ASSOCIATION INTERNATIONALE DE GÉODÉSIE

BUREAU GRAVIMETRIQUE INTERNATIONAL

BULLETIN D'INFORMATION

N° 57

Décembre 1985

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31055 TOULOUSE CEDEX
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BUREAU GRAVIMETRIQUE INTERNATIONAL

Toulouse

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Décembre 1985

N° 57

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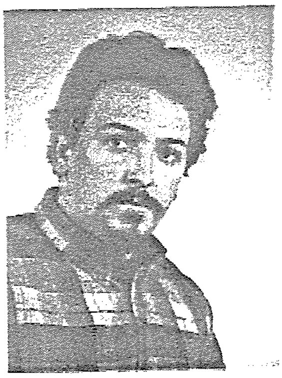
ANNOUNCEMENT



Denis Toustou has been working for us since March 1st, 1985. He was formerly working as a surveyor, and then as a computer programmer for the Institut Géographique National.
He is presently in charge of the digitization of the GEBCO bathymetric maps, and of softwares for the data base management, in place of J.F. Isaac.

Daniel Lamy is working for BGI since the beginning of September. He has been so far with IGN, working several years in Africa, and recently as the Chief of the IGN Commercial Department in Nancy.
He is now working on the computation of a new gravimetric geoid for France.

J.F. Isaac left BGI last spring. He is now working for the EUROSOFT company in Toulouse.

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Bull. d'Inf. n° 57

12TH I.G.C. MEETING SEPT. 22-26, 1986

Place : Bureau Gravimétrique International (B.G.I.)
and
Formation Internationale Aéronautique et Spatiale (F.I.A.S.)

Avenue Edouard Belin, Toulouse, (France)

AGENDA, UPDATED DEC. 1985

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1. **General Time-Table**

Monday Sept. 22

D.B. and W.G. meetings

Tuesday Sept. 23

Morning : Administrative session
Afternoon : Scientific sessions............. 1,2

Wednesday Sept. 24

Scientific sessions (cont.) a.m. 3,4
p.m. 5,6

Thursday Sept. 25

Scientific sessions (cont.) a.m. 7,8
p.m. 9,10*
(10* : special lecture)

Friday Sept. 26

Scientific sessions (cont.) a.m. 11,12
Closing session p.m.

2. Detailed Program

Monday Sept. 22

Directing Board and W.G. meetings (at B.G.I.)

a.m. 9.00 D.B. Briefing
10.00 W.G. 1
11.00 W.G. 2

p.m. 2.00 W.G. 3
(Registration for IGC participants : 2.30 p.m. - 6.00 p.m., at FIAS)
3.00 W.G. 4
5.00 D.B. meeting

- Adjourn 6.00 p.m. -

Tuesday Sept. 23 (at F.I.A.S.)

Registration continues : 9.00 a.m. to 12.00 p.m. and 2.00 p.m. to 5.00 p.m.

a.m. Administrative Session (Chairman : *C. Morelli*)

9.30 Opening : Allocution of President of French National Committee of Geodesy and Geophysics
9.45 IGC President report
10.00 BGI report
10.15 WG 1 report
10.25 WG 2 report
10.35 Coffee Break
10.50 WG 3
11.00 WG 4
11.10 Sub-Commission 1 report : North Pacific Region
11.20 Sub-Commission 2 report : South West Pacific Region
11.30 Sub-Commission 3 report : North America
11.40 Sub-Commission 4 report : Central and South America
11.50 Sub-Commission 5 report : Africa
12.00 Sub-Commission 6 report : Western Europe
12.10 Sub-Commission 7 report : Eastern Europe and USSR
12.20 Sub-Commission 8 report : India and Arab Countries

- End of Administrative Session 12.30 -

p.m. 2.15 to 3.45 Session 1. Dynamic Gravimetry
(Chairman : *J.M. Makris*)
Satellite Results, Airborne and Sea Measurements
SST and Satellite Gradiometry Projects

3.45 to 4.00 Coffee Break

4.00 to 5.30 Session 2. Absolute Comparisons
(Chairman : *G. Balmino*)

Sèvres (BIPM) Calibration Activities in June 1985

Wednesday Sept. 24 (at FIAS)

Registration will continue for late arrivals : 9.00 a.m. to 12.00 p.m. and 2.00 p.m. to 5.00 p.m.

a.m. 9.00 to 10.30 Session 3. Worldwide and Continental Networks
(Chairman : *J. Tanner*)

10.30 to 10.45 Coffee Break

10.45 to 12.15 Session 4. Regional and National Networks
New Nets and Adjustments
(Chairman : *U. Uotila*)

p.m. 2.15 to 3.45 Session 5. Geophysical Interpretations
(Chairman : *H. Kahle*)

3.45 to 4.00 Coffee Break

4.00 to 5.30 Session 6. Geoid Determination & European Geoid
(Chairman : *G. Birardi*)

Thursday Sept. 25 (at FIAS)

Registration will continue as on the other days

a.m. 9.00 to 10.30 Session 7. High Precision Gravity Techniques
New Gravimeter and Instrumentation and Improvements
(SSG. 3.85)
(Chairman : *E. Groten*)

10.30 to 10.45 Coffee Break

10.45 to 12.15 Session 8. Secular Changes of Gravity (SSG. 3.86)
(Chairman : *Y. Boulanger*)

p.m. 2.15 to 3.45 Session 9. International Absolute Gravity Base Network
(SSG. 3.87)
(Chairman : *G. Boedecker*)

3.45 to 4.00 Coffee Break

4.00 to 5.00 Session 10. Special Lecture

5.00 to 5.45 Presentation of Resolutions

Friday Sept. 26 (at FIAS)

a.m. 9.00 to 10.30 Session 11. Local Gravity Field Determination
(SSG. 3.90)
(Chairman : *C.C. Tscherning*)

10.30 to 10.45 Coffee Break

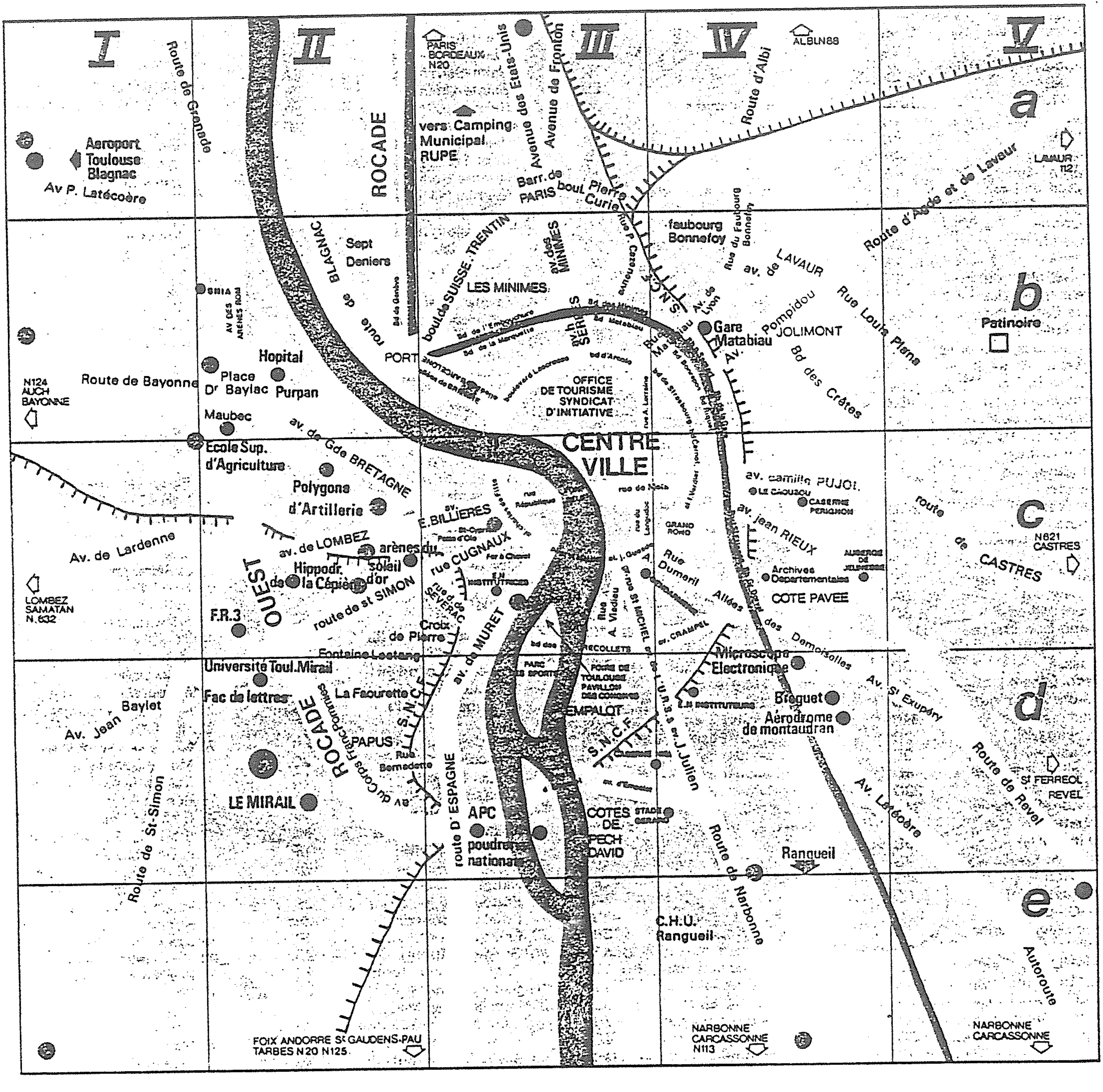
10.45 to 12.15 Session 12. Geodynamics Applications
(Chairman : *C. Boucher*)

