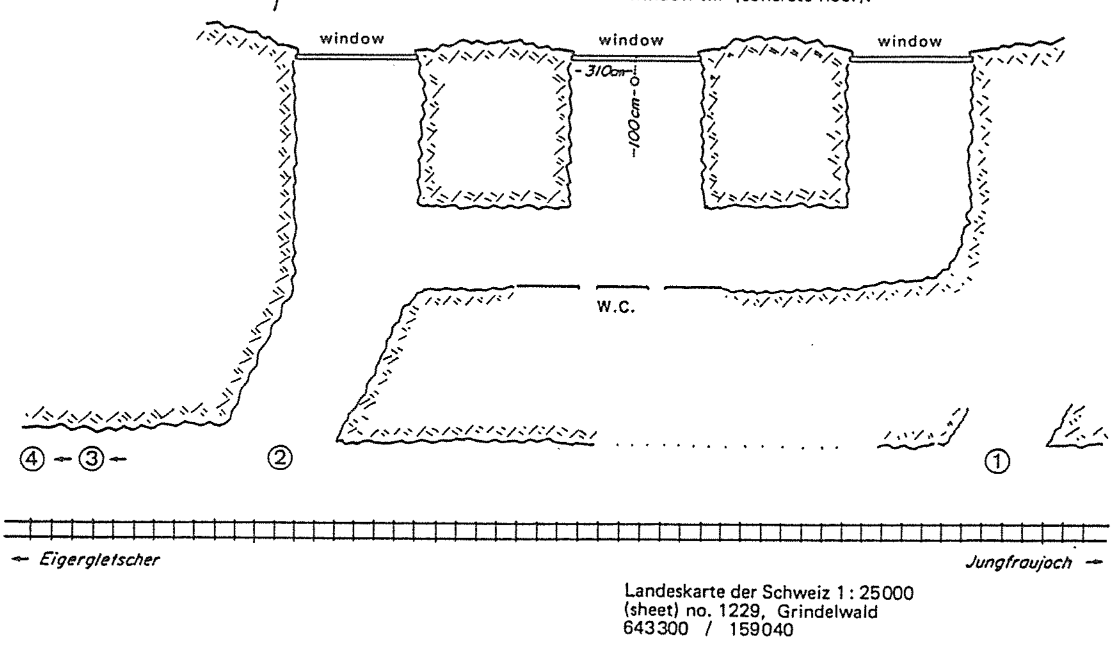
Gravimeter: on limestone slab of top step, 15 cm from edge of step, 23 cm from wall

Landeskarte der Schweiz 1 : 25000
(sheet) no. 1229, Grindelwald
641110 / 158290

EIGERWAND

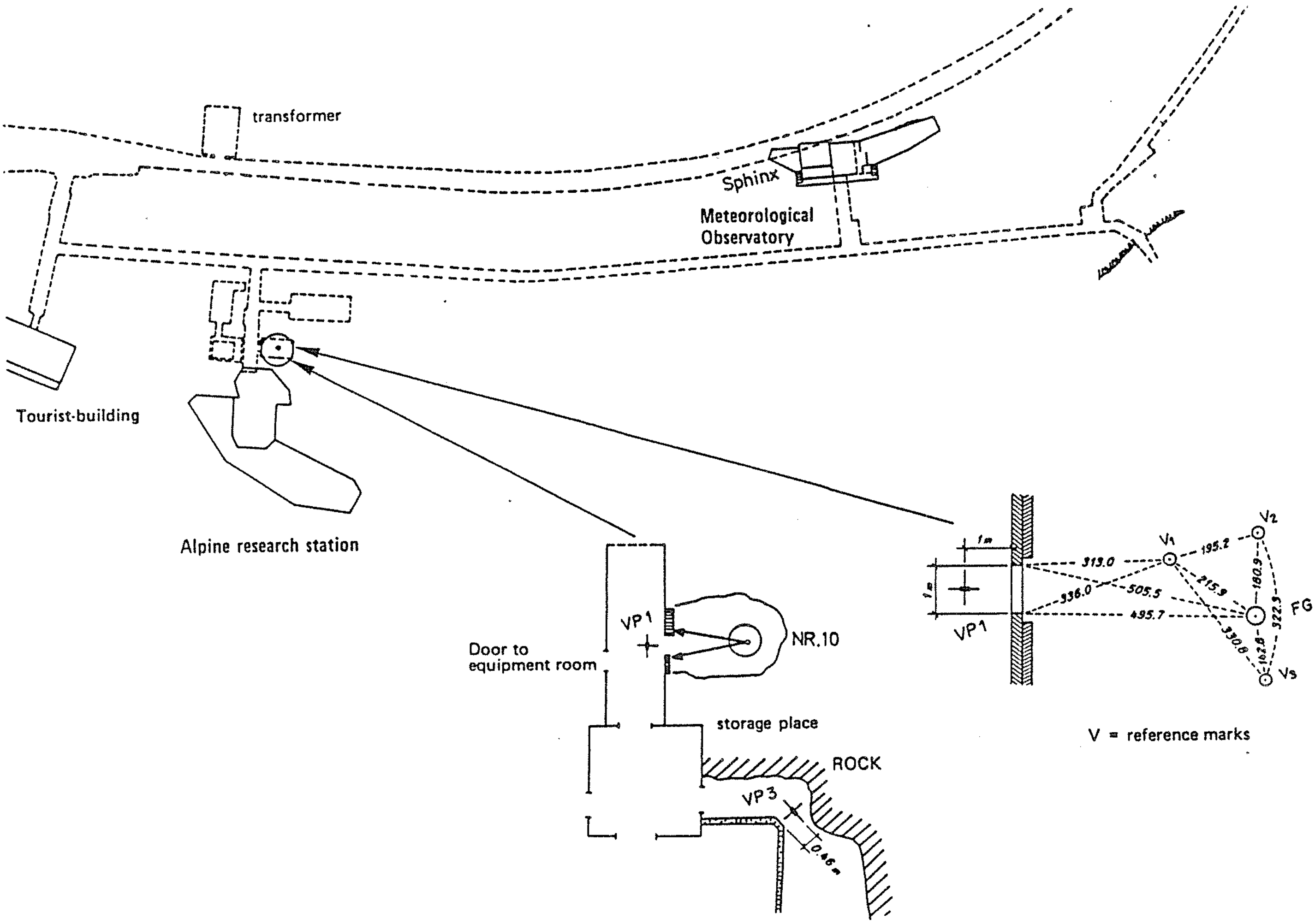
Eigerwand station

Gravimeter: gallery 2, 100 cm in front of central window, 310 cm from left side of window-frame, 86 cm below window-sill (concrete floor).



Landeskarte der Schweiz 1 : 25000
(sheet) no. 1229, Grindelwald
643300 / 159040

JUNGFRAUJOCH



The establishment of the Iranian Gravity Datum(IGD).

H. Zomorrodian

Institute of Geophysics, Teheran, Iran

Summary: By means of a relative pendulum measurement the Central Research Institute of Geodesy, Aerial Surveying and Cartography of USSR(CRIGASC) in cooperation with the Geophysics Institute, Tehran University(GITU) has connected the station Moscow(Ledovo) to the stations C-1A in Tehran and C-37A in Shiraz in 1972. Using the results of all gravity connection-measurements and also the results of the measurements, which have been carried out on the Iranian National Gravity Calibration Line(INGCL) in 1981, the pendulum gravity value is transferred to 3 identical stations, which presented also by International Gravity Standardization Net 1971(IGSN 71). A critical comparison between the values obtained by pendulum measurements and those presented by IGSN 71 gave rise to evaluate the new reference gravity values for the country. Based on this investigation the Iranian Gravity Datum(IGD) is finally presented.

1-Introduction: Gravity measurements in Iran with respect only to scientific purposes were started by GITU in the year 1958 on a trial basis and then from 1967 with the idea to establish the fundamental gravity network of the country. Up to present some 12000 gravity points exist in Iran, which have been measured by various organizations. In 1970 in the framework of the research program of GITU, the author established the Iranian National Gravity Calibration Line(INGCL 70) between Shiraz and Chalus at the Caspian See(s.fig.1) with 29 32.6 and 36 29.6 northern latitudes respectively(4,5). This line comprised 32 gravity stations. In 1972 in reply to the request of GITU, the CRIGASC(USSR) performed a relative gravity measurement between Moscow-Tehran and also on the calibration line(INGCL) between Tehran and Shiraz by means of pendulum instruments. Two points of the INGCL were covered indirectly by these measurements. The IGSN 71 comprises also 3 stations in Tehran one of them belonging to the INGCL. An investigation on the existing INGCL during the years 1979-80 showed that due to constructional alterations and other operations a great amount of the stations on the north section of the INGCL(Tehran-Chalus) and some of the stations on its south section

(Thran-Shiraz) were useless or got lost. In 1981 the lost stations on the south section were restored and, as far as possible, new stations were established, so that the number of the stations in this section were increased from 19 to 26, including two pendulum stations in Tehran and Shiraz. In the same year by means of three Lacoste & Romberg gravimeters the gravity differences between the stations in this section were simultaneously determined, including the pendulum points for the first time only as calibration stations(6). Because of non existing of the absolute gravity measurements in Iran, the almost all gravity measurements were referred to the gravity value of Mehrabad-airport(979 445.429 mgl), extracted from the World Gravity Base Survey(1); therefore this value was inevitably chosen as a provisional gravity datum(p-datum) for the country. After publishing the results of IGSN 71, some data were recalculated with the respect of the new value of this point. But the problem was herewith not nearly solved. The establishment of an acceptable gravity datum, with regard to the reference system of IGSN 71, required a comparison between the gravity values of the points of IGSN71 and those of the iranian network, derived from the gravity value of the pendulum station(C-1A). In addition some discrepancies were observed between the difference gravity values of the points 13951 J and 13951 C suggested by IGSN 71 and those measured by other organizations(s.fig.5). Therefore an investigation seemed to be necessary to clear the above mentioned problems. The only identical point, which could be used for this investigation is the one situated in the GITU, designated as 13951 C-Tehran by IGSN 71 and as C-1 by INGCL. The second identical point(13951 J-Tehran) is unfortunately in the meantime lost in consequence of the reconstruction of Mehrabad-airport. As a result the control of the gravity differences between this point and those in the GITU(13951 B, 13951 C = C1 and C1A) is no more possible. The calculation must therefore be based on the previous measurements and also on the results of the adjustment of the INGCL 81. From 1970 to 1977 the GITU has determined the gravity difference between the P-datum(13951 J) and the point 13951 C several times. This connection is measured by other organizations and in the framework of IGSN 71 as well.
This report will firstly be concerned with the pendulum measurements between Moscow, Tehran and Shiraz, then it considers the results of the adjustment of INGCL 81 shortly and finally deals with the cal-

culations relating to the agreement between the values for the identical point C1 derived from the pendulum measurements and that determined by IGSN 71, and all these to be followed by suggesting of a gravity datum for Iran based on this investigation.

2-Pendulum measurements: As mentioned before a group of 6 scientific members of the CRIGASC(USSR) has established the gravity connections between Moscow, Tehran and Shiraz in May-June 1972 in the framework of an agreement between GITU and the Interdepartmental Geophysical Committee(IGC) of USSR. The Instruments used for this investigation consisted of five pendulum sets model OVM(2), designed by CRIGASC. Each pendulum instrument was equipped with two quartz-metal pendulums mounted in thermostated and vaccumized cases. The observation plan could summerized as following:

Ledovo-Moscow(I)	*: 10-15 May*	*,*	*Tehran(II)*	*: 3-7 June*
Tehran (I)	*: 20-24 May*	*,*	*Ledovo-Moscow(II)*	*: 10-12 June*
Shiraz	*: 28-31 May*			

The calculation has been performed by using the results of only 4 instruments(6101, 6102, 6301 and 6303), since unfortunately the fifth one fell into disrepair.
According to the report of GRIGASC, which is sent to GITU(2), the period of the fictitious pendulum was determined from oscillation period of the pendulum, after taking into account the corrections for amplitude, pressure, temperature, variation of the frequency of the quartz standards, asymmetry, non-isochronism and the tidal effects. Table 1 and 2 contain the mean period values of the pendulums and the gravity differences with the mean weighted value accepted as final value for each instrument. This report suggests finally a value of $\Delta g=-2162.61\pm0.05$ mgl for gravity difference between Tehran and Moscow(Ledovo) with a relative error of $\pm2.10^{-5}$. For the gravity difference between the World Initial Base Station Potsdam Absolute Seite(21523) and Moscow(Ledovo) gives this report a value of -291.327 $\pm$0.019 mgl in old potsdam system. Therefore the absolute gravity value of Tehran, GITU(C1A), referring to Potsdam Datum amounts to 979 402.717$\pm$0.053 mgl. The gravity difference value for Tehran-Shiraz is given by 559.13$\pm$0.053 mgl with a relative error of $\pm1.10^{-4}$.

Through this precious collaboration the main gravity base of Iran is connected to the World Initial Gravity Base Station Potsdam over Moscow by means of pendulums. Since the P-datum in Mehrabad is also connected to the stations of the World Gravity Network by means of gravimeters, a comparison between these two values is of great interest. Considering the fact that the gravity network of USSR is not directly connected to the World Gravity Network(WGN), therefore such comparison, which is important for establishing the gravity datum of Iran, could also indirectly serve to evaluate the datum of the gravity network of USSR, which is scientifically of great significance.

3- The adjustment of the INGCL 1981: The first measurement on the INGCL was performed in 1970 by means of 4 Lacoste & Romberg gravimeters model G nos. 59, 114, 116 and 138. Since at that time neither absolute- nor pendulum-stations were existed in Iran, one of the 4 gravimeters, which proved to be the best was chosen as the base gravimeter with the scale factor equal to one(4,5). By an adjustment technic after the method of variation of the coordinates the scale factors of other 3 meters with respect to the base gravimeter and also the preliminary gravity differences, $\overline{\Delta g_i}70$, were determined. The preliminary absolute gravity values for the stations on the INGCL have been obtained by using the absolute value of the P-datum (Mehrabad-airport).

In 1981 the gravity differences of the stations on the south section of INGCL(Tehran-Shiraz) were measured by means of 3 Lacoste&Romberg gravimeters model G nos. 263, 296 and 440. The two pendulum stations C1A in Tehran and C37A in Shiraz have been considered as normal calibration stations in this line.