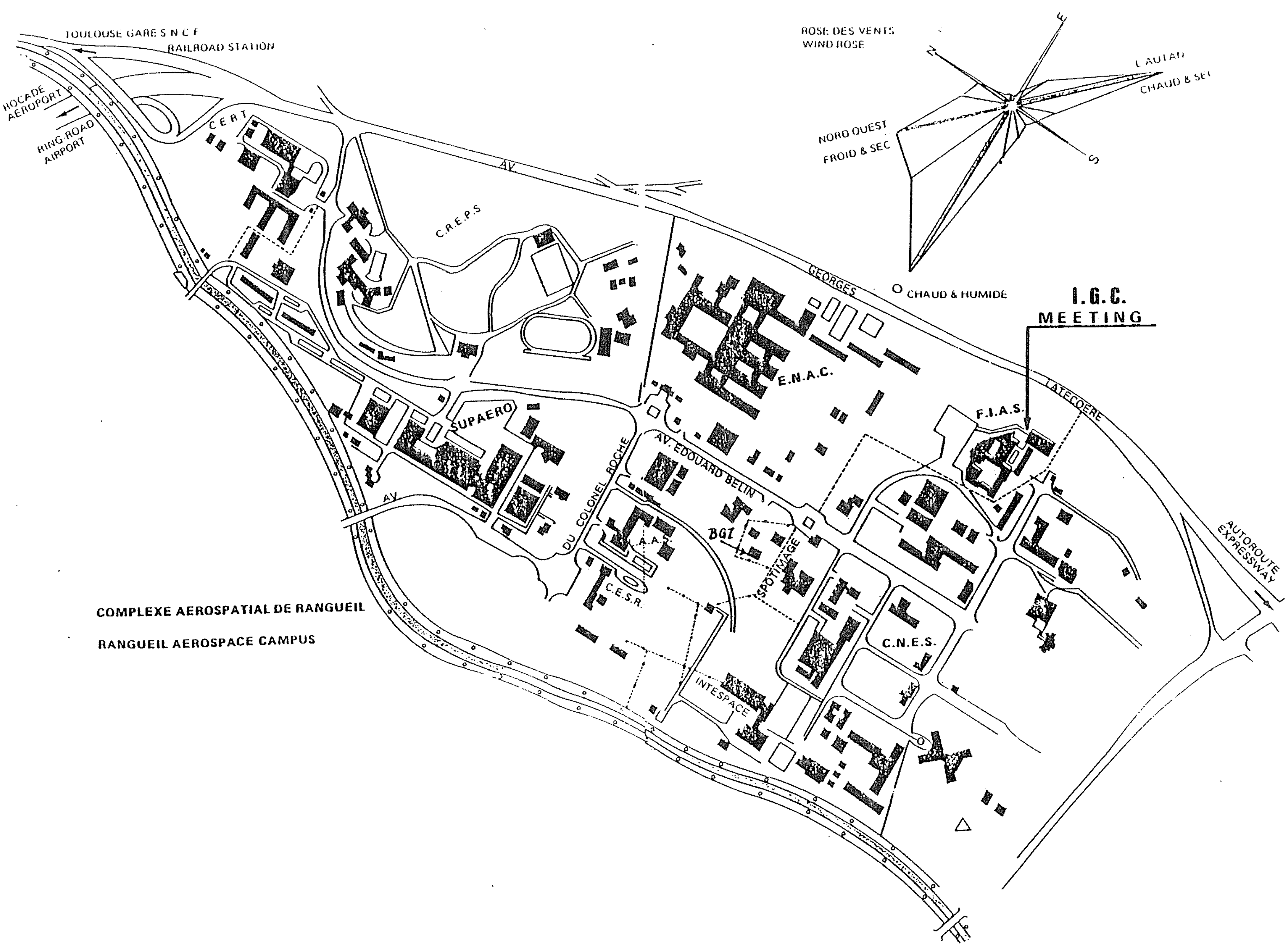
p.m. 2.15 to 3.45 Closing Session
(Chairman : *J. Tanner*)
Proposals and Resolutions
Various Items
Program of the Next Quadriennal

- Closure : 4.00 p.m. -

All persons who wish to attend the meeting should send back at their earliest convenience but no later than May 1, 1986 the attached form with ad'hoc informations.

Toulouse et sa banlieue





COMPLEXE AEROSPATIAL DE RANGUEIL

RANGUEIL AEROSPACE CAMPUS

PART I

INTERNAL MATTERS

FREE AIR GRAVITY ANOMALIES OVER THE OCEANS

FROM SEASAT AND GEOS 3 ALTIMETER DATA[1]

G. Balmino, B. Moynot, M. Sarrailh, N. Valès

Introduction

Satellite altimetry measurements have been extensively used in the last few years to compute local or global grids of values of geoid heights with respect to a given reference ellipsoid (see, for instance, Balmino et al. [1979], Marsh and Martin [1982], Marsh et al. [1982], Marsh et al. [1984]). Such grids have different spacings in latitude and longitude, the typical stepsize being 0°.5 x 0°.5 ; they have been used for a variety of applications (Lazarewicz et al. [1982]) and especially for correlating the high and medium frequency part of the gravity field with bathymetry (see for instance Cazenave et al. [1983]). Equal angular 1° x 1° mean free-air gravity anomalies have also been derived, generally by collocation (Rapp [1979, 1983]), and used in global geopotential models in spherical harmonics (Reigber et al., [1984]). Plane approximation and Fourier transform have also been successfully used to compute gravity anomalies with higher resolution ; the most known work is by Haxby et al. [1983], who further enhanced the small wavelength variations of gravity by using a very fine color image processing technique.

What we present here is the result of the computation of 15' x 15' free air gravity anomalies all over the oceans between latitudes 72° N and 60° S, using the inverse Stokes operator method combined with a high degree and order spherical harmonic model of the gravity field, and based on the most recent global mean sea surface derived from Seasat and Geos 3 (Marsh, [1985]). It is a geodetic type work which should serve a variety of investigators in geophysics.

The Data Processing

The gridded sea surface heights, at 1/4 degree interval, are point values given with respect to the 1980 reference system ellipsoid, of semi-major axis $a = 6378137$ m and flattening $f = 1/298.257$. They contain, superimposed to the geoid highs and lows, dynamic topography information. This is subtracted by using the 2250 dbar surface of the Levitus [1982] model, taken as a grid of 1° x 1° mean values. The values are assigned to the centroid of each bin, and interpolation is performed for correcting each value of the input sea surface grid. The result is $N(\varphi,\lambda)$, the geoid height function, sampled at nodal points separated by 1/4 degree in latitude (φ) and longitude (λ).

For working out the inverse Stokes equation computations, we further need a spherical harmonic reference model, consisting of normalized coefficients $\overline{C}_{lm}$, $\overline{S}_{lm}$ up to a certain degree and order L. As a basis to future usage, we have first taken the spherical harmonic coefficients of the GRIM 3-L1 model (Reigber et al. [ibid]), up to degree and order 36, and determined the coefficients above that limit, and up to L = 180, as follows : (i) by computing 1° x 1° point values of geoid heights all over the world, in integrating (by Stokes

[1] Submitted to EOS, October 1985.

formula) terrestrial and marine mean values of gravity from Rapp [1983b] data set n° 1, and using the GRIM 3-L1 model as a reference, local second degree polynomials were then fitted to compute averaged 1° x 1° values : $\langle N \ (\varphi,\lambda)\rangle$; (ii) by replacing these values over oceanic areas by 1° x 1° mean values $\langle N \ (\varphi,\lambda)\rangle$ derived from the above 15' x 15' grid (merged set is noted $\overline{N} \ (\varphi,\lambda)$) ; (iii) by deriving the searched for harmonics as being the components of $\overline{N} \ (\varphi,\lambda)$ on the base functions $\overline{P}_{lm}$ (sin φ) exp (imλ) - normalized spherical harmonics. In other words we have, in spherical approximation :

$$\overline{C}_{lm} + i\,\overline{S}_{lm} = \frac{1}{4\pi\overline{R}} \iint \overline{N}\ (\varphi,\lambda)\ \overline{P}_{lm}\ (\sin\varphi)\ e^{im\lambda}\ d\sigma \qquad (1)$$

$(36 < l \leqslant 180 \ ; \ 0 \leqslant m \leqslant l \leqslant 180 \ ; \ \overline{R} = 6371 \text{ km})$

These integrals have been computed by using a fast Legendre transform package based on the exact expression of the integral of Legendre functions $\overline{P}_{lm}$ (sin φ) between two latitudes, and on the reordering of the double summation which appears in the discretized form of (1) - which allows to use fast recursive formulae.

The obtain reference model coefficient set will be referred to as GRIM 3-L1-180 in the following. The reason why we adopted the above procedure is twofold : (i) we did not want to make use in the model of the already inverted 1° x 1° gravity anomalies (from Seasat derived geoid heights) as it would have been the case by directly analyzing Rapp [1983b] merged set, for instance ; (ii) we believe the long wavelength part of the GRIM 3-L1 model is quite reliable at the wavelength level of 1000 km (Reigber et al., [ibid], table 8), which is of great importance for the procedure to be described next.

The Derivation of Gravity Anomalies

This is performed by using, in spherical approximation, the inverse Stokes operator (also known as Molodensky integral equation), that is :

$$\Delta g_P = -\frac{\overline{\gamma}}{\overline{R}} \left[N_P + \frac{1}{16\pi} \iint \frac{N_Q - N_P}{\sin^3 \psi/2}\ d\sigma_Q \right] \qquad (2)$$

where P is the point at which we compute the free air gravity anomaly (Δg_P), $\overline{\gamma}$ is the mean Earth gravity, ψ the geocentric distance between P and Q on the unit sphere. Practically, this equation also uses a reference field in spherical harmonics, here GRIM 3-L1-180, from which reference quantities $\Delta\hat{g}$ and N are derived. For our problem, we have first computed : (i) a worldwide grid (at 15' interval) of point and mean values of geoid heights N (the mean values are used in the discretized form of (2), and the point values are necessary for the regularization procedure - see below) ; (ii) a corresponding grid of 15' x 15' values of $\Delta\hat{g}$. A very fast algorithm for point (as well as for mean) values has been implemented for doing this ; it is the dual of the fast Legendre transform mentioned earlier, which also performs a reordering of a spherical harmonic development and then uses a fast recursive equation (no F.F.T. is required as it is in other known algorithms). These reference functionals are used to save a lot of computer time when performing the quadrature, since we have, by limiting it to a maximum distance ψ_0 :

$$\Delta g_P = \Delta\tilde{g}_P - \frac{\bar{\gamma}}{\bar{R}} \left[\delta N_P + \frac{1}{16\pi} \iint \frac{\delta N_Q - \delta N_P}{\sin^3 \psi/2} d\sigma_Q \right] + E_P \qquad (3)$$

with : $\delta N = N - \tilde{N}$, E_P : truncation error at P.

There are two difficulties in this approach : (a) one must estimate as well as possible the truncation error, which is a function of ψ_o and of the reference field used ; (b) the singularity at $\psi = o$ must be regularized. All details may be found in Balmino [1982], we just recall here the main points.

For evaluating E_P, we assume the reference model coefficients have errors $\varepsilon_{lm} = \varepsilon(\bar{C}_{lm}) + i\,\varepsilon(\bar{S}_{lm})$ for $l \leqslant 180$, and that above degree 180 missing coefficients can be modeled for instance by using a power law for the behaviour of the power spectrum coefficients $U_l = \Sigma_m (\bar{C}^2_{lm} + \bar{S}^2_{lm})$. The ε_{lm} were derived by taking the term by term differences between the GRIM 3-L1 and the GEM 10 B (Lerch et al., [1981]) models, that is up to m = l = 36 ; then, and up to 180, we took the differences between GRIM 3-L1-180 and Rapp [1982] set of coefficients ; above 180, we modeled U_l by extrapolating the overall tendency of the previous differences such as $U_l \approx 1.5\ 10^{-10}/l^3$. For $l \leqslant 180$, corresponding error spectrum coefficients are computed as $U_l = \Sigma_m \|\varepsilon_{lm}\|^2$, and finally we compute the geoid height error spectrum terms $\eta_l = \bar{R}^2 U_l$. In our case, we limited it to $l \leqslant 720$ in accordance with the resolution of the grids.

It is then possible to evaluate the r.m.s. error $E = \sqrt{\langle E_P{}^2\rangle}$ over the whole sphere as being :

$$E = \frac{\bar{\gamma}}{8\bar{R}} \left[\sum_l (K_l - K_o)^2 \eta_l \right]^{1/2} \qquad (4)$$

where the K's are truncation coefficients : $K_n = \int_{\psi_o}^{\pi} P_n(\cos\psi)/\sin^3\psi/2\ .\ \sin\psi\, d\psi$ (P_n : Legendre polynomial), all computed by recursive formulae. Table 1 gives E (computed) as a function of ψ_o and for two values (180 and 720 - our case) of the maximum degree l_{max} to which the series in (4) is considered.

Table 1. Troncation error E (in mgal) as a function of ψ_o and l_{max}

l_{max} \ ψ_o (deg.)	1	2	3	4	5	6	7	8	9	10
180	11.3	8.3	6.4	5.1	4.2	3.6	3.1	2.7	2.4	2.2
720	11.8	8.4	6.5	5.2	4.3	3.7	3.2	2.7	2.4	2.2

At the considered resolution, the effect of the unmodeled part of the reference gravity field (beyond l = 180) appears to be rather small, from this table. We chose to limit ourselves to $\psi_o = 5°$, which implies E = 4.3 mgal, in view of the more important error which may come from the input grid itself. This one may be essentially attributed to the errors remaining after the cross-over point adjustment and the smoothing interpolation process which produces the grid values. We performed a simulation in a 10° x 10° area around the equator, with ascending and descending tracks separated by about 50 km (parameter Δ), with measurements taken every 10 km (and corrupted by a random noise of 0.15 m), also with cross-over point residuals ranging from - 1.5 to + 1.5 m (extreme values) but having a r.m.s. of 0.25 m ; by using a $1/\psi^2$ interpolation algorithm (ψ being the distance of a grid point to the measurement points) and up to $\psi = 1°$, we obtained residuals with respect to a simulated true surface with an r.m.s. ε_N of 0.11 m ; this would create, in the r.m.s. sense, errors on gravity anomalies : $\varepsilon_g \approx \varepsilon_N \pi \bar{\gamma}/\Delta$ that is 6.7 mgals, in assuming that the largest part of the error comes from the misadjustment between tracks. The total r.m.s. error of the computed gravity anomalies is therefore 8 mgal.

The regularizing procedure which we use at $\psi = o$ consists of approximating $(\delta N_Q - \delta N_P)/(\sin^3 \psi/2)$ by : $\{x.\partial(\delta N_P)/\partial x + y.\partial(\delta N_P)\partial y + 1/2\ [x^2.\partial^2 (\delta N_P)/\partial x^2 + 2xy.\partial^2 (\delta N_P)/\partial x\ \partial y + y^2.\partial^2 (\delta N_P)/\partial y^2]\}/(\psi/2)^3$, where $x = \psi \cos \alpha$, $y = \psi \sin \alpha$ (ψ, α are the polar distance and azimuth of Q with respect to P). This is done in the vicinity of each grid point, the integral

$$I = \iint (N_Q - N_P) \sin^{-3} \frac{\psi}{2}\, d\sigma \text{ being splitted into}$$

$$I_o = \iint_{\psi \leqslant \bar{\psi}} (\ldots) \qquad \text{and} \qquad \bar{I} = \iint_{\psi > \bar{\psi}} (\ldots).$$

I_o can be analytically computed from the above approximation ; we find $I_o = 4 \pi \bar{\psi}^o [\partial^2 (\delta N_P)/\partial x^2 + \partial^2 (\delta N_P)/\partial y^2]$; the second derivatives are numerically evaluated from the grided point values $N - N = \delta N$. The choice of $\bar{\psi}$ is part of the quadrature algorithm and depends on the grid stepsize ; in the present case, it was close to 0°1.

The Results. Evaluation.

Half a million point values were computed, from which dozens of large and small scale contour maps were produced. The total range of the recovered gravity values is greather than 500 milligals, larger values being of course due to subduction zones and oceanic trenches. That is why, in order to show as many detailed variations as possible even on global maps, we have : (i) subtracted the GRIM 3-L1 gravity field up to degree and order 12 ; (ii) limited the coloured representation to residual values between - 30 and + 40 (Δg's smaller than - 30 mgal are all of the same colour and Δg's larger than + 40 are of another colour). Maps of figure 1 have been processed accordingly. The visual correlation with bathymetry, noticed by several authors since a long time, is striking, but we need external elements of comparison to validate our result. We performed three tests :

(a) we derived 1° x 1° averaged gravity values in order to compare them with Rapp's set [1983] ; the histogram of the differences is shown on figure 2 ; their r.m.s. (6.5 mgal) is a little smaller than our estimated error (8 mgal) although we have noted in Rapp's set abnormal residual patterns, especially in the Pacific ocean, which correlate with the Seasat track geometry, an indication that the cross over point adjustment which was performed was of poor quality in this area.

(b) we computed 30' x 30' mean values from our set, and also 30' x 30' mean values from the 6' x 10' set of anomalies over Northern Europe and the North Atlantic made available by Torge et al. [1984]. The difference histogram is given on figure 3 and shows a rather large dispersion which we were unable to explain.

(c) we compared our gravity anomalies with those measured on ships along some legs of given cruises. As an example, figure 4 shows both sets of values plotted along a leg parallel to the equator at the latitude 0°5 S and which runs across the Ninety-East ridge between East longitudes 87° and 93°. Ship values may be affected by a bias and drift along a cruise coming from instrumental errors and position uncertainties, but we had no precise information about these in the present case. The similarity of the signals is striking, even though we notice some smoothing in our data set, obviously due to the used procedure and the grid stepsize as compared with the sampling data rate we have on the ship (every arcminute sometimes) ; some trend in the difference is seen at the end and may be attributed to the above mentioned error sources. On the whole, the mean difference is 1.5 mgal (not significant) and the r.m.s. difference 11 mgal, that is about one and a half time our computed global r.m.s., which we consider satisfactory.