In the new adjustment of 1981 the preliminary gravity differences, $\overline{\Delta g_i}70$, are used together with the values obtained by the three gravimeters as approximate values(Δg_i) in the observation equations. The observation equations are of the type:

$$v_{ik} = f_j(\Delta g_{ik}) - \Delta g_{ik} + \overline{\Delta g}_{ik} \text{ , where}$$

v_{ik} = residual of the gravity difference observed between i and k.
f_j = scale factor of the gravimeter j.

Δg_{ik} = observed gravity difference between i and k by gravimeter j.
$\overline{\Delta g}_{ik}$ = gravity difference between i and k.

The difference of the gravity values of the pendulum stations is supplied with the weight 20 and used as quasi forcing condition in the adjustment. Therewith the scale factors of the used gravimeters as well as the fictitious scale factors for differences $\overline{\Delta g}_i 70$ were established. The values of the $\overline{\Delta g}_i 70$ were firstly processing with the weight 2 in this calculation, whereas the weight for the other Δg_i values were selected to one. The residual could be seen in fig.2. In order to make it sure that the new results are free from the eventually existing scale effect of $\Delta g_i 70$, the adjustment has been carried out once more by processing all Δg_i values with the weight one. The residuals are plotted in fig. 3. Comparing the figs. 2 and 3, no significant varieties are recognized. The approximate great tolerance by residuals in both cases could be attributed to the periodical spindle errors. The gravity values against elevations are plotted in fig. 4. Table 3 shows the calibration stations, the adjusted gravity differeences and the scale factors. Column 6 contains the absolute gravity values referring to the new defined gravity datum of Iran(see § 4).

4- Establishment of the Iranian Gravity Datum(IGD): For the establishment of a new IGD, the gravity value of the pendulum station in Tehran (C1A) is firstly transferred to the identical station(C1) by means of the mean values extracted from the numerious measurements, which have been made between these two points during the past years. Using the correction for the Potsdam(old) system, which amounts to 13.96 mgl(3), and also by applying the results of the adjustment of INGCL 81, the absolute gravity value of C1 based on the pendulum measurements is determined. In a second step the mean value of all existing gravity difference measurements between the points 13951C(C1) and 13951J was calculated and the absolute gravity value of Mehrabad(13951J) referring to the pendulum station C1A is determined. Table 4 shows these results. The calculated mean gravity values for the three identical stations 13951B, 13951C and 13951J, as well as the equivalent gravity values given by IGSN 71 and also for the P-datum are registered in table 5. As this table shows the mean gravity values for the stations 13951B and J are in agreement with the values suggested by IGSN 71 within the limit of 0.01 mgl. The coresponding mean value for the station 13951C = C1 differs from that of IGSN 71 in the order of 0.08 mgl; it is due to the existing variation between the gravity difference values of the points 13951J and 13951C presented by IGSN 71 and the mean value for this difference calculated from the measurements of all other organizations. The GITU has measured this gravity difference in the different periods of time and by means of different instruments. The results are in full agreement(in the order of 0.01 mgl) with each other and also with the results of other organizations (see table 4). Therefore it could be suggested that in consequence of the above mentioned discrepancy the gravity level of the station 13951C has rather been chosen high(in the order of 0.08 mgl)in IGSN 71 system. The same difference appears in the gravity value of the point 13951B, derived from the value of the point 13951C, in the order of 0.07 mgl and with the opposite sign(see fig.5). However this disagreement lies in the range of the overlapping standard errors of the used gravity values, it is, in regard to the equality of the variations of the both gravity values(13951 C and B) from the calculated mean values, preferable to accept only the gravity value of the point 13951J in IGSN system as reference value. This point,on the other hand, exists no more. Therefore we have no other choice to elect the point 13951C(in the GITU) as reference point, provided that its gravity value be derived from the value of the point 13951J with the respect of the mean gravity difference value(13951J - 13951C) calculated in the table 4. With this decision the values of two stations of the IGSN 71, 13951B and 13951J, have exactly and the value of its third station, 13951C, in limitation of 0.08 mgl been chosen as reference gravity values. The value of the P-datum shows a discrepancy in the order of 0.79 mgl at the station 13951J in comparison to the new reference values, after be affected by the correction of the Potsdam old system.

5-Conclusions: Based on this study following suggestions could be concluded:

a) Because the old reference station(Mehrabad-Airport, 13951J) does no more exist, it has no longer validity as a reference point. During the measurements on the

INGCL in 1985, a new station has been established in Mehrabad(near the old station) as INGCL station and connected also to the reference stations in GITU.[1]

b) The provisional gravity datum(P-datum) of Iran with an absolute gravity value of 979 445.429 mgl(in the old Potsdam system) is no more applicable, because of its great difference with respect to the new reference values.

c) As new Iranian Gravity Datum(IGD), we suggest the station C1=13951C with an absolute gravity value of 979 388.18 ± 0.034 mgl. This datum could be retained until sufficient absolute gravity measurements will be performed and the new Adjustments are carried out.

d) The suggested IGD is in good agreement with the gravity values of the stations of IGSN 71(greatest variation amounts to 0.08 mgl).

e) The transferred gravity value from this datum to the pendulum station(C1A) is in full agreement with the value derived from the pendulum measurements carried out by CRIGASC(USSR). It suggests that in spite of non existing direct connection between IGSN 71 and the USSR gravity network, the data of both networks are in good agreement within limitation of their standard errors. This investigation could be considered as an indirect connection between the two networks.

f) The above mentioned results of the relative pendulum measurements has proved that by means of such pendulum apparatus the gravity differences over the long distances could be determined with an accuracy of about 0.08-0.10 mgl.

g) Using the gravity difference value between Tehran and Shiraz, derived from the pendulum measurements, in the

1- The results of this measurements(INGCL 85) will be published soon.

adjustment of the INGCL 81, the linear scale factor of the used gravimeters were determined. the results of this adjustment were used together with all other available data for determination of the mean gravity differences of the stations C1A-C1 and C37A-C37. These gravity differences were in turn used for transformation the gravity reference values to the pendulum stations, in order to render a comparison feasible.

h) Finally it is recommended to recalculate all gravity data measured up to now in Iran with respect to the new reference value(IGD), in order to be able to present a homogeneous gravity system for the country.

Acknowledgements: The author wishes to express his appreciations and thanks to the following persons and organizations:

-- Prof. Dr. H. K. Afshar, the former director of GITU who supported the pendulum measurements in 1972.
-- The GITU for the financial, instrumental and personnel support during the entire work from 1970-81.
-- The IGC(USSR) for his approval of this cooperative project and the CRIGASC for the completion of the pendulum measurements and preparing its report.
-- The national Cartographic Centre of Iran(NCC) for the financial and personnel support during the gravity measurements on the INGCL in 1981.
-- The National Iranian Oil Company(NICO) for putting in our disposal two Lacoste & Romberg gravimeters in 1981.

A part of this report, the adjustment of INGCL 81, has been completed by the author during a two months research staying at the Institut für Angewandte Geodäsie(IfAG), Frankfurt/M., in 1984. I express my deep appreciations to Dr. W. Satzinger, director, to Prof. Dr. E. Reinhart, chief of the department of Geodätische Forschung(GF), to Prof. Dr. D. Lelgemann and other scientists of this department for valuable discussions, using the computer facilities, etc. .
Non least are thanks and acknowledgements due to Deutscher Akademischer Austauschdienst(DAAD) for supporting my staying in Germany.

References:

1- Afshar,H. ; Zomorrodian,H., The measurements and the adjustments of the first order gravity network of Iran, pub. No. 48, GITU, Tehran 1970.

2- CRIGASC ; Acceleration of gravity at points Tehran and Shiraz as determined from pendulum observations; The Central Research Institute of Geodesy, Aerial Surveying and Cartography, USSR, Moscow 1972.

3- Morelli, C.; The International Gravity Standardization Net 1971 (IGSN 71), Bureau Central de L'Association International de Geodesie

4- Zomorrodian, H. ; The establishment of the Iranian National Gravity Calibration Line(INGCL), pub. No. 58, GITU, Tehran, 1972.

5- Zomorrodian, H. ; Gravimetermessungen zum Aufbau einer iranischen nationalen Gravimetereichlinie(INGCL), ZfV, Nr.2 Deutschland, 1973.

6- Zomorrodian, H. ; The gravity measurements on the south section of the Iranian National Gravity Calibration Line, 1981(INGCL 81), pub. No....., GITU, Tehran(in press).

Table 1. Mean period-values of the pendulums, after the report of CRIGASC, USSR

STATIONS		MEAN PERIOD	M	NOS. OF PERIODS
		Instrument 6101		
Ledovo	I	$0.4915\ 4403_6$	± 0.24	10
Tehran	I	$0.4920\ 8642_2$	± 0.57	10
Shiraz		$0.4922\ 2692_6$	± 0.52	7
Tehran	II	$0.4920\ 8638_5$	± 0.46	9
Ledovo	II	$0.4915\ 4402_4$	± 0.33	6
		Instrument 6102		
Ledovo	I	$0.4949\ 3204_8$	± 0.73	12
Tehran	I	$0.4954\ 7814_2$	± 0.96	11
Shiraz		$0.4956\ 1962_5$	± 1.31	7
Tehran	II	$0.4954\ 7814_2$	± 0.41	9
Ledovo	II	$0.4949\ 3194_3$	± 0.88	8
		Instrument 6301		
Ledovo	I	$0.4830\ 3537_8$	± 0.27	12
Tehran	I	$0.4835\ 6840_1$	± 0.55	6
Shiraz		$0.4837\ 0649_4$	± 0.51	6
Tehran	II	$0.4835\ 6838_4$	± 0.55	7
Ledovo	II	$0.4830\ 3539_0$	± 0.53	7
		Instrument 6303		
Ledovo	I	$0.4854\ 2484_2$	± 0.85	8
Tehran	I	$0.4859\ 6048_6$	± 1.18	9
Shiraz		$0.4860\ 9931_8$	± 1.66	10
Tehran	II	$0.4859\ 6058_0$	± 2.02	14
Ledovo	II	$0.4854\ 2493_7$	± 0.45	6

Table 2. The gravity differences (in mgl) between the stations Ledovo-Tehran and Tehran-Shiraz, after the report of CRIGASC, USSR.

Station-connections	INSTRUMENTS				Mean value	Weighted mean value
	6101	6102	6301	6303		
Ledovo-Tehran	-2162.55 ± 0.08	-2162.68 ± 0.09	-2162.64 ± 0.09	-2162.64 ± 0.08	-2162.63 ± 0.07	-2162.61 ± 0.05
Tehran-Shiraz	-559.12 ± 0.09	-559.08 ± 0.09	-559.17 ± 0.07	-559.17 ± 0.21	-559.14 ± 0.06	-559.13 ± 0.05

Table 3. The results of the adjustment of INGCL 1981. The absolute gravity values are based on IGD-value.

1	2	3	4	5	6
Station names	St. nos. 1981	St. nos. 1970	Adjusted grav.-diff.	Adjusted g_i 81, $g_{C-1A} = 0$ (mgl)	Abs. gravity val. (mgl)
Tehran (pendl. st.)	C- 1A			0. ±0.008	979 388.77 ± 0.037
			- 0.591		
Tehran 13951 C	C- 1	C- 1		- 0.591±0.015	388.18 ± 0.034
			+ 70.404		
Hassan-Abad	C-15	C-15		+ 69.792±0.021	458.56 ± 0.043
			- 39.424		
Pole-Autobahn	C-16	-		+ 30.368±0.024	419.14 ± 0.044
			+ 4.528		
Shukuhieh	C-17	C-16		+ 34.896±0.021	423.67 ± 0.043
			- 39.355		
Ghom (RRS)	C-18	C-17		- 4.459±0.021	384.31 ± 0.043
			-103.487		
Salafchegan	C-19	-		-107.946±0.024	280.82 ± 0.044
			- 12.002		
Neizar (gas-st.)	C-20	-		-119.948±0.024	268.82 ± 0.044
			- 54.171		
Delidjan	C-21	-		-174.119±0.025	214.65 ± 0.045
			-129.042		
Varkan (gas-st.)	C-22	-		-303.161±0.027	085.61 ± 0.046
			- 36.553		
Vazvan	C-23	-		-339.714±0.028	049.06 ± 0.046
			+ 40.619		
Murcheh-Khort	C-24	-		-299.095±0.027	089.68 ± 0.046
			- 26.941		
Esfahan (o. A. P.)	C-25	C-22		-326.036±0.025	062.73 ± 0.045
			- 53.316		
Hossein-Abad	C-26	C-23		-379.352±0.026	009.42 ± 0.045
			- 88.173		
Ghomsheh	C-27	C-24		-467.525±0.028	978 921.25 ± 0.046
			- 78.544		
Amin-Abad	C-28	C-25		-546.069±0.030	842.70 ± 0.048
			- 31.681		
Izad-Khast (O)	C-29	-		-577.750±0.034	811.02 ± 0.050
			+ 4.458		
Abadeh (NW)	C-30	C-26		-573.292±0.031	815.48 ± 0.048
			+ 23.633		
Surmagh (SE)	C-31	-		-549.659±0.033	839.11 ± 0.050
			- 65.850		
Khaneh-Khorreh	C-32	-		-615.509±0.035	773.26 ± 0.051
			- 60.223		
Ghaleh-Murcheh	C-33	C-29		-675.732±0.034	713.04 ± 0.050
			+ 65.919		
Pasargad	C-34	-		-609.813±0.035	778.96 ± 0.051
			+ 26.473		
Sivand	C-35	-		-583.340±0.034	805.43 ± 0.050
			+ 30.750		
Pol-e-Khan	C-36	-		-552.590±0.033	836.18 ± 0.050
			+ 2.901		
Shiraz A. P.	C-37	C-32		-549.689±0.031	839.08 ± 0.048
			- 9.441		
Shiraz (pendl. st.)	C-37A	-		-559.130±0.009	978 829.64 ± 0.038

Table 3 continued...