Conclusion

A new set of 15' x 15' point values of free air gravity anomalies, computed from satellite altimetry derived geoid heights, is available at the Bureau Gravimétrique International. It can be used for a variety of investigations in marine geophysics.

Acknowledgements

Research reported in this paper was supported by the Centre National d'Etudes Spatiales and by the Institut National des Sciences de l'Univers.

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Fig. 1. Map of gravity anomalies with respect to a (12,12) field, limited to values between - 35 and + 35 mgals.

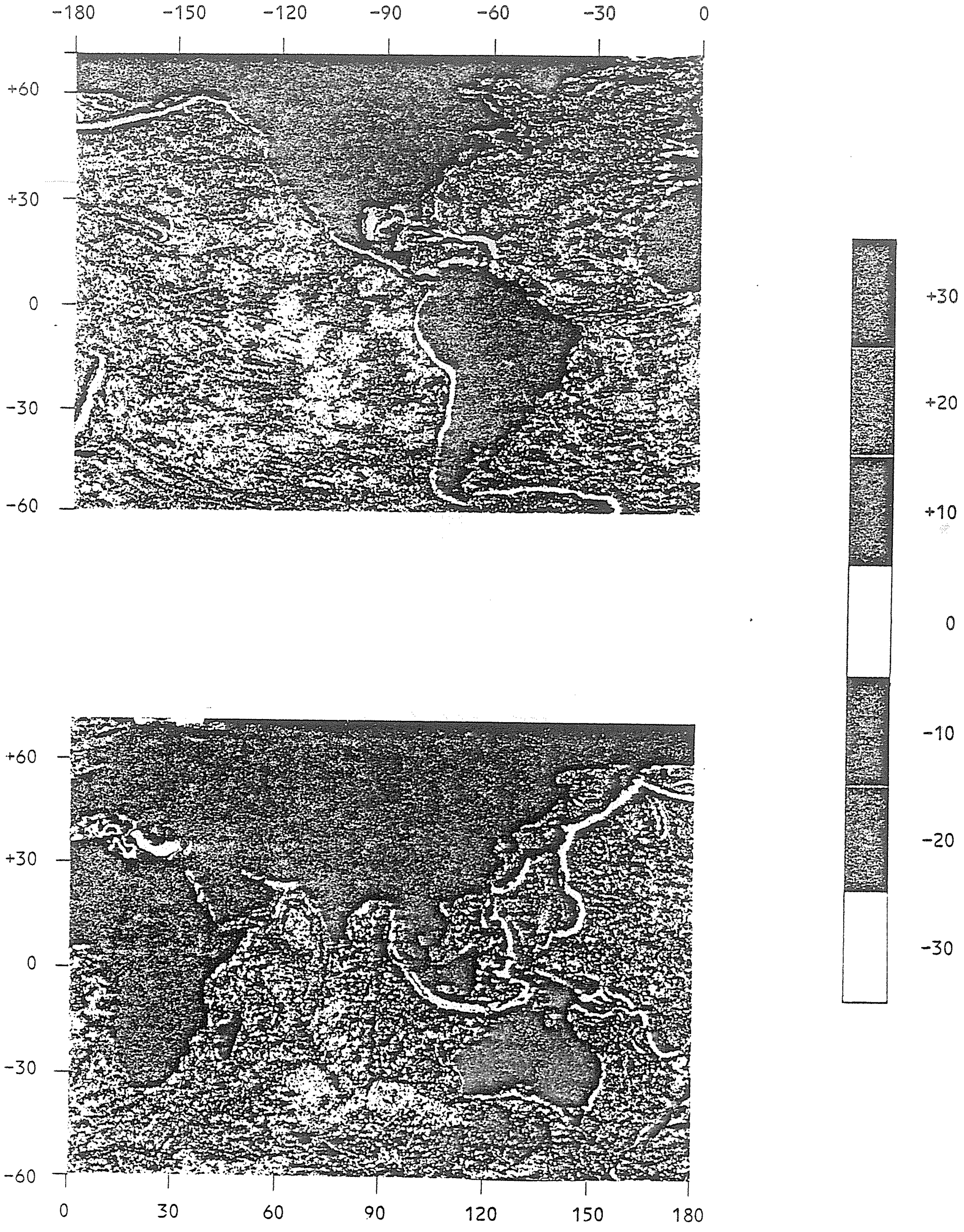


Fig. 2. Histogram of <1° x 1°> differences : this work minus Rapp [1983] (over oceans). 31 091 values. Min. = - 138 ; max. = 109 ; r.m.s. = 6.5 ; mean = 0.3.

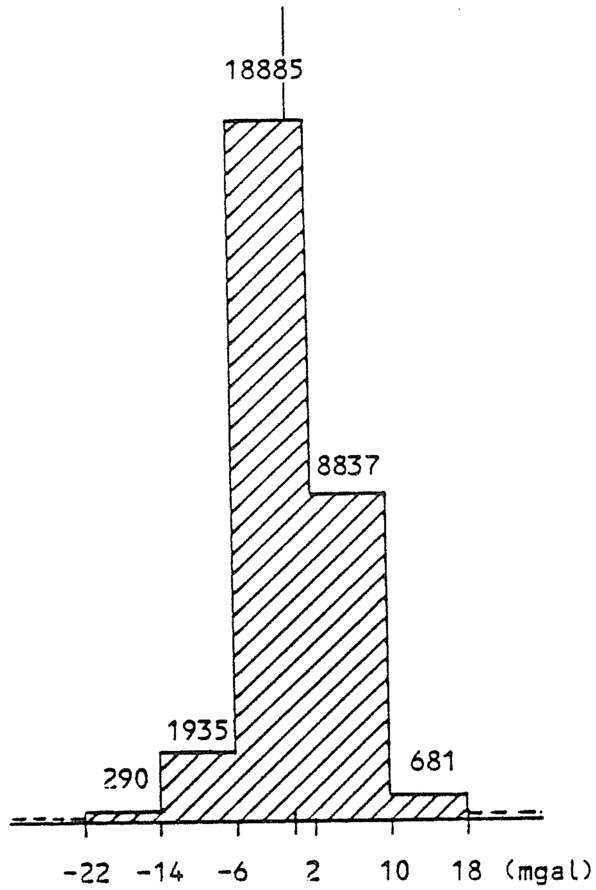


Fig. 3. Histogram of 30' x 30' differences over North Atlantic and North Sea : this work minus Torge et al. [1984]. 4 543 values. Min. = - 110. ; max. = + 150. ; r.m.s. = 19.8 ; mean = 2.2.