Instrument	LCR-296	LCR-263	LCR-440	$\overline{\Delta g_i}$ 70
Scale factor	1.001006682 ±0.000044501	1.000208069 ±0.000044466	1.000182226 ±0.000044465	0.999392843 ±0.000047444

Table 4. The results of the difference - measurements.

organization	year	Instrument	Gravity diff. (mgl)
			C1—C1A
GITU	1972	LCR-59	0.612
GITU	1974	LCR-296	0.603
GITU-NCC	Adj. 1981	{ LCR-440, LCR-263, LCR-296, Δg_i 70 }	0.611
GITU-NCC	1985	LCR-296	0.596
GITU-NCC	1985	LCR-440	0.609
GITU-NCC	1985	LCR-731	0.540
		mean value	0.595
			C1—13951 J
GITU	1972	LCR-59	42.56
GITU	1974	LCR-296	42.50
GITU	1976	LCR-296	42.49
TOPOCOM	--	---	42.48
IfGH*	1977/78	---	42.45
		mean value	42.50 ± 0,018
			13951 B.—C1
GITU-NCC	1985	LCR-296	0.268
GITU-NCC	1985	LCR-440	0.250
GITU-NCC	1985	LCR-731	0.294
		mean value	0.271
			13951 B—C1A
GITU-NCC	1985	LCR-296	0.864
GITU-NCC	1985	LCR-440	0.859
GITU-NCC	1985	LCR-731	0.834
		mean value	0.852
mean value with respect to the triangle rest-error on fig. 5			C1 - C1A : 0.591 ± 0,015 13951 B - C1 : 0.267 ± 0,013 13951 B - C1A : 0.858 ± 0,010

*Institut für Geophysik, Hamburg

Table 5. The gravity values for three identical points from different sources and for the pendulum station in Potsdam - old (O) and - new (N) systems.

Source	Absolute gravity value (mgl)			
	13951 J (Mehrabad)	13951 B	13951C=C1	C-1A=Pend. St.
from mean-gravity values based on the abs. val. of 13951C	979 430.68 ± 0.029	979 387.91 ± 0.036	979 388.18 ± 0.034	979 388.77 ± 0.037
IGSN 71	979 430.68 ± 0.029	979 387.92 ± 0.031	979 388.25 ± 0.034	-----
CRIGASC	---	---	---	979 402.72 (O) ± 0.053 979 388.76 (N) ± 0.053
P-datum	979 431.47	---	---	---

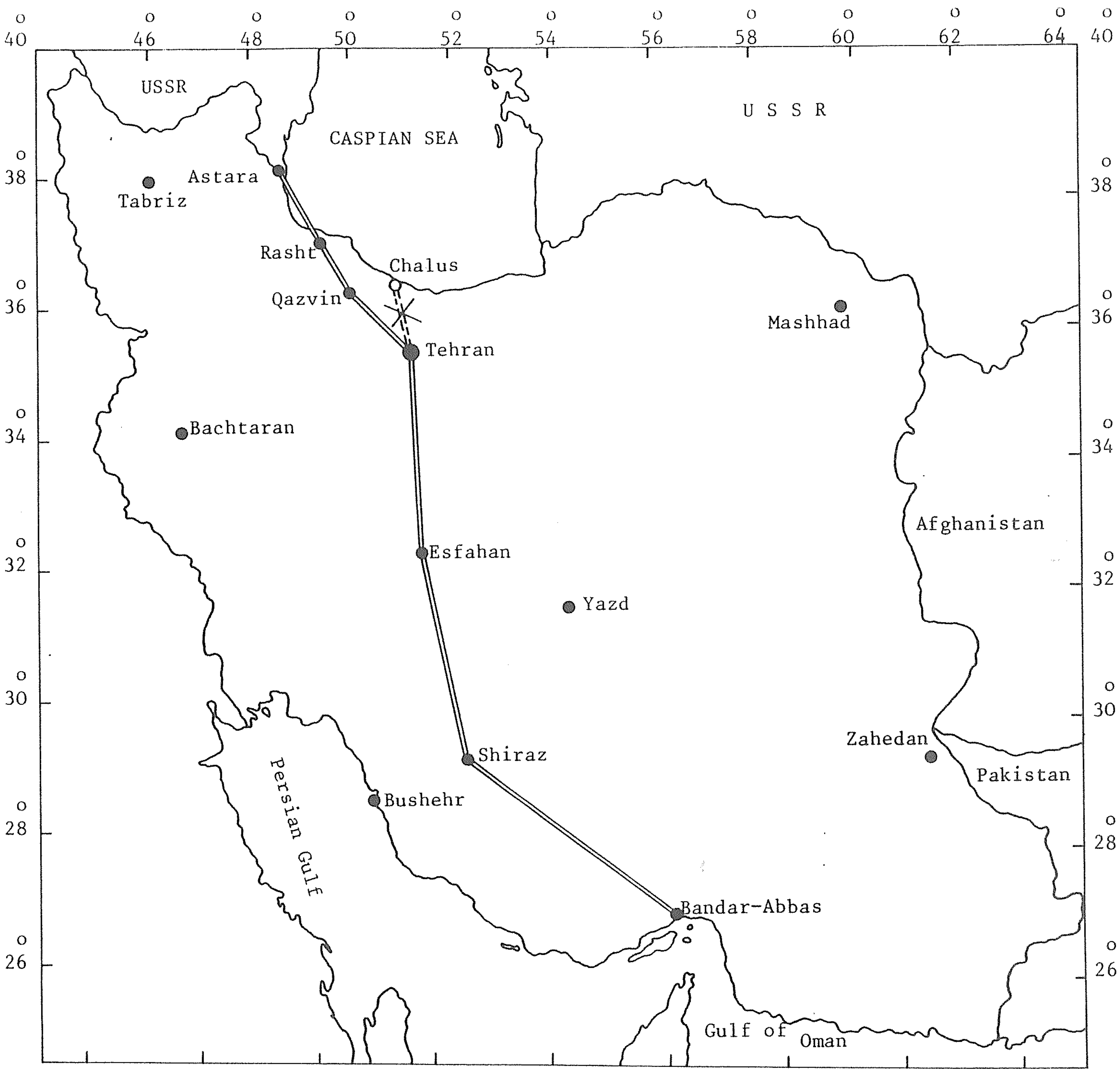


Fig. 1: The Iranian National Gravity Calibration Line 1985 (INGCL 85).

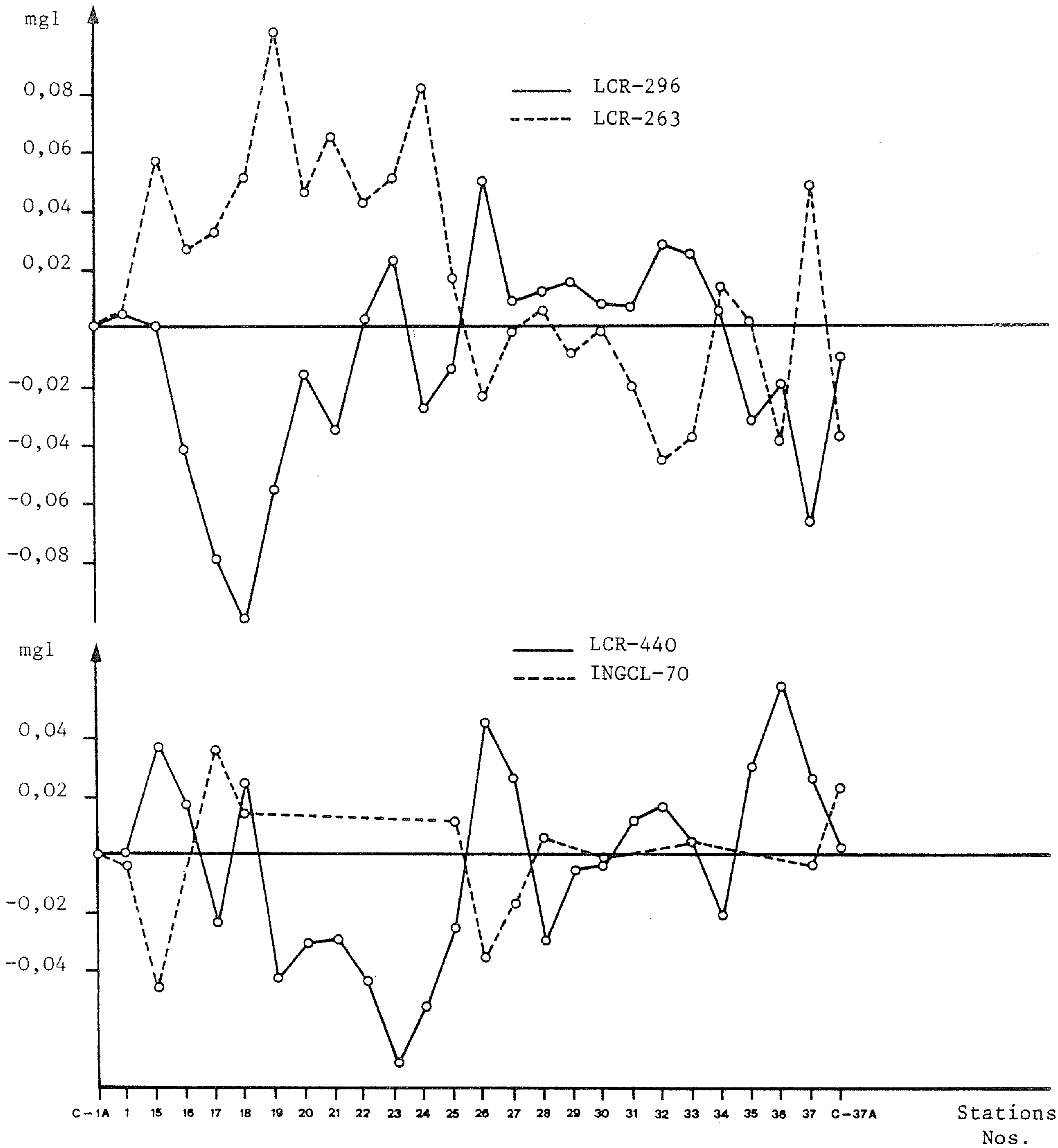


Fig. 2: The residuals of the adjustment of INGCL-81. Δg_i 70 with the weight equal to 2 and other Δg_i with the weight equal to 1.

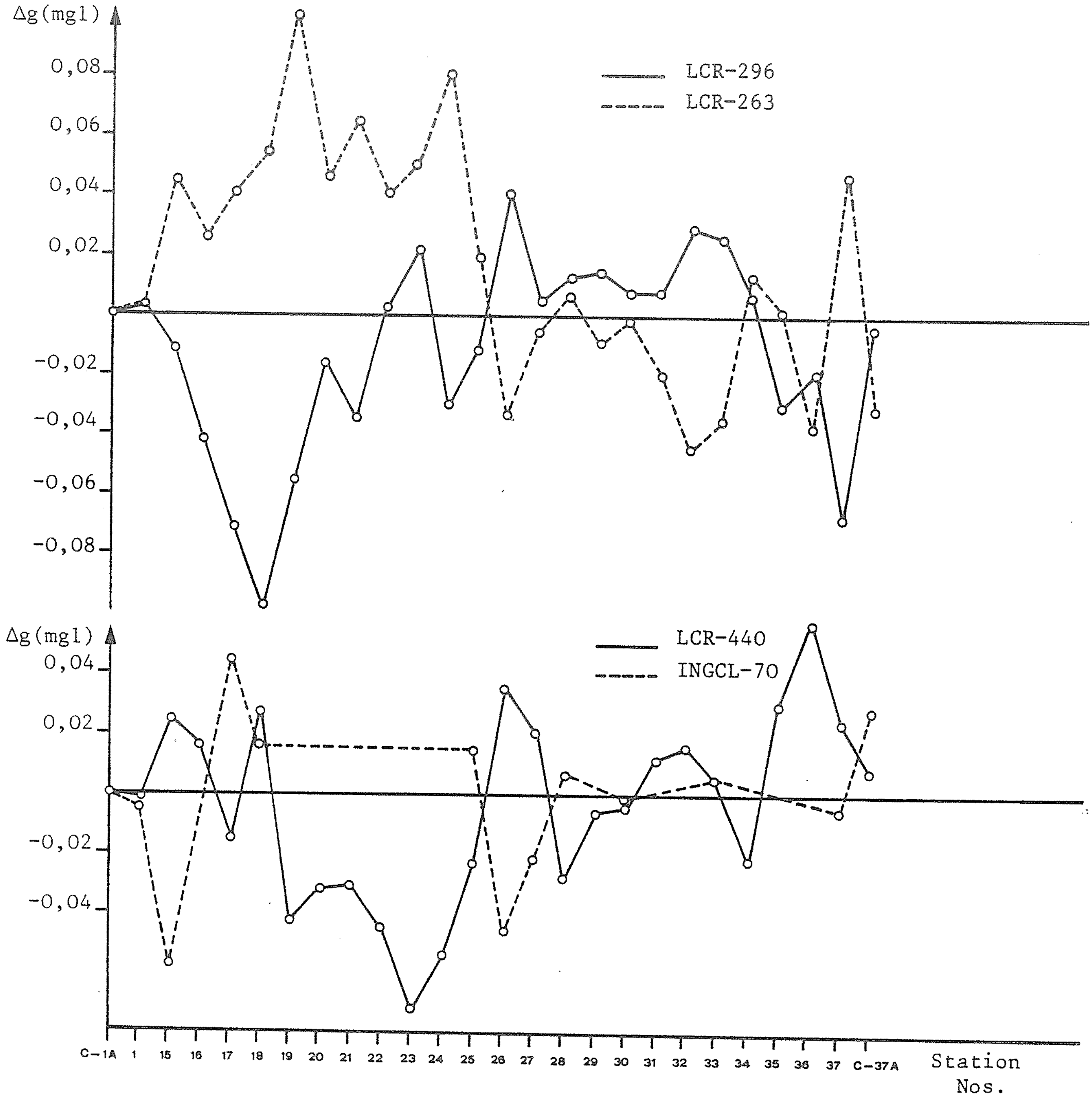


Fig. 3: The residuals of adjustment of INGCL-81; all Δg_i furnished with the weight equal to 1.

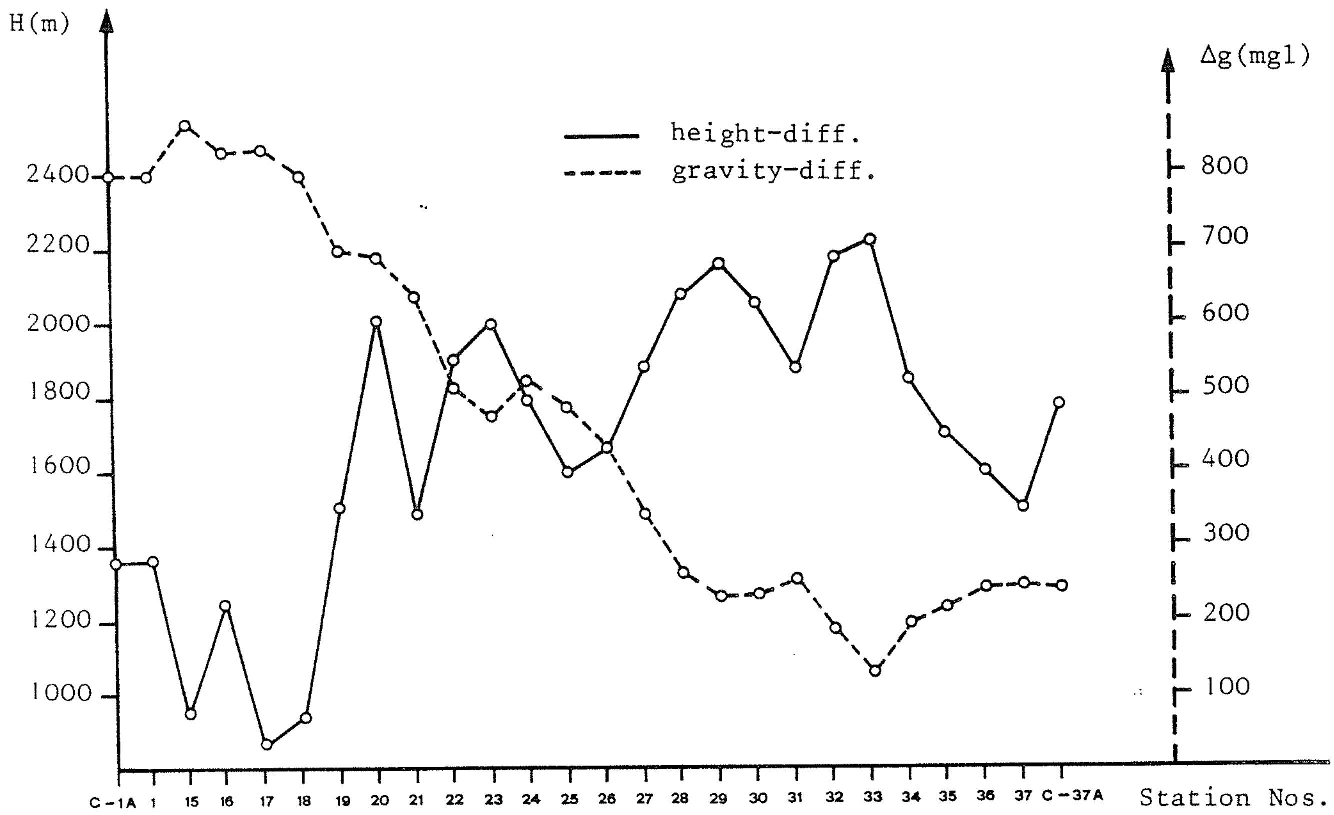


Fig. 4: Gravity against elevation-differences.

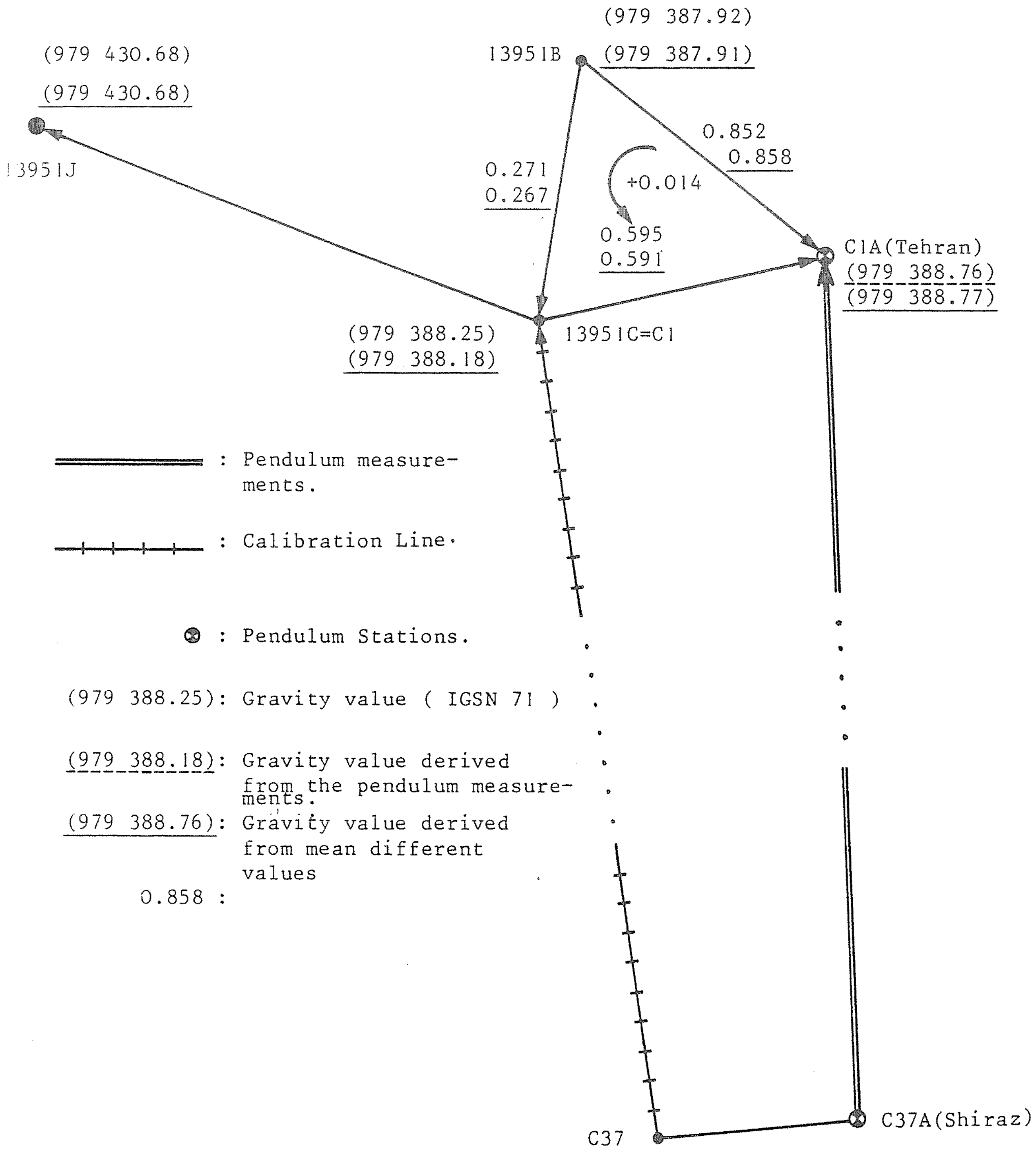


Fig. 5: Gravity differences between the reference points and the pendulum measurements.

ON THE DETERMINATION OF THE HEIGHT CORRECTION IN THE MEASURED ABSOLUTE GRAVITY VALUE

M. B. Shteyman[+], A. V. Kopayev[*], I. A. Leontyev[+]

[+] The All-Union Research Institute of Natural Gases

[*] The P. K. Shternberg State Astronomical Institute, Moscow State University

Abstract

An analysis of the preliminary results of the measurements of vertical gravity gradients obtained during the Second International Comparison of absolute gravimeters in Sevres 1985 has been conducted. At all points the non-linearity of gravity changes with height has been found which, if neglected, may cause errors while determining the height correction in reducing the measured absolute gravity values to the points' surfaces. The technique of determining the vertical gravity gradient and the height correction value has been made more precise on the basis of approximating the vertical gravity differences measured using relative gravimeters with a second-degree polynomial. The results of the measurements of the vertical gravity gradients above the postaments at the Ledovo, Medeo and Turgen laboratories are given. The variations of their values with time of various periodicity have been detected which considerably influence the height correction value.

1. The vertical gravity gradient changes with height. Theory

To reduce the result of a gravity measurement using the absolute gravimeter from a certain effective height H to the point's level the height correction is usually determined as

$$\Delta g_H = (\Delta g/\Delta h) * H , \qquad (1)$$

where Δg - a gravity difference within a height interval Δh measured using a relative gravimeter with working height h_0. However, its working height in the upper position on a special stand $h_0+\Delta h$ often does not coincide with H, especially during comparative measurements when using several absolute devices (Becker, 1985). In this case the height correction is determined on the basis of linear interpolation or extrapolation, which does not take into account the non-linearity of the gravitational field above most of the postaments (Sagitov et al., 1985; Rukavishnikov et al., 1985) and hence is incorrect. The quantity ($\Delta g/\Delta h$) in the expression (1) is the mean value of the vertical gravity gradient within the interval Δh and may change with height. The neglect of this fact in measuring vertical gradients at six points (A, A_3, A_4, A_5, A_6, A_7) during the Second International Comparison of absolute gravimeters in Sevres 1985 (Becker, 1985) resulted in systematically too high gradient values for some LaCoste-Romberg gravimeters which operated on the stands of lower height (G54, G290). Assuming that gradients change linearly above all points and using all the gravimeters' results one can determine the gradients' dependence on height with the help of the weighted least squares method (Fig. 1). Taking into account the gradient's height change will lead to an increase in the results of the Italian and Soviet absolute gravimeters which were placed at the point A_3 by 3.0 and 1.5 mcgal respectively. It should be emphasized that for the analysis we used the preliminary results of the gradients' measurements in Sevres and the correction of the absolute gravimeters' results is somewhat premature. However, the necessity is evident of taking into account the gradients' height changes when measuring the absolute gravity values with an accuracy of 1 mcgal.

To make the analysis of the influence of the gradient's height change on the result of absolute gravity measurements more comprehensive we shall point out its influence on the very process of the test body's falling (Sagitov, 1984). The length of the path travelled by the test body in the Soviet gravimeter is nearly 0.7 m and the vertical gradient within this interval at the point A_3 changes by 16 mcgal/m (Fig. 1), which will add to the instrument's result approximately 1 mcgal.

The problem of determining the height correction value with an accuracy of 1 mcgal can be succesfully solved in a general form using the approximation with a second-degree polynomial of the vertical differences of gravity measured with relative gravimeters within the height interval from 0.05 m to 1.5 m from the postament surface (this interval includes the working heights of all existing gravimetric devices). Using the methods of optimal planning for the reliable determination of the three polynomial coefficients it is sufficient to make relative measurements at seven levels with respect to the postament's surface (Kopayev, 1986). The weighted least squares method (weights are inversely proportional to the squares of r. m. s. errors of the corresponding gravity differences values) efficiently smoothes the measurement "noise". To determine the height correction value it is advisable to use a straight line describing the gradient height dependence and multiply the value of the gradient at the height H/2 by the value H. The error of the reduction can be expressed with the residual sum of the squares. The obtained dependence of the gradient on the height can be used to make the result of the absolute gravity measurement more precise in accordance with (Sagitov, 1984).

2. The vertical gravity gradient changes with height. Measurements

We carried out a number of experiments to determine the dependence of gravity on the height in laboratories using the Sodin gravimeters and a special installation providing seven levels (positioned vertically at 0.2 m intervals) for measuring gravity differences relative to the postament surface. A single measurement error fluctuated from 3 to 6 mcgal. To raise the accuracy of the determination of gravity difference to 1 mcgal measurements were repeated 15-30 times. The total period of observations was about 3-4 hours. The results were processed using a"full zero-point" method which enables one to determine the instrument drift on the basis of repeated observations at all levels (Shteyman, 1983).

The measurements were carried out at three points at postaments P_1 and P_3 at the Ledovo gravimetric laboratory (Moscow) and at the Medeo and Turgen laboratories (Shteyman et al., 1986). The results are shown on Fig.2 and Fig.3. It is of interest to note that above the point in the centre of the postament P_1 in Ledovo (mark 5035 of the International Gravity Basestation Network) and above the Turgen point the vertical gradient increases just as above the point A in Sevres (Fig.1).

3. The vertical gravity gradient changes with time

During the repeated measurements of the vertical gradients in Sevres 1985 the new values obtained at points A_3 and A_6 differed considerably from the previous ones (Becker, 1985). These discrepancies can be partially due to the neglect of the gradient height dependence and (or) the horizontal non-uniformity of the gravitational field affecting the value of the gradient in the case of the non-coincidence of the verticals along which the measurements were made (Boulanger, 1985; Rukavishnikov et al., 1985). However, during the measurements carried out in 1985 (Becker, 1985) even the same gravimeters on the same stands yielded different values of gradients in independent sets of measurements. For instance, the difference 3.0 ± 1.5 mcgal/m was found at the point A_4 by gravimeters D8F and G709F. The reason for this can be the neglected measurement errors. But the possibility of the time variations of the vertical gradients should not be excluded, especially, that similar phenomena have been observed by us at various points.

At the Medeo and Turgen geophysical laboratories the gradients were measured three times - in May 1984, May 1985 and October 1985, when it was done twice a day - at night and in the daytime - in order to try to detect short-period variations. From May 1984 (Line 1 in Fig.3) to May 1985 (Line 2) the gradient value in Medeo decreased approximately by 10.5 ± 1.5 mcgal/m and remained almost unchanged five months later (Line 3). In October 1985 the gradient was measured also at night (Line 4) and its value was almost 5.0 ± 1.0 mcgal/m less than in the daytime (Line 3).

For eighteen months (May 1984 - October 1985) the gradient at the Turgen point remained practically unchanged (Lines 5 and 6 in Fig.3) and a short-period variation ("day" - "night") in October 1985 was approximately 3.5 ± 1.2 mcgal/m (Lines 6 and 7).

Short-period variations of the vertical gradients of a somewhat less amplitude were also detected at the Ledovo laboratory (Fig.2). At the point on the edge of the postament P_1 the experiment was conducted twice - on the 13th of December, 1985 when in the daytime the gravity value was nearly by 200 mcgal greater than at night due to the influence of the tides and on the 30th of January, 1986 when the tidal effect at night and in the daytime was the same. The resulting graphs of the gradient's dependence on the height practically coincided ("night" with "night", "day" with "day") within the accuracy of the measurements, which showes the stability of the phenomenon observed and its independence on the tides. This is possibly due to daily variations of hydrogeological factors (the level of underground waters in the vicinity of artesian wells).