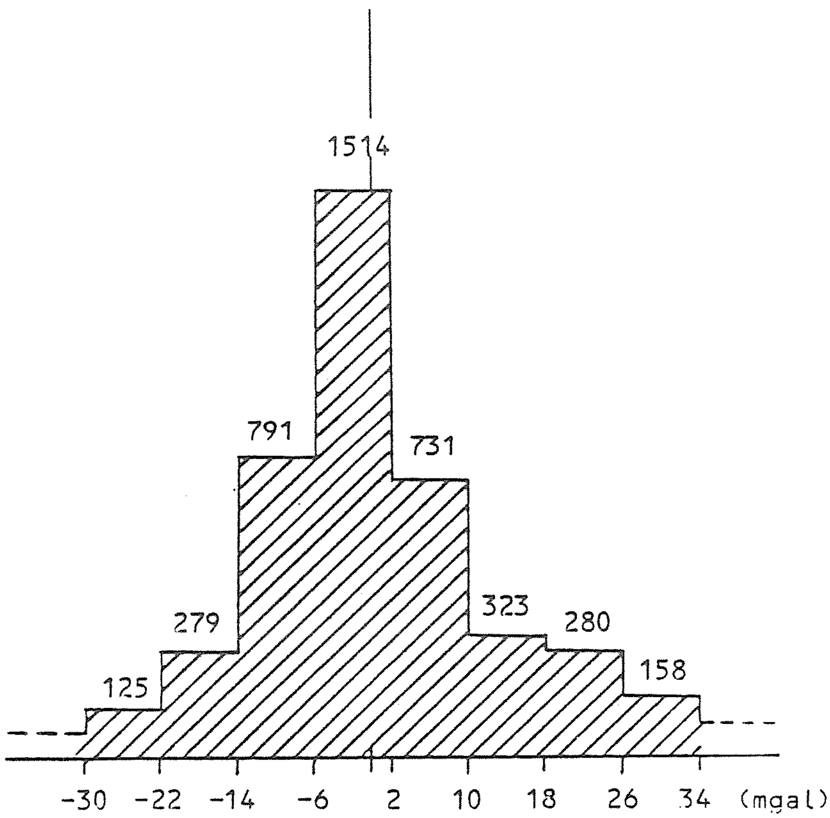
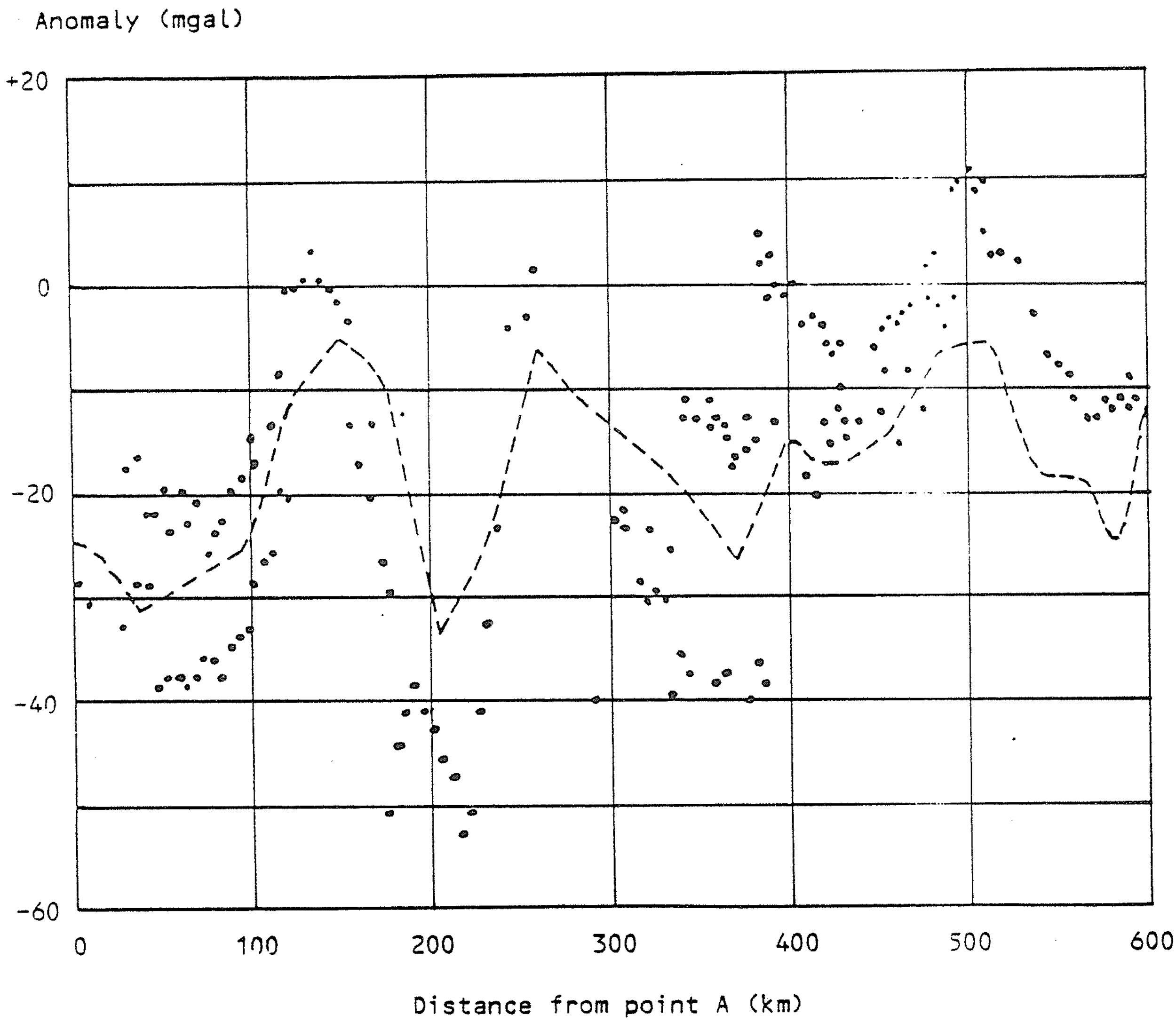


Fig. 4. Comparison of recovered (---) and measured (...) gravity anomalies along a cruise leg AB : A (lat. = 0°.5 S, long. = 87° E), B (lat. = 0°.5 S, long. = 93° E).



PART II

JOINT GRAVIMETRIC WORKSHOP OF S.S.G.´S 3.85, 3.86, 3.87

I. A. G.

JOINT GRAVIMETRIC WORKSHOP OF S.S.G.'S 3.85, 3.86, 3.87

Paris, July 2-3, 1985

Held in Connection with the Absolute Gravimetric Campaign 1985

July 2, 1985

9.00 a.m. Registration

10.00 a.m. Opening Session :

Dr. G. Balmino	(B.G.I.)
Pr. W. Torge	(Pres. Section III)
Pr. Y. Boulanger Pr. E. Groten Dr. G. Boedecker	(Chairman of SSG's)

. Zumberge

10.40 a.m. Coffee Break

11.00 a.m. Absolute Gravimetry - Session 1 (Chairman : W. Torge)
. Sakuma
. Faller
. Boulanger

12.00-12.15 Organisation Meeting for the Relative Gravimetry People

2.00 p.m. Absolute Gravimetry - Session 2 ; and Relative Gravimetry (Chairman : Y. Boulanger)
. Marson
. Gu Yoguang
. Becker et al.
. Wenzel et al.

3.00 p.m. Coffee Break

3.30 p.m. Discussion (led by W. Torge):
- African Gravity Network Project
- Combination of Data of the Absolute Gravity Campaign
- Publication of Results (Relative and Absolute)

5.00 p.m. Adjourn

July 3, 1985

9.00 a.m. Absolute Gravimetry - Session 3 (Chairman : G. Boedecker)

. Biro (distributed paper)
. Hanada et al.
. Gu Yoguang
. Poitevin

10.30 a.m.	Coffee Break
10.50 a.m.	Discussion Closing Session
12.00 a.m.	End of Workshop

LIST OF PARTICIPANTS

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Joint Gravimetric Workshop

IAG Special Study Groups 3.85, 3.86, 3.87

Paris 2.-4.7.1985

Welcome Address of IAG Section III President

It is a great pleasure for me to give a welcome address on behalf of IAG to this Joint Gravimetric Workshop of three Section III Special Study Groups, which is held at the occasion of the second international absolute gravimeter campaign in Sèvres. Section III activities are directed to the determination of the gravity field, and although space techniques nowadays contribute significantly to the solution of this problem, terrestrial gravimetry still plays an important role. On the contrary, new and exciting possibilities are offered for gravimetry. This is due to the high accuracy level of 10 μgal or even more, which has been reached now and which represents an accuracy increase of four orders of magnitude since the days of Richer and Bouguer, and to the availability of transportable absolute gravity meters, which call for a drastic change in gravimetric control network philosophy. Main challenge for gravimetry consequently now comes from the demands of geodynamic research, at global, regional and local scale. As the μgal level has to be strived for this objective, a variety of new problems must be attacked and solved.

I am very happy, that the three technically orientated Special Study Groups of section III meet here, in order to discuss some of the outstanding problems and the potential offered by absolute techniques. The experiences from the current absolute gravimeter comparison, and from the connecting relative measurements, will certainly provide us with new information, and give an impetus for future research in this field. As many highly experienced scientists from different countries all over the world participate at this workshop, I am sure that fruitful discussions will take place here, and that we make another step forward towards a better understanding of high precision gravimetric technique, and its geoscientific application.

I thank Dr. Balmino for the local organization of this meeting, and the Institut de Physique du Globe for providing the workshop facilities. Especially, I appreciate very much the efforts of the workshop convenors Professor Boulanger and Professor Groten, who enriched the gravimeter campaign through this meeting, and of Dr. Boedecker who is going to use the expertise of the specialists assembled here, for discussing the world absolute gravity network.

I wish you full success for this meeting.

Wolfgang Torge

DISSIMILARITY OF THE GRAVITY FIELD ON AND ABOVE POSTAMENTS

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Abstract

Measurements of small gravity differences were carried out by high-precision gravity meters W.Sodin 420 P and 410G (Canada) in Ledovo on two postaments both in the same laboratory 3 meters apart from each other. It was found out that vertical gradients can vary by about 20 per cent. Horizontal gradients can reach 30-35 mkgal/m on the surface of a postament and can be several times less vising above the postament. The great number of errors can occur in the (last) absolute gravity determinations if one doesn't know the distribution of the gravity above the postaments.

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

However, it isn't sufficient to know only normal values of gravity gradients if one deals with solution of the "chamber gravimetry" problems /2/..

Theoretical calculations taking into account sizes and shape of the postament for gravity measurements indicate that the real gravity field essentially differs from the normal one. It is especially important in absolute gravity determinations and in measurements of small gravity differences (1-3 mkgal) done by high - precision relative gravity meters. It's quite possible to solve such problems now /1/.

For the determination of the real gravity distribution on and above postaments in the Ledovo laboratory measurements of horizontal and vertical small gravity differences have been carried out using high-precision quartz astatic gravity meters W.Sodin (models 420 P and 410 G). The estimated error of the mean value of the single difference is + 0.6-1.0 mkgal.

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

Vertical gradients were obtained for the central point of each postament by measuring small gravity differences on several heights up to 100-130 cm with intervals of 20 cm. Its mean value as measured on the postament B is 340 mkgal/m and doesn't depend upon the high in range of m.s.r. error of 1.0 mkgal. On the surface of the postament A the vertical gradient in the center is 285 mkgal/m but increases with height. On high of 100 cm it becomes 307 mkgal /m (with m.s.r. error of 0.6 mkgal).

Thus, the mean vertical gradient value proved to change at about 20 mkgal/m /3,4,5,6/.

The vertical gradients on the postament B were determined in its geometrical centre as well as in 8 points evenly arranged all over the surface of the postament. Equivalent accurate measurements were repeated on 4 levels above the postament each 20 cm higher. Eight ties: 0-1,0-2,.....0.8 - have been measured forty times each on every of five levels. As a result we have constructed the spatial picture of the gravity distribution above the postament B. As figure 1b shows gravity anomality becomes less with height and at the height of 80-100 cm the gravity differences values are only 3-4 mkgal (Fig.2).

The horizontal anomalies on the surface of the postament B are negative compared with the central point and its values are: -12,-15 and even -17 mkgal (Fig.1). Hence the horizontal gradient averages 30-35 mkgal /m.

On the surface of the postament A small gravity differences measurements tied the centre with 15 points were made. As figure 3 shows the distribution of gravity on the postament A substantially differs from this one on the postament B and is far from results of theoretical calculations /2/, though all 15 anomalies are also negative in regard to the centre.

It's absolutely obvious that the distribution of the gravity is influences by not only the shape of the postament but of the room configuration and of the masses arrangement around /5,6/.

The experiments discribed above determined that it is necessary to study carefully the unevenness of the gravity distribution on and above the postament before carring out high accuracy absolute or relative measurements. Disregarding of this factor can influence the accuracy of measurements because of differnt working heights of instruments and of its arrangement on the postament surface /1,3,4,5,6/.

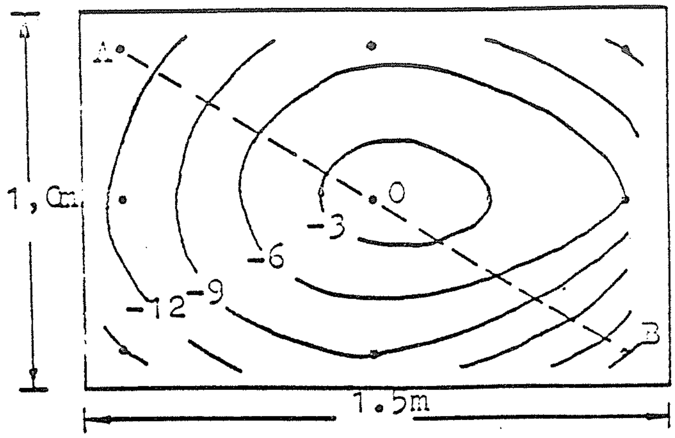

Fig.1

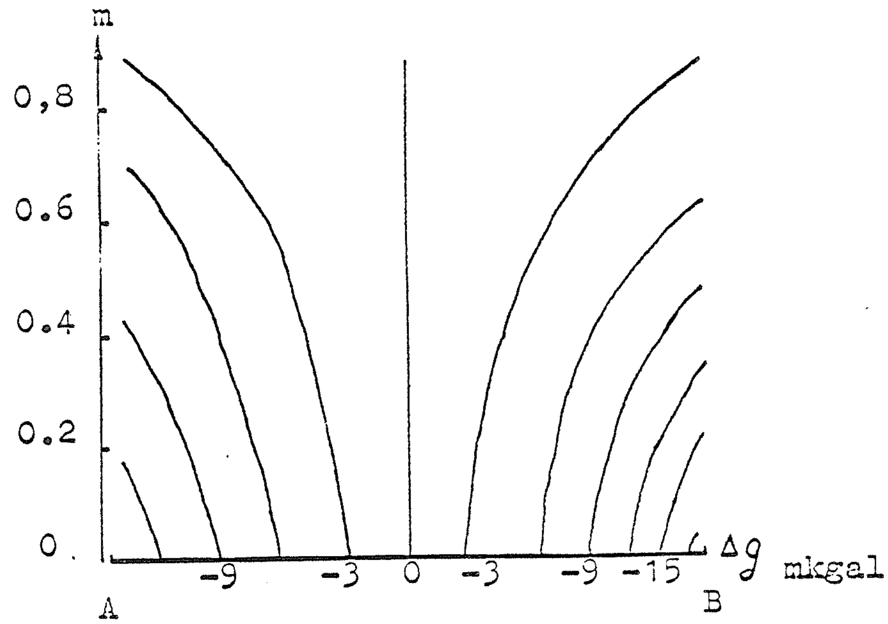

Fig.2

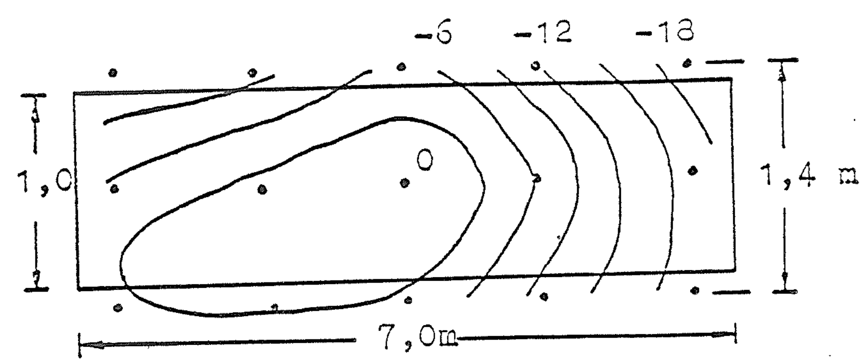

Fig.3

Fig. 1 The distribution of the gravity field on the postament B surface (isoanomals' interval 3 mkgal)

Fig. 2. The distribution of the gravity field in the space above the postament B(section AB; the interval between the lines of the equal Δg values is 3 mkgal)

Fig. 3. The distribution of the gravity field on the postament A surface (isoanomal' interval 3 mkgal)

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High Precision Gravity Measurements Across The North Anatolian Fault Zone

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Abstract

In close cooperation between Turkish and German Institutes a local high precision gravity network was installed across the North Anatolian transform fault in the region of Bolu, Turkey. Repeated observations were conducted with two LaCoste Romberg gravimeters starting 1982. Point gravity values for 10 stations were determined with an accuracy of 1 to 2 microgals in single epochs. Time-dependent changes in gravity from 1982 to 1985 are investigated.

1. Introduction

In the eastern mediterranean region the "North Anatolian Transform fault", NATF, is a major field of tectonic activity. Lateral strike slip movements at a rate of centimeters per year are taking place. In the context of a large number of geological, geophysical and geodetic activities for studying the mechanisms and the consequences of the faulting a local gravity network was established across the central part of the NATF.

The NATF is a right lateral fault zone taking up most of the

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motion between the Eurasian Plate and the Anatolian Scholle. The fault being more than 1000 km long is characterized by a distinctive rift morphology. The seismicity is characterized by bursts of activity. There have been 4 earthquakes with magnitude 7.3-8 since 1939. In the 1944 earthquake 2 m right lateral movements occured. Today's creep measurements in the central region of the fault show rates of about 1-2 cm/year. Paleomagnetic studies (Orbany, 1979) reveal also a considerable rise of the northern block in addition to the lateral movements. The structure of the NATF is of the same type as and often compared to the San Andreas fault in USA. For more information about the NATF see eg. (Yilmaz et al., 1980) and Sengor et al., 1980). Fig. 1.1 shows the situation of the measuring area.

2. Site selection and observation scheme

The fault zone in the area selected is marked by a distinct rift topography with lineated sub-parallel faults and offsets. The local features are showing a variety of small faults NE to SW and NW to SE direction accompagnying the major fault but also vertical, steplike faults on the Southern mountain sides.

The measuring sites are shown in Fig. 2.1. Two points are situated in upper cretaceous clay on the center of the major fault. Point 4 is in the sag area around a pond. Stations 3,7,8,9 are in upper cretaceous crystalline limestones and stations 5 and 6 are in an area of cretaceous flysh. This configuration with its almost profile-line structure was designed to monitor gravity changes associated with faulting activities.

Observations were performed in loops starting from point 3, two consecutive days with 12 to 14 observations were needed to cover the whole network twice. In order to avoid systematic effects the loops were changed from one day to the other. In order to achieve highest accuracy gravity differences were kept small, however due to road conditions and the demand for short distances between stations the maximal gravity difference is about 37 mgal.

3. Results of network adjustments

Observations in all campaigns were made with the same two instruments, namely G258 and D38.
The gravimeter observations of each instrument are adjusted in groups - usually one day - to determine adjusted gravity differences and a drift estimation, see (Becker, 1981) for details. The single groups of one or more instruments are then combined for a network adjustment.

The accuracies in these single groups are varying slightly from day to day according to the conditions during the observations, the average accuracy of a reading is about 3 μgal both for G258 and D38.

In 1982 and 1983 observations were performed in intervals of about 4 weeks. The results are given in Tab. 3.1.

Data	Mean square error		Degrees of freedom	Number of observ.
	of unit weight	of point gravity values		
1982.11	0.98	5.51	15	24
1982.12	1.94	4.43	23	32
1983.0	2.09	3.73	23	32
1983.1	1.48	3.28	7	16
1983.2	1.68	3.79	23	32
1982/83	1.82	1.84	127	136
1984	4.36	1.91	90	99
1985	5.18	1.46	86	95
1984/85	5.56	1.24	185	194
all obs.	4.53	0.97	321	330
1982/83G	1.36	2.59	59	68
1984.G	3.00	2.02	40	49
1985.G	2.21	1.91	41	50
1982/83D	1.80	2.17	59	68
1984.D	3.89	2.32	41	50
1985.D	4.95	1.57	36	45

Tab. 3.1. Results of Network Analysis μgal

The average error for the point gravity values in a free-network adjustment was about 4 μgal.