4. Conclusions

When determining the height correction in the absolute gravity values with accuracy of about 1 mcgal one should take into account both the possible dependence of the vertical gravity gradient on height and its possible time variations. That is why it is advisable to determine the gravity value dependence on height above the point from relative measurements of its differences at several levels approximating it by a second-degree polynomial. We have developed a computer program for the data processing and the graphic representation of the computations results. To avoid possible errors due to short-period time variations of the gradients measurements should be made at the time of the day when the absolute gravity value is being determined. All this should be taken into account when the next comparison of absolute gravimeters is performed and when designing the International Absolute Gravity Basestation Network (Boedecker, 1985). Considering the increasing accuracy of absolute and relative gravity measurements the study of the vertical gravity gradients' time variations can be of special interest.

5. Acknowledgements

The authors wish to express their profound gratitude to Yu. D. Boulanger for the many discussions of this work and his valuable comments.

6. References

Becker M. Relative Gravimeter Measurements at the 1985 Absolute Gravimeter Campaign in Sevres. Preliminary Results. BGI, Bull. d'Inform., No. 57, Decembre 1985, pp. 46-71.

Boedecker C. On the design of the International Absolute Gravity Basestation Network (IAGBN), BGI, Bull. d'Inform., No. 57, Decembre 1985, pp. 113-131.

Boulanger Yu. D. Once more about comparison of absolute gravimeter in Sevres 1981. BGI, Bull. d'Inform., No.56, June 1985, pp.21-27.

Kopayev A. V. Principles of Optimum Planning of Gravimetric and Variometric Surveys Above Postaments. In the book: Repeated Gravimetric Observations (Coll. Scientific Works), Moscow, MGK Publishers, 1986, pp. 39-43 (in Russian).

Rukavishnikov R. B., Pushchina L. V., Shteyman M. B. Dissimilarity of the gravity field on and above postaments. BGI, Bull. d'Information, No. 57, Decembre 1985, pp. 25-30.

Sagitov M. U. Influence of Non-uniformity of Rooms' Gravity Field on the results of Gravitational Experiments. "Izvestiya AN SSSR, Fizika Zemli", 1984, No. 4, pp. 46-59 (in Russian).

Sagitov M. U., Kopayev A. V., Kharitonov S. V. Spatial Reductions When Measuring Absolute Gravity Values. In the book: Repeated Gravimetric Observations, Moscow, MGK Publishers, 1986, pp. 19--30 (in Russian).

Shteyman M. B. Improvement of the Procedure of the Regime Gravimetric Observations. In the book: Repeated Gravimetric Observations (Coll. Sci. Works), Moscow, "Neftegeofizika" Publishing House, 1983, pp. 92-97 (in Russian).

Shteyman M. B. Leontyev I. A., Strokin Yu. A. Determination of Vertical Gravity Gradients When Conducting Gravimetric Measurements at the Alma-Ata Prognostic Testing Ground. In the book: Repeated Gravimetric Observations (Coll. Sci. Works), Moscow, MGK Publishers, 1986, pp. 79-82 (in Russian).

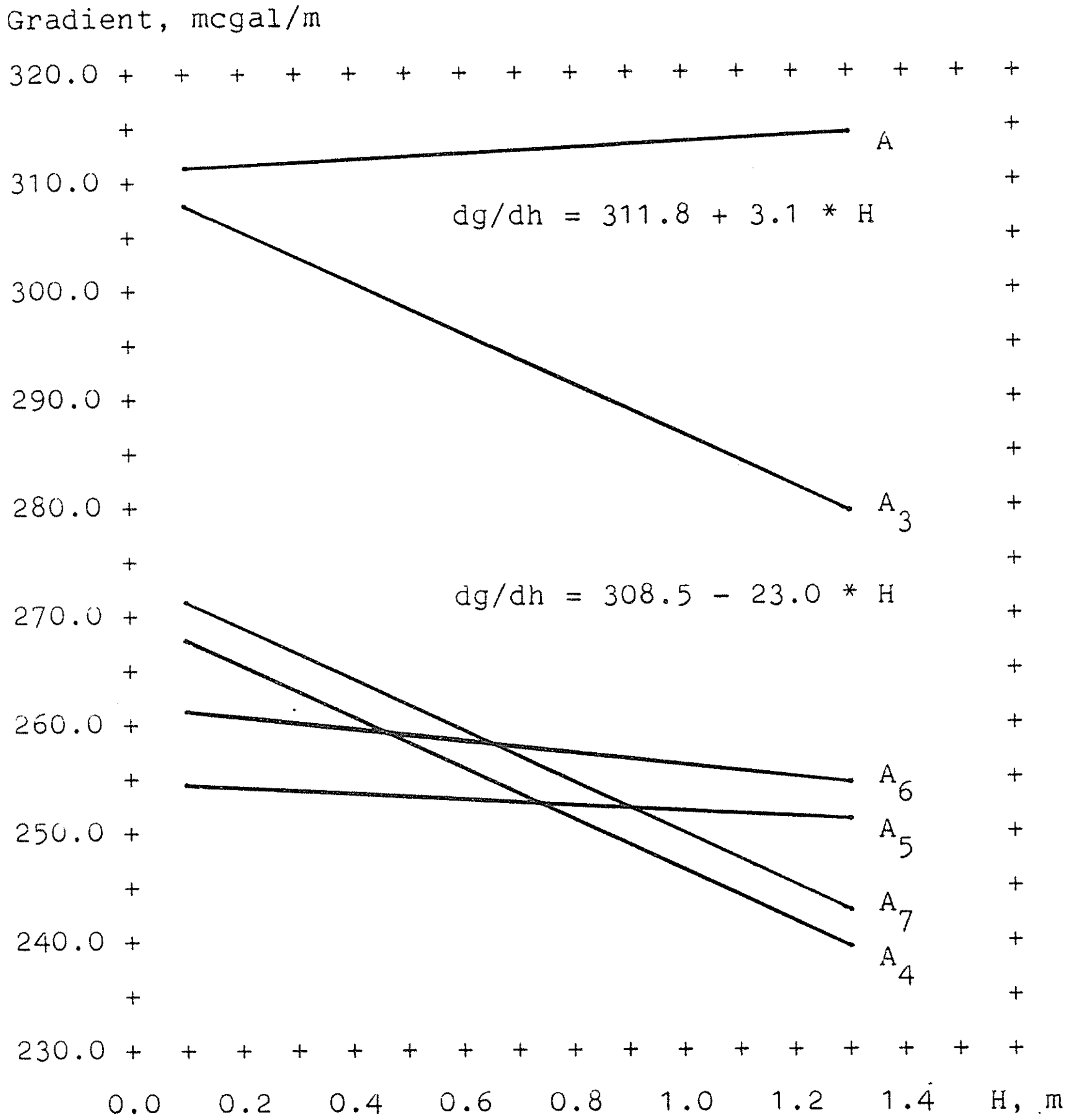


Fig. 1: Graphs of the dependence of vertical gravity gradients on height above the points in Sevres

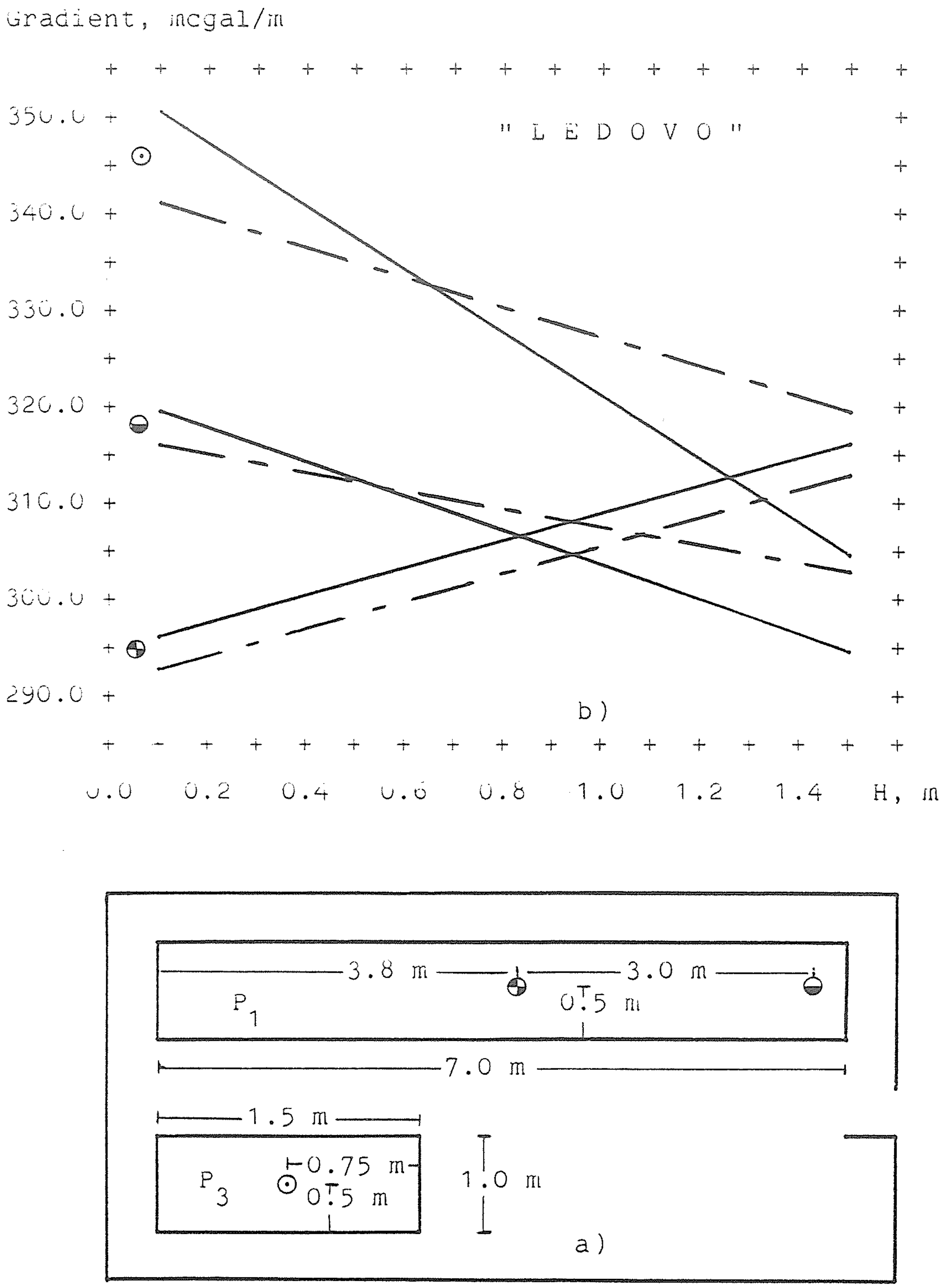


Fig. 2: a) - Abris of the "Ledovo" gravimetric laboratory's room

b) - Graphs of gradients' dependence on height Solid lines are "day" gradients and dashed-dotted lines are "night" gradients

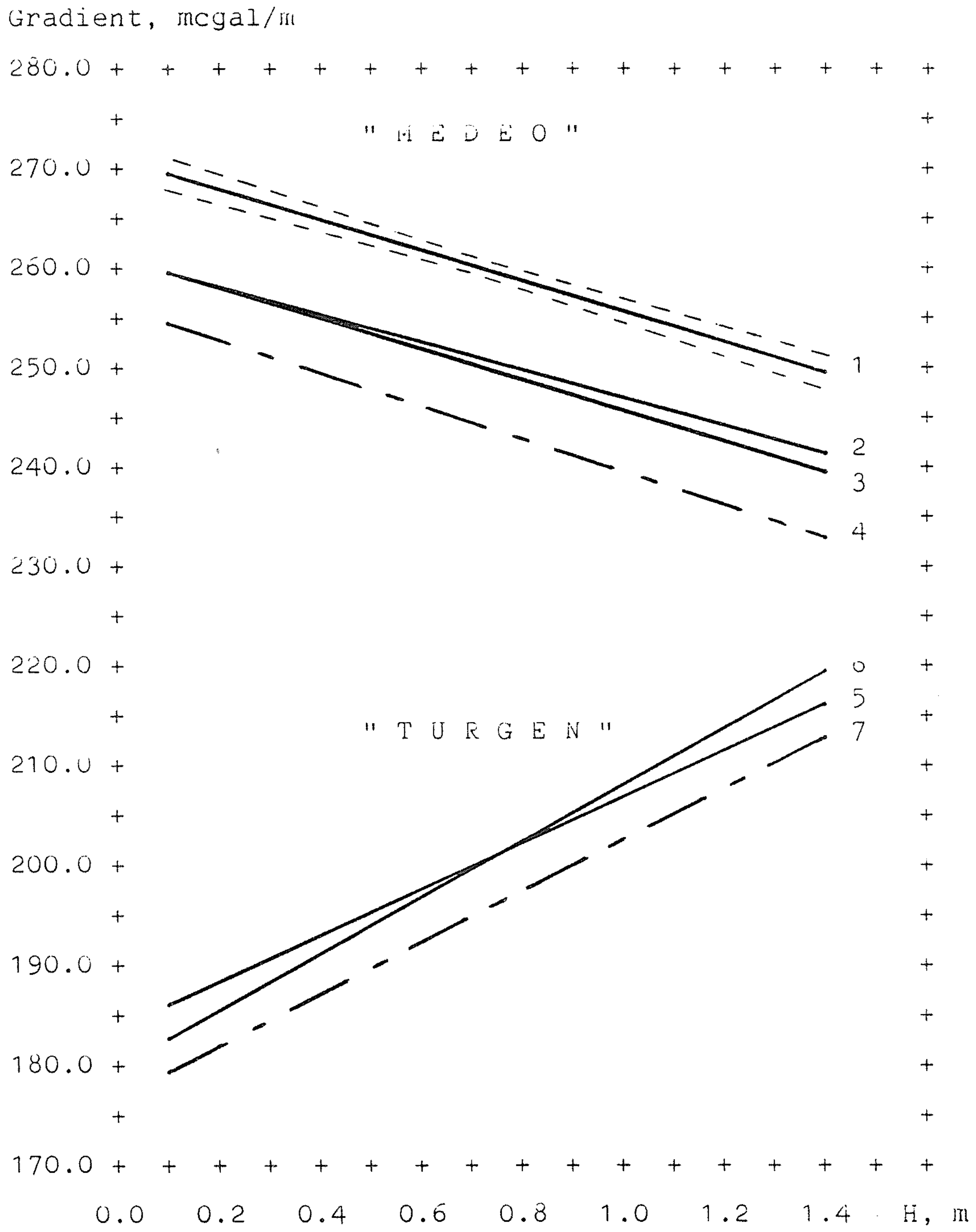


Fig. 3: Graphs of gradients' dependence on height above postaments at the "Medeo" and "Turgen" laboratories

Solid lines are "day" gradients, dashed-dotted lines are "night" gradients and dotted lines are the confidence intervals (for graph 1 only)

The AFGL Absolute Gravity System's Error Budget Revisited

R.L. ILIFF and R.W. SANDS

1. INTRODUCTION

The Air Force Geophysics Laboratory (AFGL) has been involved in research for the development and improvement of a transportable system to measure absolute gravity for several years. Several absolute gravity stations have been established in the United States and cooperative gravity projects have been pursued, both nationally and internationally. A description of the system and its operational and data reduction techniques has been described earlier.[1] Following the October 1980 absolute gravity measurements for the calibration line, Great Falls, Mont., Sheridan, Wyo., Boulder, Colo., Trinidad, Colo., and McDonald Observatory, Tex., the AFGL absolute gravity measuring system acquired an apparent bias in the measurements at the AFGL site. Although equipment problems precluded immediate verification of a systematic shift in the measured value, efforts were finally made to locate and rectify errors that could influence the data.