In 1984 and 1985 two campaigns with 6 observation days each were conducted, see Tab. 3.1. Here the accuracy was about 1.5 to 2 μgal. Tab. 3.1 furthermore lists the results of the combined adjustments for the epochs 1982/83, 1984/85 and of all observations.

Separate adjustments for G258 and D38 were made in order to study the internal accuracy of both instruments. As can be seen in Tab. 3.1 the average error for G and D meter being 3 μgal is almost equal in all campaigns. That means, that in view of precision there is no difference between the two types of LaCoste gavimeters

4. Gravity changes

The gravity network was designed to monitor the changes in gravity possibly associated with the faulting activities at the NATF. As there is no information on stable points, the single epochs, 4 in 1982/83 and 2 in 1984/85, were compared with the combined adjustment of all epochs. The differences related to the mean value on single stations and the standard deviation of the differences were used as a measure for stability. Tab. 4.1 shows, that on stations 3,7,8,9 the smallest variations occur. Therefore for studying the time-dependent variations in gravity, the mean value of the changes on these 4 stations at each epoch is subtracted from the differences of all stations. Remaining variations on stations 3,7,8,9 are considered to be measurment noise. This procedure corresponds to the introduction of a datum level formed by the four stable sites. Fig. 4.1 and Tab. 4.2 show the results.

It seems that the first epoch at station 9 is affected by some measuring error, as the subsequent variations are rather small.

From Fig. 4.1 it is seen that the measurements in 1982/83 are rather noisy in general. However there seems to be a common trend for some stations, e.g. stations 5 and 6, stations 1 and 2.

Therefore the differences are reordered in terms of distance from the main fault lines and only the combined epoch 1982/83 is compared with the 1984 and 1985 values. Fig. 4.2 shows the variaions, the dashed line with triangles being the sum of the other two lines. There is no obvious trend, however the values of the 4 stable sites are correlated. This may be due to the fact that they are situated in the same geological formation. By focussing on the changes from 1984 to 1985 it seems that there is an increase in gravity on stations 1 and 2 in the fault and a decrease on 5 and 6 which have the largest distance from the fault. This could be associated with a rise of the northern part of the fault. However as there is only a time span of 3 to 4 months between measurements, seasonal effects may be superposed to any secular change.

From Fig. 4.2 it is obvious that point 4 does have a special behavior different from the neighboring stations. This is probably caused by its position in sediment area close to a pond leading to instability.

Due to the fact that, with the D-meter, one always can use the same counter position in spite of the instrumental drift between the epochs and due to a rather small drift rate of G258 the systematic errors between the gravimeters should be almost constant. This is clearly revealed in Fig. 4.3. There is a surprisingly big systematic discrepancy on station 9. As investigations showed, this discrepancy is not related to screw or scale errors (especially the periodical errors of 35 and 70 c.u. in the G-meter could be the cause). Up to now there is no explanation for this difference of more than 15 μgal. However, as it is constant in all epochs the investigation of time-dependent gravity changes is not affected.

5. Conclusions

Up to now there is no indication of a significant gravity change in the high precision network. The analysis of the results revealed the existence of an unstable point, station 4, and of systematic errors between instruments. Further measurements will be conducted in intervals of 2 years. Future data analysis may then include an multivariate analysis with trendpolynomials for time-dependent gravity changes. It is planned to connect the gravity stations to the leveling network and to monitor height changes by precise leveling between the stations.

As to the fact of appearently no change in gravity it is interesting to note that also the ongoing repeated triangulation and trilateration observations in the high precision network of the Technical University Istanbul running across the NATF do not indicate lateral movements of the fault either.

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DIFFERENCES

Point	Mean Value	Max.	Min.	Std. Dev.	11/82	12/82	1.0/83	1.1/83	2/83	12/84	4/85
2	-21.0236	9.73	-7.77	6.42	-7.77	-7.17	0.83	5.73	1.13	-2.47	9.73
1	-18.3176	8.51	-13.19	7.04	-1.49	-13.19	-2.29	8.51	0.41	1.61	6.41
4	2.8226	10.19	-9.51	6.61	1.19	10.19	-0.11	1.39	3.89	-7.01	-9.51
3	7.4050	9.07	-3.73	4.36	-2.33	-1.23	-3.13	-3.73	0.77	0.57	9.07
7	-2.0056	5.67	-4.23	3.15	5.67	-0.13	-4.23	-0.53	1.77	-2.43	-0.13
9	2.4907	4.01	-8.59	4.38	-8.59	3.41	1.01	4.01	2.51	0.11	-2.49
8	-1.4405	6.60	-4.30	3.79	0.90	-1.10	6.60	3.00	-2.70	-2.40	-4.30
6	13.8553	6.73	-8.77	6.54	5.93	2.93	6.73	-6.67	-4.87	4.73	-8.77
5	16.2137	7.23	-11.67	7.14	6.53	6.13	-5.37	-11.67	-2.87	7.23	0.03

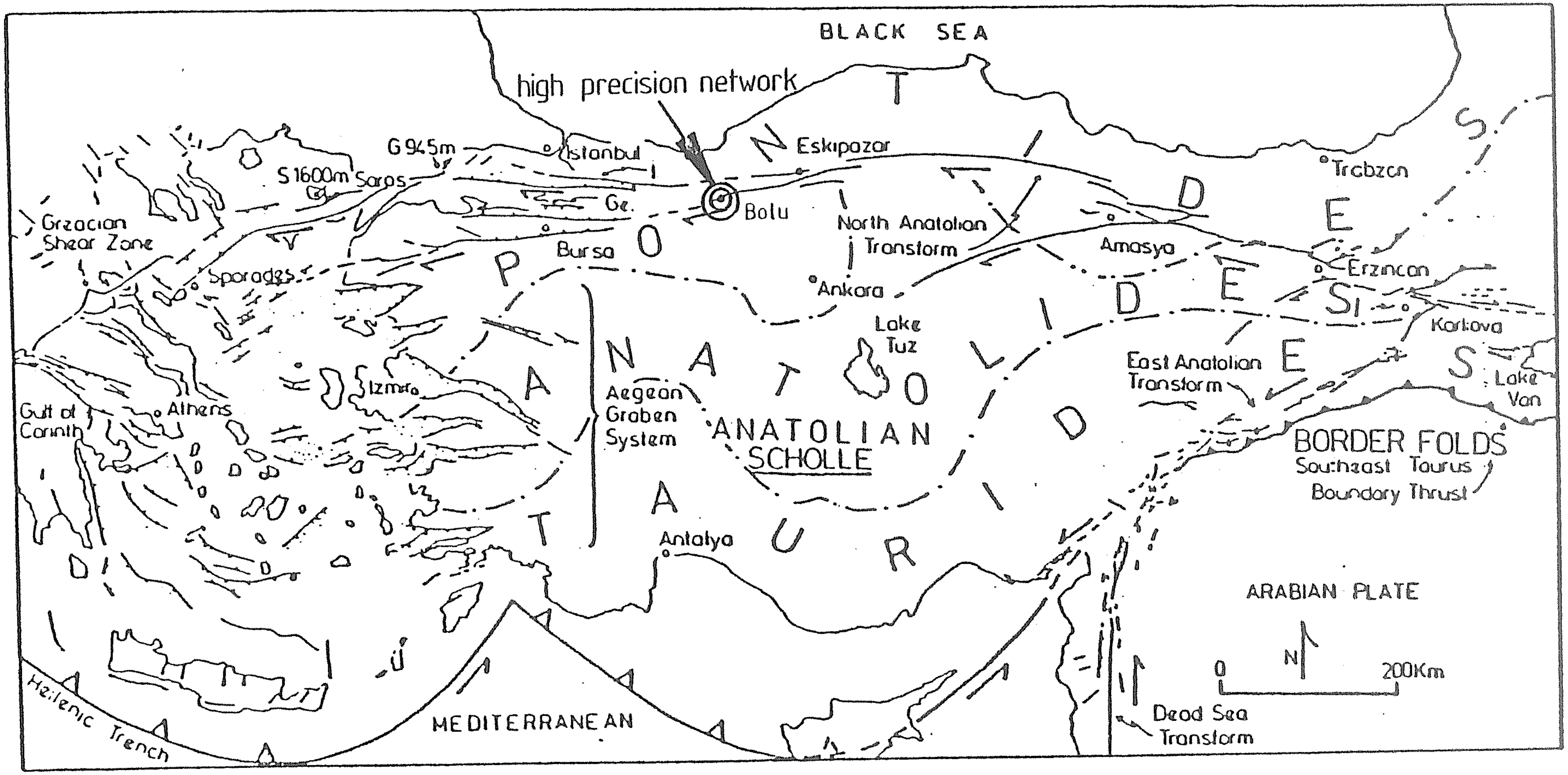
Tab. 4.1 Differences of Single Epochs Gravity Values to Mean Value of all Epochs