Plausible causes of a shift in the measurements are:

(1) Laser wavelength change (length standard)

(2) Time standard change

(3) Verticality shift

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

Plausible causes of a shift in the measurements (Contd)

(4) Shift of the optical center with respect to the center-of-mass of the dropped object

(5) Real gravity change

(6) Equipment change

(7) Pressure gauge error

A detailed analysis of the cause and effect of errors that could be introduced by the first four error sources can be found in References 1 through 3.

2. LASER WAVELENGTH

The standard of length is based on the wavelength of light from the Spectra Physics Model 119 stabilized He-Ne laser. A change in the wavelength of the laser of nearly a part in 10^7 would be required to cause a change of 80 μgal in the measurement of g. The normal drift rate of this laser has been measured[1] to be about one part in 10^8 per year (a correction is made for laser wavelength drift). The Spectra Physics specification[4] for long-term stability is 1 MHz/day with servo control to lock the laser to the Lamb dip and 75 MHz/day without servo locking. The data taken both with and without locking the laser showed no significant difference in the resultant measured value of gravity. No unexpected change had occurred in the laser wavelength at the time it was checked and the standard of length was therefore dismissed as a cause of error.

3. TIME STANDARD

The system timing is derived from a Tracor Model 304A Rubidium frequency standard which is locked to an atomic transition yielding a frequency accuracy of one part in 10^{11} and a drift rate of less than three parts in 10^{11} per month.[5] A change of about five parts in 10^9 would be required to cause an 80 μgal shift in our measurements. One of the equipment problems encountered after the October 1980 field trip was the inability to lock the frequency standard to the atomic transition. Therefore, the frequency standard was considered a candidate for causing an error. Upon acquisition of a newer Tracor Model 308A Rb standard, the old

---

2. Hammond, J.A. (1970) A Laser-Interferometer System for the Absolute Determination of the Acceleration of Gravity, Joint Institute for Laboratory Astrophysics (JILA) Report No. 103.

3. Zumberge, M.A. (1981) A Portable Apparatus for Absolute Measurement of the Earth's Gravity, Ph.D. Thesis, University of Colorado.

4. Spectra Physics Model 119 Gas Laser Operation and Maintenance Manual.

5. Tracor Operation and Service Manual (for theory of operation of the Rubidium Frequency Standard).

standard was checked out and found to be accurate to better than three parts in 10^{11} even when not locked, so it is concluded that this could not have been a large enough source of error to be concerned about.

4. VERTICALITY

If the laser light path is not vertical, that is, not coincident with the direction of free-fall, the measured value of g will be greater than when it is vertical. A departure from verticality was therefore considered a possible contributor to the apparent bias. The method used to align the light path, as described elsewhere,[1] uses the reflection from a mercury pool as a self-leveling horizontal surface. The light is reflected back through a 5-micron pinhole at the focal point of the collimator. Since the returning light can be very well centered in the pinhole aperture, the error introduced is negligible. However, a verticality error of such magnitude to produce an 80 μgal shift could possibly be introduced by the meniscus at the mercury-container interface, but care has always been taken to center the light beam on the mercury pool; further we were unable to align the system at all when attempts were made to use the edge of the mercury pool. Non-verticality then is not considered a source of the problem.

5. SHIFTING OF CENTER-OF-MASS AND OPTICAL CENTER

Unlike non-verticality, a bias introduced by rotation of the dropped object when the optical center and the center-of-mass are not coincident can be either positive or negative depending on the direction of non-coincidence. The drop-to-drop scatter would also be expected to be high since the release in a mechanical system such as this is not uniform. No evidence of a shift of sufficient magnitude to cause an 80 μgal change was found, thus ruling this out as the source of bias. The procedure for aligning and checking the locations of the optical center and center-of-mass is explained in Reference 1.

6. REAL GRAVITY CHANGE

A real change in gravity at a particular site could be caused by a change in the water table or tectonic shift; neither has been detected to the extent that would be required to cause a shift of 80 μgal. Note that there is a 28 μgal difference in gravity between two piers at the Hanscom absolute gravity site. The Geodetic Survey Squardron (DMAHTC-Frances E. Warren AFB, Wyo.) also observed this difference using relative gravity meters. The centers of these two piers are separated by only 2 m. This anomaly remains unchanged. Although a short-lived gravity change may have existed early in 1981, it is highly unlikely and is dismissed as a cause of the gravity discrepancy.

7. EQUIPMENT CHANGES

Errors, both random and bias, can be introduced when electronic equipment is changed since each can have its own peculiarities in such areas as rise time, phase shift, time delay, threshold, etc., while still meeting published specifications (this also applies to models with identical specifications). These differences can be important when the equipment is being pushed to the accuracy limits as is in these measurements.

A routine was devised* to investigate error sources exclusive of the mechanical portion of the equipment. The exclusion of this section allows checks to be made without concern for random or bias errors introduced by seismic noise, shock of the mechanical release of the dropped reflector (the moving arm in the Michelson interferometer), air drag, gravity gradient, earth tides, correction for the wavelength of light, and the correction for the finite velocity of light. These tests also eliminated concern for any phase shift that might be introduced by the photomultiplier.

The absolute gravity measuring system is shown in block form in Figure 1. The signal that is generated in the mechanical portion and converted to an electrical signal by the photomultiplier (shown inside the dashed lines in Figure 1) is replaced by a Hewlett Packard Model 3325A sweep frequency generator (synthesizer). The synthesizer can be programmed to generate a sweep frequency from 0 up to 20 MHz, which is used to simulate the signal generated by the dropped reflector in the Michelson interferometer. The initial portion of this accelerating sine wave is shown in Figure 2. The advantage of using the synthesized signal is its reproducibility. Real data have scatter and therefore the system requires literally hundreds of drops to arrive at a statistically significant value, while synthesized data allow the equivalent of a few drops to observe a difference in the resultant data. A change (in signal threshold for example) can be made and the effect can be immediately observed.

*This routine was jointly devised with The Joint Institute for Laboratory Astrophysics (JILA) of the University of Colorado.

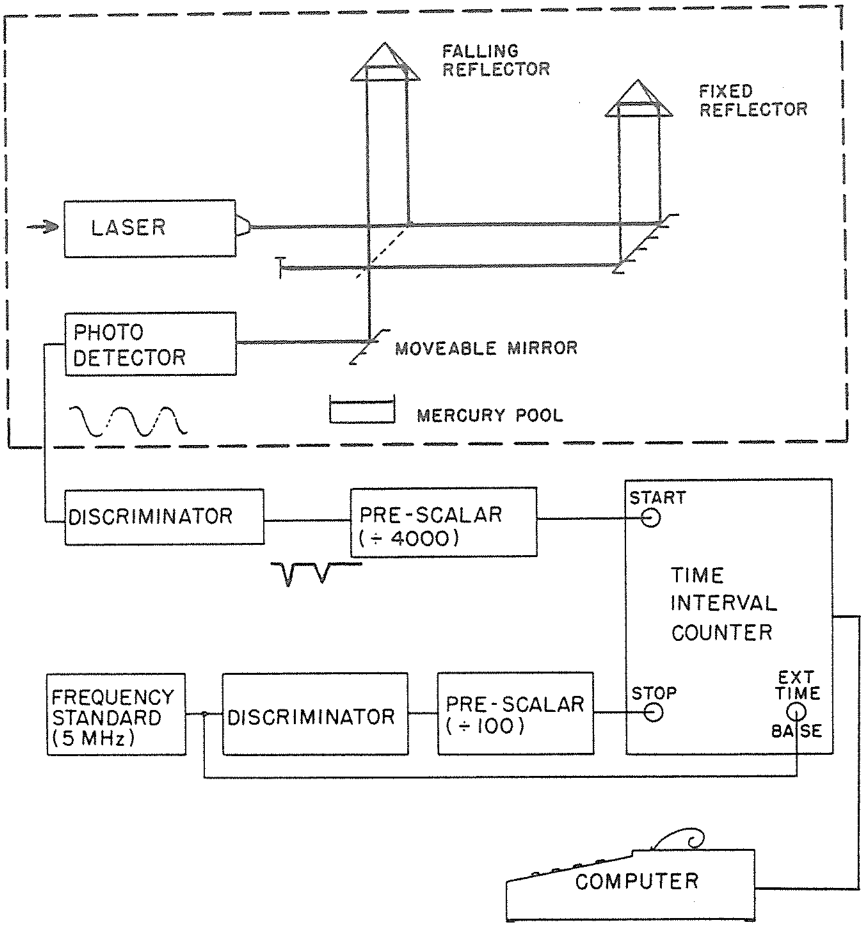


Figure 1. Block Diagram of AFGL Absolute Gravity Measuring System

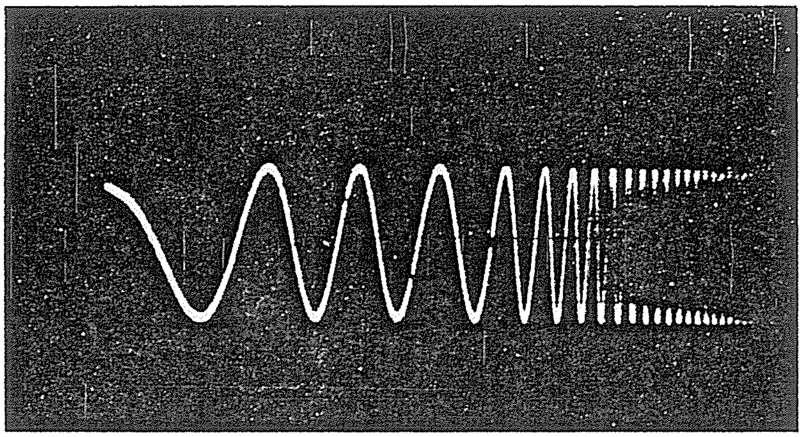


Figure 2. Accelerating Interferometer Fringe Signal

The final frequency (ν) after a specified time (t) is determined by the relationship

$$\frac{\lambda\nu}{2} = v = gt \quad , \tag{1}$$

where

λ = wavelength of the laser light,

ν = final frequency (that is, 0 Hz to ν),

v = velocity of falling object at time t (with no forces other than g acting on the dropped object and zero initial velocity), and

g = acceleration of gravity.

The factor of 2 accounts for two fringe counts per wavelength. For our system we have taken

$\lambda = 6.329914700 \times 10^{-5}$ cm, and

t = 0.4 sec, exactly

and, using $g = 980 \text{ cm sec}^{-2}$, the final frequency is

ν = 12.385632938 MHz .

The signal first goes into the EG&G Model T140/N zero crossing discriminator (Figure 1). The zero crossing discriminator is used to eliminate the problem of skewing, which occurs with amplitude threshold discrimination when the frequency is not constant. Skewing would be severe in this application since the frequency sweeps from 0 to over 12 MHz.

The first test with the synthesized signal was at the input to the zero crossing discriminator using ac and dc coupling. The results of this test showed a difference of 19 μgal, depending on the coupling. The measured value of g was 19 μgal higher with ac coupling than with dc coupling. Data taken with equipment used previously did not show this difference. ac coupling has been used because the dc output level of the photomultiplier is dependent on the ambient light, and the fluctuating dc level made it difficult to observe the signal on an oscilloscope. Since ac coupling was always used this coupling discrepancy had no influence on the higher measured g value.

Next, using the synthesizer, the time (t) and the corresponding frequency (ν) [Eq. (1)] were changed such that the swept frequency corresponded to the correct frequency for g = 980 cm sec^{-2} after falling 0.4 sec in vacuum. The frequency was changed from ν = 12.385632938 MHz for t = 0.4 sec to ν = 18.578449404 MHz corresponding to t = 0.6 sec. The measured value of g remained constant, verifying that the synthesized signal was repeating the frequency from 0 to 12 MHz regardless of the final programmed frequency.

The output amplitude from the synthesizer was varied from just above the discriminator threshold of 0.4 V peak-to-peak to five times threshold, 2 V peak-to-peak with no change in the resultant calculation of g.

Next the signal is divided by 4000 by the prescalers, the division of which was checked and verified to be accurate using the constant frequency from the rubidium frequency standard.

Next the signal goes into the HP Model 5370A time interval counter. Using the synthesized signal as input, the trigger levels of the start and stop inputs were varied from 0.00 to -0.70 V with no variation in the resulting value (the outputs from the zero crossing discriminator and the divide by 4000 scalers are negative going and therefore the counter trigger is negative). This was not the case with similar equipment at JILA. JILA not only observed variations with threshold settings but found differences when different time interval counters were substituted, even though all six counters were the same HP Model 5370B's.

Another test that was made to check the overall performance of the electronic and computational portion of the system was to vary the value of g with the simulated signal. The value of g, and the corresponding frequency [Eq. (1)], was varied from 960 cm sec^{-2} to 1000 cm sec^{-2} with the resulting computation of g changing as it should (± 1 μgal).

The linearity of the frequency sweep of the HP Model 3325A used in these experiments was checked and found to be adequate for our purpose. The calculated value of g was not exact as predicted from Eq. (1), but this was of no consequence since we were looking for changes in g as we varied different electronic conditions. The value of g is calculated using 440 data points during the 55 cm free-fall of the dropped reflector and is therefore an average value. Figure 3 is a plot of the residuals as a function of distance the object has fallen. If the sweep frequency was linear the residuals would follow a straight line centered around zero. The calculation of g was also measured by using 100 data points starting at data point 99, 100 starting at 199, etc. for the full drop. This exercise also showed the nonlinearity of the frequency sweep. Even with this limitation the synthesized signal proved to be a valuable tool for evaluating the electronics.

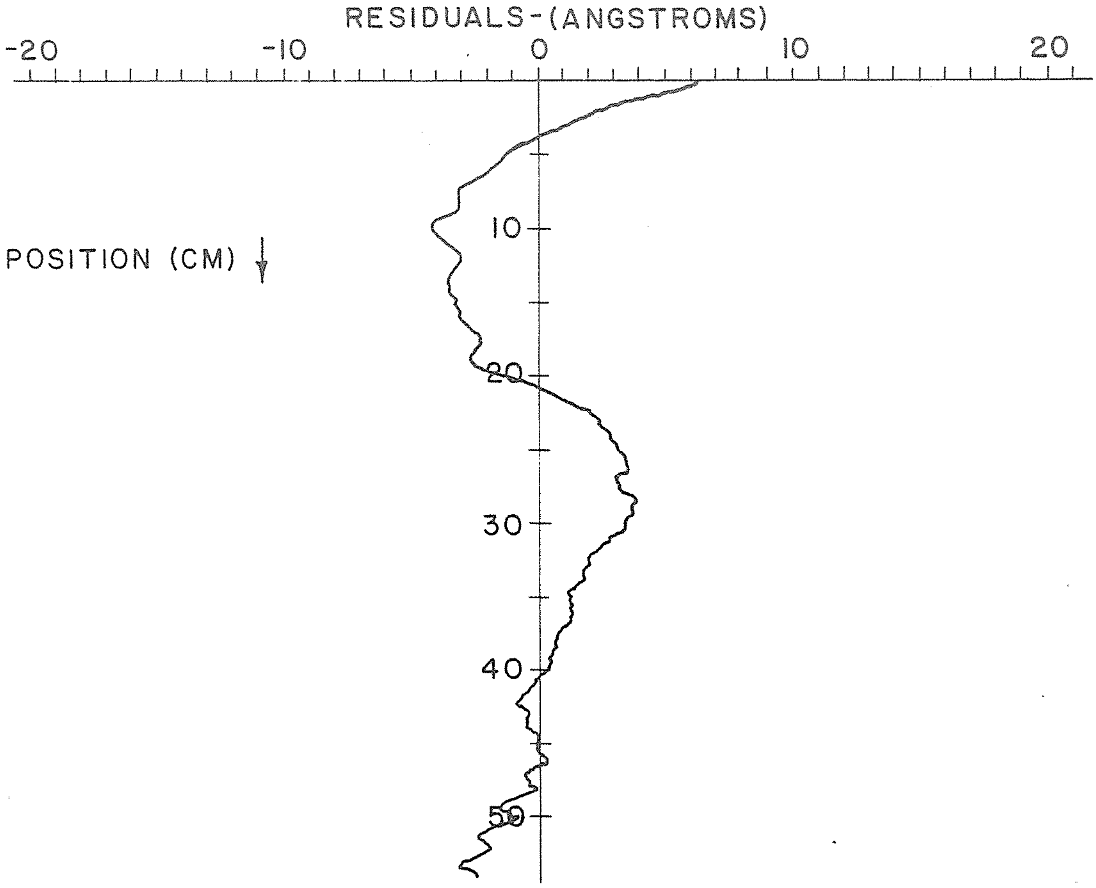


Figure 3. Residuals in Position for Least Squares Fit of Synthesized Signal

Errors can also be induced by equipment not associated with the system. A systematic bias of 68 μgal was observed by the Istituto di Metrologia "G. Colonnetti" (IMGC) during a field trip to the United States. This bias was determined[6] to be caused by a gyroscope that was being tested in another room a few meters away. We investigated this type of interference at the Hanscom AFB Gravity Laboratory and found no evidence that any interference of this nature was present.

8. PRESSURE GAUGE

A Varian Model 845 power supply and controller, and a Model 564 nude ionization gauge tube are used to monitor the vacuum chamber pressure. If the filaments on the vacuum gauge tube become contaminated, an outgassing condition can exist in the area of the tube's sensing grid resulting in a pressure reading that is higher than the actual pressure inside the chamber. Since the correction for air drag vs pressure is logarithmic in the region of our concern,[1] the pressure reading is an increasingly critical measurement as the pressure rises. An 80 μgal error would result due to the pressure correction if the gauge read 7×10^{-6} Torr, while the actual vacuum was 10^{-7} Torr. After the October 1980 field trip the recorded pressure was higher than usual but since a correction was made for this we were not concerned at that time. During the reevaluation this became the prime suspected error source. Installation and check-out of a new gauge tube showed that the old vacuum gauge tube was in error. This resulted in a gravity correction of about 65 ± 10 μgal too high. The resulting error in the corrected value of gravity of 65 μgal led to questioning the validity of the October 1980 field trip results.

During the period in question absolute gravity measurements were made at sites previously occupied by AFGL and other instruments. The stations were: McDonald Observatory, Tex., Trinidad, Colo., Boulder, Colo. (JILA), Sheridan, Wyo., and Great Falls, Mont. The reevaluation of the raw data revealed minor reduction errors of unknown origin, but the final results compared favorably with previous and subsequent data. Also the pressure readings had not shown a high value until returning from the field trip. The data log book showed that the pressure readings during the field observations were in the range of 5×10^{-7} Torr and nearly 6.5×10^{-6} Torr after the trip. From this and the close agreement of previous gravity values we conclude that the October 1980 absolute gravity values are valid. This was not the case for the international gravity comparison made in Sevres, France, at the Bureau International des Poids et Mesures (BIPM) in

---

6. Marson, I., and Alasia, F. (1980) Absolute Gravity Measurements in the United States of America, AFGL-TR-81-0052, AD A099017.

October 1981. Reevaluation of these data revealed an omission in the original data reduction. The original preliminary value for the BIPM site, point A4, was 980926.617 mgal, and the recalculated value is 980926.645 mgal. After applying the correction of 0.065 mgal for the pressure gauge error, the final gravity value for point A4 is 980926.580 mgal.

Table 1 is a listing of the final AFGL gravity values at all the sites where this instrument has made measurements along with the values obtained by the JILA and IMGC instruments.

List of Agencies Referred to in Table 1

Instrument	
AFGL:	Air Force Geophysics Laboratory, Hanscom AFB, Mass.
JILA:	Joint Institute for Laboratory Astrophysics, Univ. of Colo., Boulder, Colo.
IMGC:	Istituto di Metrologia "G. Colonnetti", Torino, Italy

Table 1. Absolute Gravity Values at Various Sites in the U.S. and Sevres, France as Determined by Different Instruments

Instrument	Hanscom AFB, Mass.	g (mgal)
AFGL	1978-1980	980378.685
JILA	May 1982	980378.697
IMGC	Dec 1977	980378.659
	NBS Gaithersburg, Md.	
AFGL	Mar 1980	980103.257
JILA	Apr 1982	980103.259
	McDonald Observatory, Tex.	
AFGL	Oct 1980	978820.074 (978820.087)*
IMGC	Jun 1980	978820.097

*Denotes previous published AFGL gravity values.

Table 1. Absolute Gravity Values at Various Sites in the U.S. and Sevres, France as Determined by Different Instruments (Contd.)

Instrument	Holloman AFB, N. Mex.	g (mgal)
AFGL	Jul 1979	979139.600
	May 1980	979139.600
JILA	Mar 1982	979139.615
IMGC	Jun 1980	979139.584
	Trinidad, Colo.	
AFGL	Jul 1979	979330.370
	Oct 1980	979330.384
		(979330.393)*
	Denver, Colo.	
AFGL	Apr 1979	979598.277
JILA	Dec 1981	979598.322
	Mar 1982	979598.302
IMGC	Oct 1977	979598.268
	Mt. Evans, Colo.	
AFGL	Jul 1979	979256.059
	JILA - Boulder, Colo.	
AFGL	Oct 1980	979608.583
		(979608.601)*
JILA	Dec 1981	979608.568
	Apr 1982	979608.565
IMGC	May 1980	979608.498
	Casper, Wyo.	
AFGL	Jul 1979	979947.244
	Sheridan, Wyo.	
AFGL	Jul 1979	980208.912
	Oct 1980	980208.925
		(980208.964)*
JILA	Apr 1982	980208.952
IMGC	Jun 1980	980209.007
	Great Falls, Mont.	
AFGL	Jul 1979	980497.311
	Oct 1980	980497.325
		(980497.367)*
IMGC	Jun 1980	980497.412

*Denotes previous published AFGL gravity values.

Table 1. Absolute Gravity Values at Various Sites in the U.S. and Sevres, France as Determined by Different Instruments (Contd.)

Instrument	Vandenberg, Calif.	g (mgal)
AFGL	Jun 1980	979628.190
JILA	Mar 1982	979628.137
	Lick Observatory, Calif.	
AFGL	Jun 1980	979635.503
JILA	Mar 1982	979635.503
	Sevres, France	
AFGL	Oct 1981	980926.580
BIPM (A4 transfer)	Oct 1981	980926.577

The A4 transfer gravity value[7] is relative to the gravity value at point A, obtained by Sakuma at the BIPM. These relative measurements were made with three Model D and three Model G La Coste-Romberg gravity meters. These instruments were operated by the following agencies.

Institut fur Angevandte Geodasie (IFAG), Frankfurt FRG
Defense Mapping Agency (DMA), Cheyenne, Wyo.
Institute fur Physikalische Geodasie (IPG), Darmstadt FRG

9. GRAVITY CORRECTION VS PRESSURE

A correction is applied to the measured value of gravity (g_m) due to air drag, which is a function of chamber pressure. As stated earlier, the vacuum gauge tube was found to be defective and gave an incorrect value of chamber pressure reading, which resulted in assigning a correction to g_m that was about 65 μgal too high. Replacement of the gauge tube necessitated a recalibration of the gravity correction vs the new pressure readings. Note that the absolute pressure need not be known since the correction is made based on the pressure reading that must only be a repeatable reading at the same pressures for a given calibration. Further, we have an accepted absolute gravity value at this site and a priori information that the correction will be on the order of 1 μgal at a pressure of 10^{-7} Torr.

7. Becker, M., and Groten, E. (1983) Relative Gravimeter Measurements at the 1981 Absolute Gravimeter Campaign in Paris-Sevres, Bureau Gravimetrique International Bulletin D'Information No. 52.

Although we were not able to achieve a vacuum as high as we would have liked, extrapolation of the correction curve yields a gravity correction of about 1.5 μgal at 10^{-7} Torr, which is consistent with theory and our experience.

The pressure was varied from 7.9×10^{-7} up to 5×10^{-5} Torr. The data are plotted in Figure 4 along with the previous calibration curve. Although it is not immediately obvious, since the curves are nearly parallel, the slopes of the lines are different. The old (dashed) line has a slope of 12 μgal/μTorr, while the new calibration line has a slope of 20 μgal/μTorr. Since our gravity measurements are made with a vacuum in the 10^{-7} Torr range there is very little difference in the corrections from the old and new calibrations.

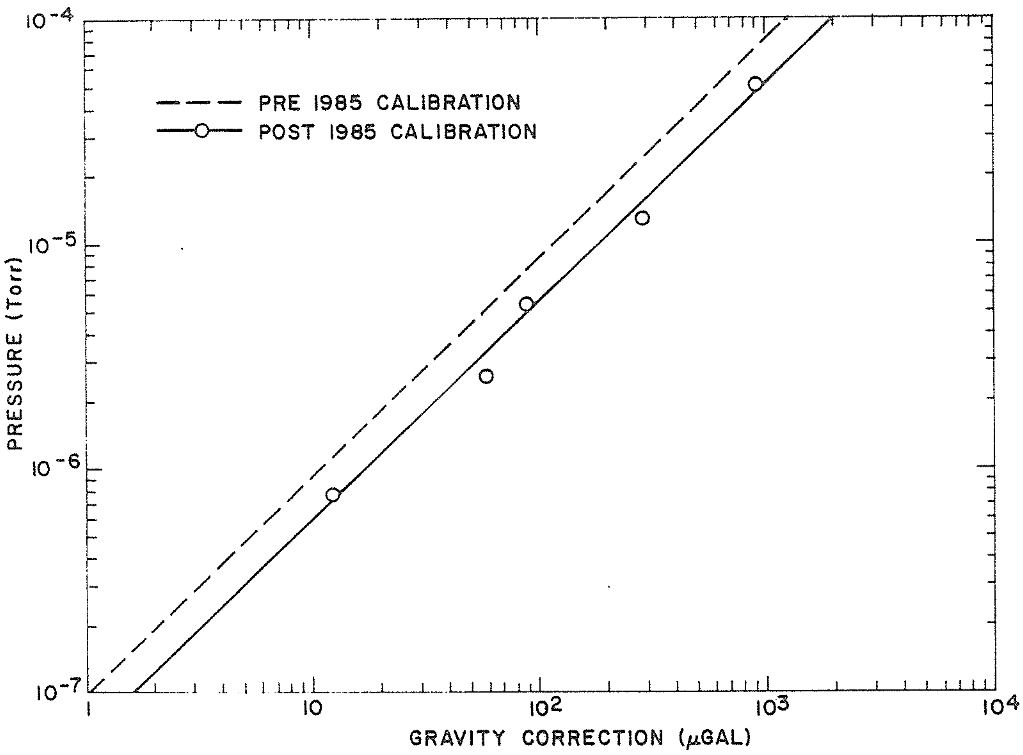


Figure 4. Gravity Correction as a Function of Pressure

The physics of the forces acting on the dropped object is quite complicated, since the predominant forces change with pressure. For this application we are only concerned with the region of free molecular flow, that is, the molecular mean free path is large compared to the dimensions of the confining chamber so that molecules collide much more frequently with the chamber walls and dropped object than with other molecules. Below about 10^{-3} Torr, the interaction of molecules with solid surfaces is the main concern. In this domain a molecule that strikes a surface may undergo an elastic collision with no energy exchange or sustain an inelastic collision whereby the molecule may be permanently absorbed or remain at the surface for a short period of time. The exchange of energy (elastic vs inelastic collisions) is determined by the accommodation coefficient of the material. The dropped object should be made of a material with an accommodation coefficient as small as possible. For more detail on drag forces in the free molecular flow region see, for example, References 8 and 9.

From the foregoing it can be seen that each apparatus requires its own calibration. Here we are concerned with the correction to the measured value of gravity for our system as a function of pressure over the range of interest regardless of the physics behind it.

Each data point on the graph of Figure 4 is the average of 100 or more individual drops. The standard deviations of the data were comparable at all pressures but the residuals as a function of position during the drops deteriorated at higher pressures. The residuals at a pressure of 7.9×10^{-7} Torr (Figure 5) follow the theoretical curve for a freely falling body in a gradient field in a vacuum (smooth curve). Figure 6 shows the deterioration of the residuals at 1.5×10^{-5} Torr. The data plotted in Figure 7 (pressure = 5×10^{-5} Torr) have been reduced by a factor of three (that is, the peak-to-peak amplitude is actually about 50 Å and is completely out of phase with the gradient field).

---

8. Heer, C. V. (1972) Statistical Mechanics, Kinetic Theory, and Stochastic Processes, Academic Press, New York.
9. Kauzmann, W. (1966) Kinetic Theory of Gases, W. A. Benjamin Inc.

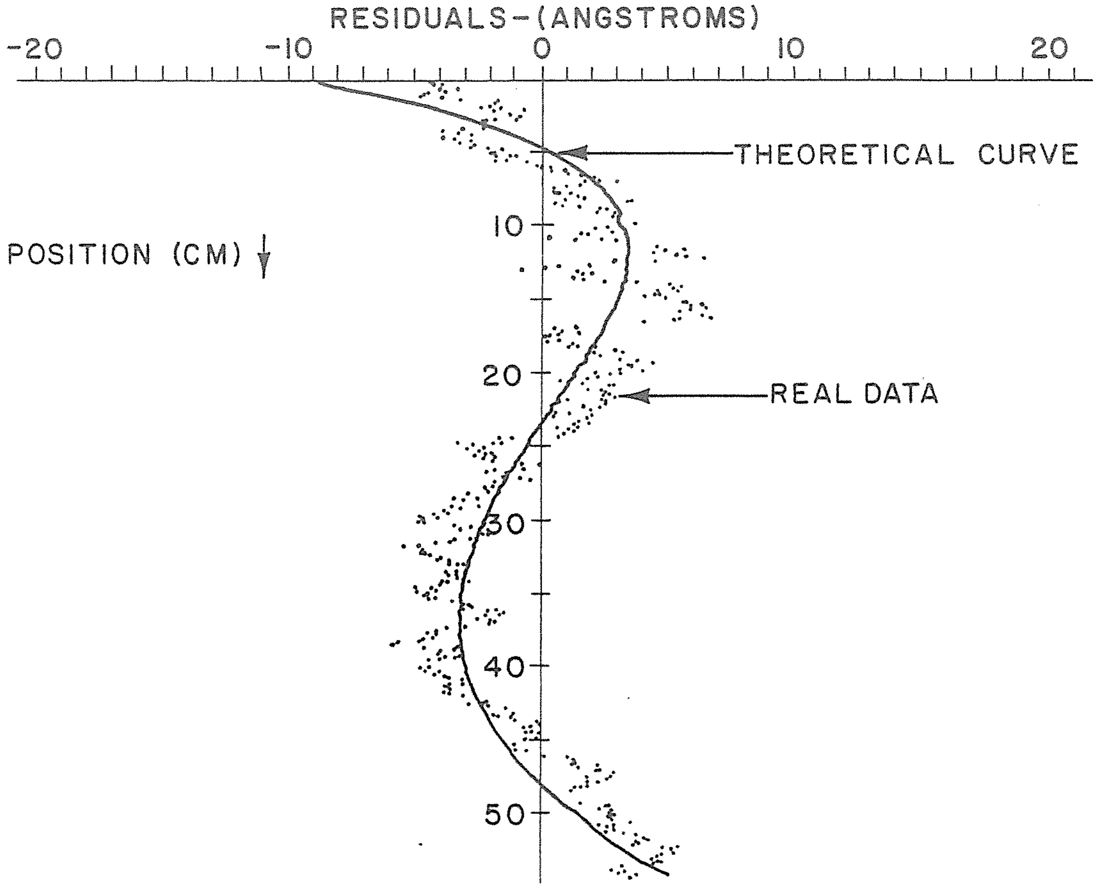


Figure 5. Gravity Residuals (Å) vs Distance After Drop (cm)
Pressure = 7.9×10^{-7} Torr

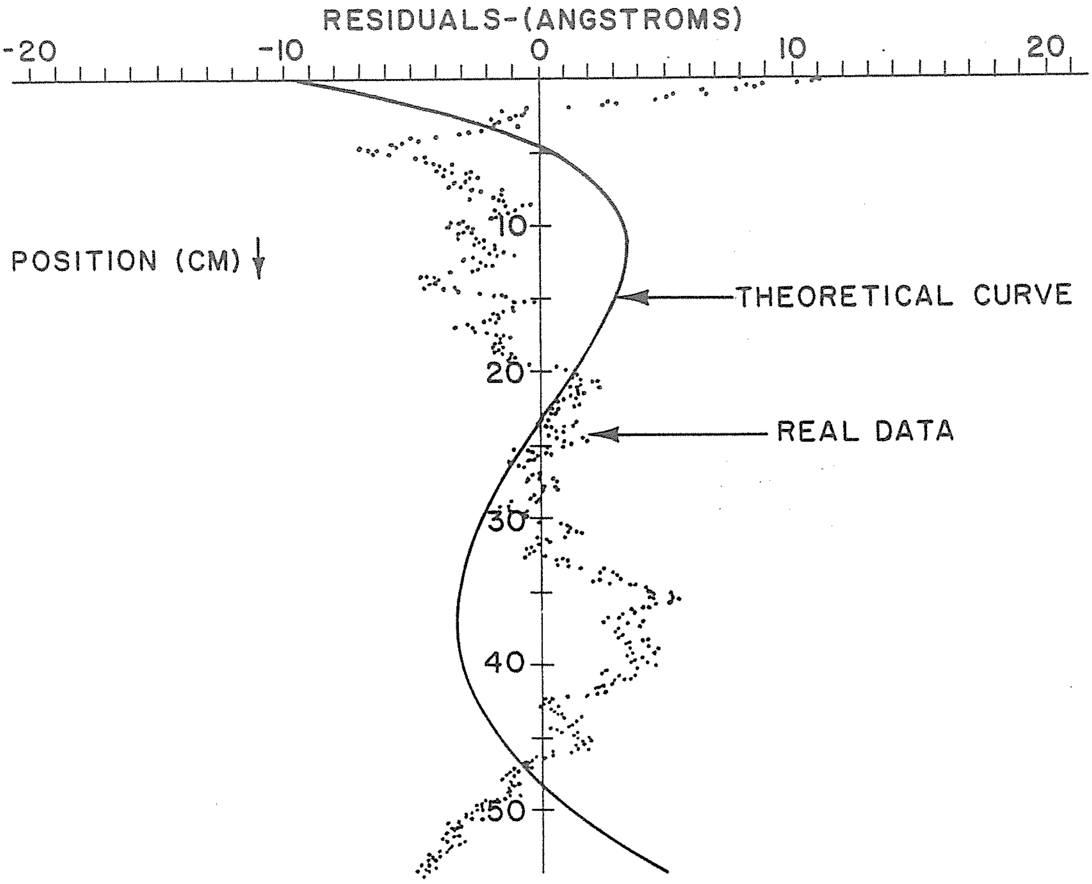


Figure 6. Gravity Residuals (Å) vs Distance After Drop (cm)
Pressure = 1.5×10^{-5} Torr

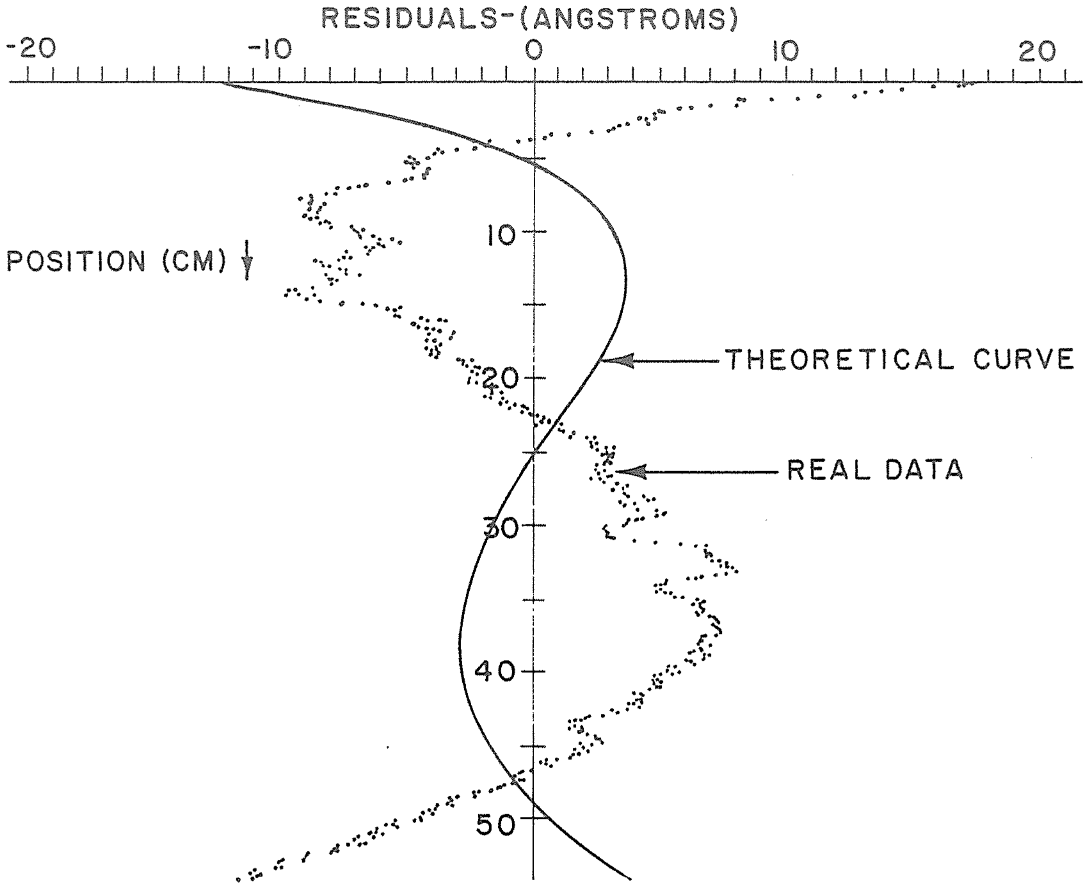


Figure 7. Gravity Residuals (Å) vs Distance After Drop (cm)
Pressure = 5×10^{-5} Torr

10. FINDINGS

The AFGL absolute gravity system has proven to have a sound approach for the measurement of gravity and, as with any system, periodic checks of the various components must be made. For this system six major checks should be performed. First, the laser wavelength should be measured frequently enough to establish the ageing rate so that corrections can be made during extended field trips; second, the time standard can generally be accepted as valid as long as it is in the locked mode; third, verticality should be checked several times a day during the measuring period. This is a simple check and does not disrupt the measurement process; fourth, the displacement between the optical center and the center-of-mass should be checked whenever there is reason to believe it may have shifted such as because of rough handling in shipment or high scatter in the data. This check is made infrequently because it is highly unlikely that there is a shift and an extended period of downtime is required to perform this operation; fifth, a synthesized signal was found to be very helpful and should be available for checking out any electronics and software changes. When electronic components are changed, whether a direct component exchange or an upgrading of the system with a completely new component, errors can be introduced. By using a synthesized signal before and after equipment changes, errors (or differences) can be identified and taken into account. Similarly, the artificial signal can be used to preclude errors that could be caused by software changes. Sixth, since the correction for g as a function of chamber pressure is logarithmic, the system should be operated in a pressure range that requires only a small correction for air drag. This pressure region is dependent on the system's physical configuration and will vary from one system to another. Data should be taken periodically at a higher pressure as a check on the pressure correction calibration.

11. CONCLUSIONS

The cause of the incorrect absolute gravity value obtained at the Hanscom AFB gravity laboratory, Haskell Observatory, during the first few months of 1981 was found to be a faulty component in the vacuum readout portion of the system. This malfunction resulted in assigning a correction to the measured value of g that was 65 ± 10 μgal too high. It was further determined that this component failure occurred at a time such that the absolute gravity calibration line measurements made prior to this failure were not affected, but the pressure gauge error in the original Sevres gravity value has now been taken into account and our final value at this site compares extremely well with the value obtained by Sakuma at the BIPM, Sevres, France.

References

1. Iliff, R.L., and Sands, R.W. (1983) The Absolute Gravity Measuring System A Final Report and Operating/Maintenance Manual, AFGL-TR-83-0297, AD A147853.
2. Hammond, J.A. (1970) A Laser-Interferometer System for the Absolute Determination of the Acceleration of Gravity, Joint Institute for Laboratory Astrophysics (JILA) Report No. 103.
3. Zumberge, M.A. (1981) A Portable Apparatus for Absolute Measurement of the Earth's Gravity, Ph.D. Thesis, University of Colorado.
4. Spectra Physics Model 119 Gas Laser Operation and Maintenance Manual.
5. Tracor Operation and Service Manual (for theory of operation of the Rubidium Frequency Standard).
6. Marson, I., and Alasia, F. (1980) Absolute Gravity Measurements in the United States of America, AFGL-TR-81-0052, AD A099017.
7. Becker, M., and Groten, E. (1983) Relative Gravimeter Measurements at the 1981 Absolute Gravimeter Campaign in Paris-Sevre, Bureau Gravimetrique International Bulletin D'Information No. 52.
8. Heer, C.V. (1972) Statistical Mechanics, Kinetic Theory, and Stochastic Processes, Academic Press, New York.
9. Kauzmann, W. (1966) Kinetic Theory of Gases, W. A. Benjamin Inc.