DIFFERENCES

Point	Mean Value	Max.	Min.	Std. Dev.	11/82	12/82	1.0/83	1.1/83	2/83	12/84	4/85
2	-21.0314	17.50	0.00	10.57	0.00	0.60	8.60	13.50	8.90	5.30	17.50
1	-18.3191	8.60	-13.10	7.04	-1.40	-13.10	-2.20	8.60	0.50	1.70	6.50
4	2.8238	7.20	-12.50	7.35	-1.80	7.20	-3.10	-1.60	0.90	-10.00	-12.50
3	7.4027	8.57	-4.23	4.39	-2.83	-1.73	-3.63	-4.23	0.27	0.07	8.57
7	-1.9999	-1.20	-11.10	8.06	-1.20	-7.00	-11.10	-7.40	-5.10	-9.30	-7.00
9	2.4821	13.50	0.90	11.14	0.90	12.90	10.50	13.50	12.00	9.60	7.00
8	-1.4396	7.33	-3.57	3.87	1.63	-0.37	7.33	3.73	-1.97	-1.67	-3.57
6	13.8612	0.80	-14.70	9.15	0.00	-3.00	0.80	-12.60	-10.80	-1.20	-14.70
5	16.2202	0.70	-18.20	10.03	0.00	-0.40	-11.90	-18.20	-9.40	0.70	-6.50

Tab. 4.2 Differences of Single Station Gravity Values to the First Epoch, Mean Value of Change on 3,7,8,9 Removed

ACTIVE PLATE AND SCHOLLE BOUNDARIES OF TURKY



STRIKE SLIP FAULTS

THRUST FAULT

SUBDUCTION ZONE

NORMAL FAULTS

UNSPECIFIED FAULTS

Fig. 1.1 Location of the measurement area with respect to the NATF

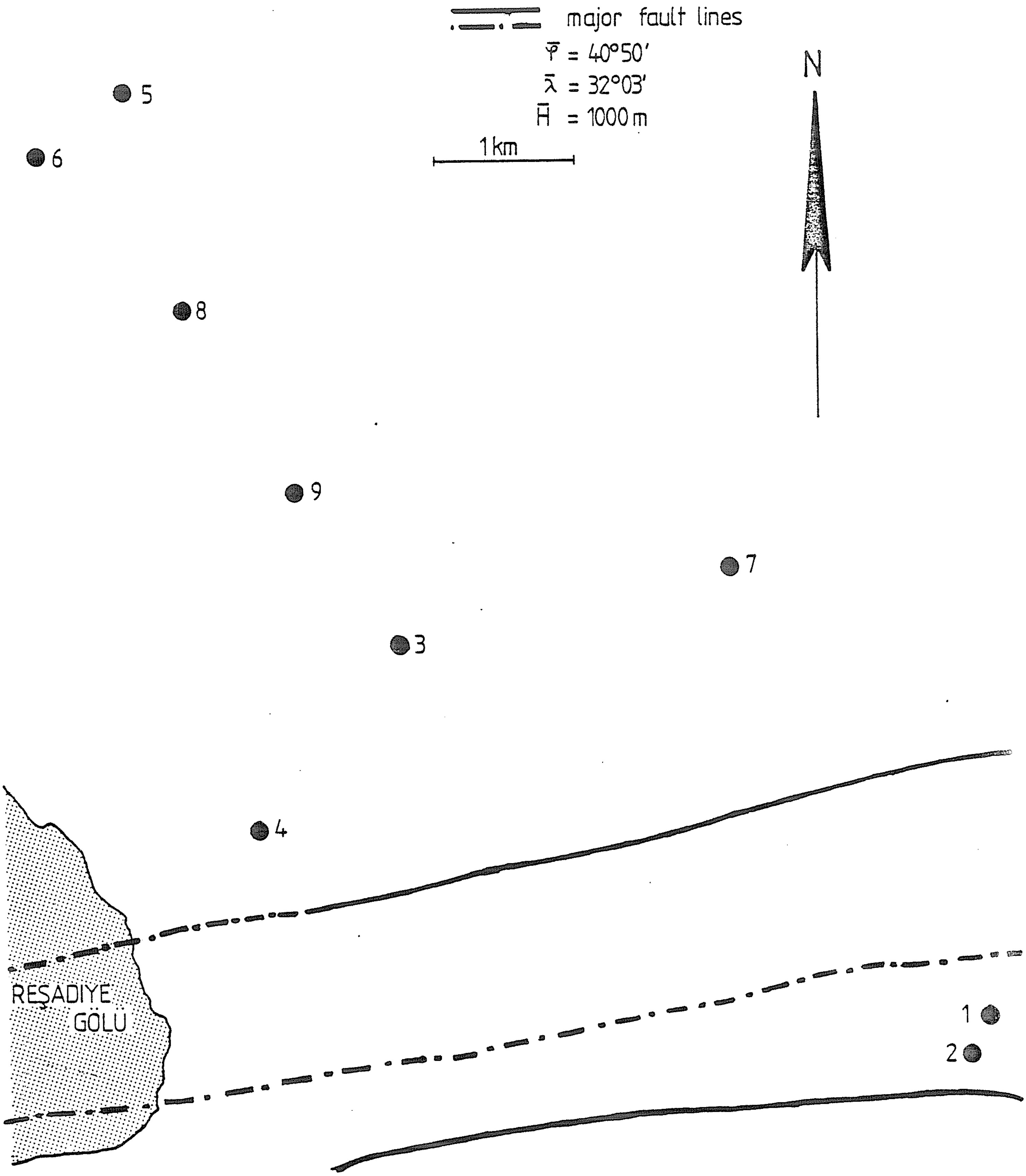


Fig. 21 Sketch of the high precision gravity network

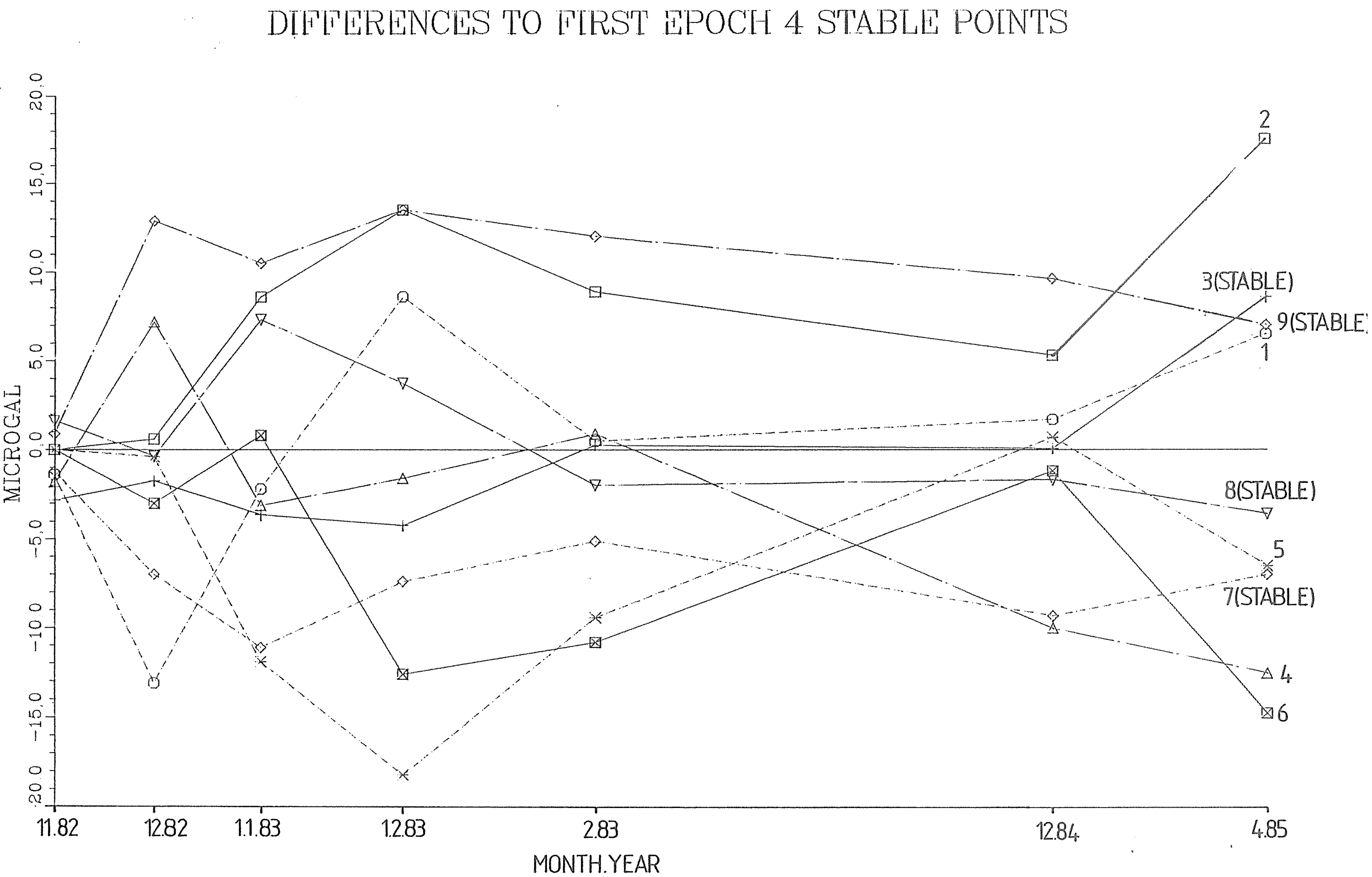


Fig. 4.1 Differences in the gravity values of the measuring stations since 1982

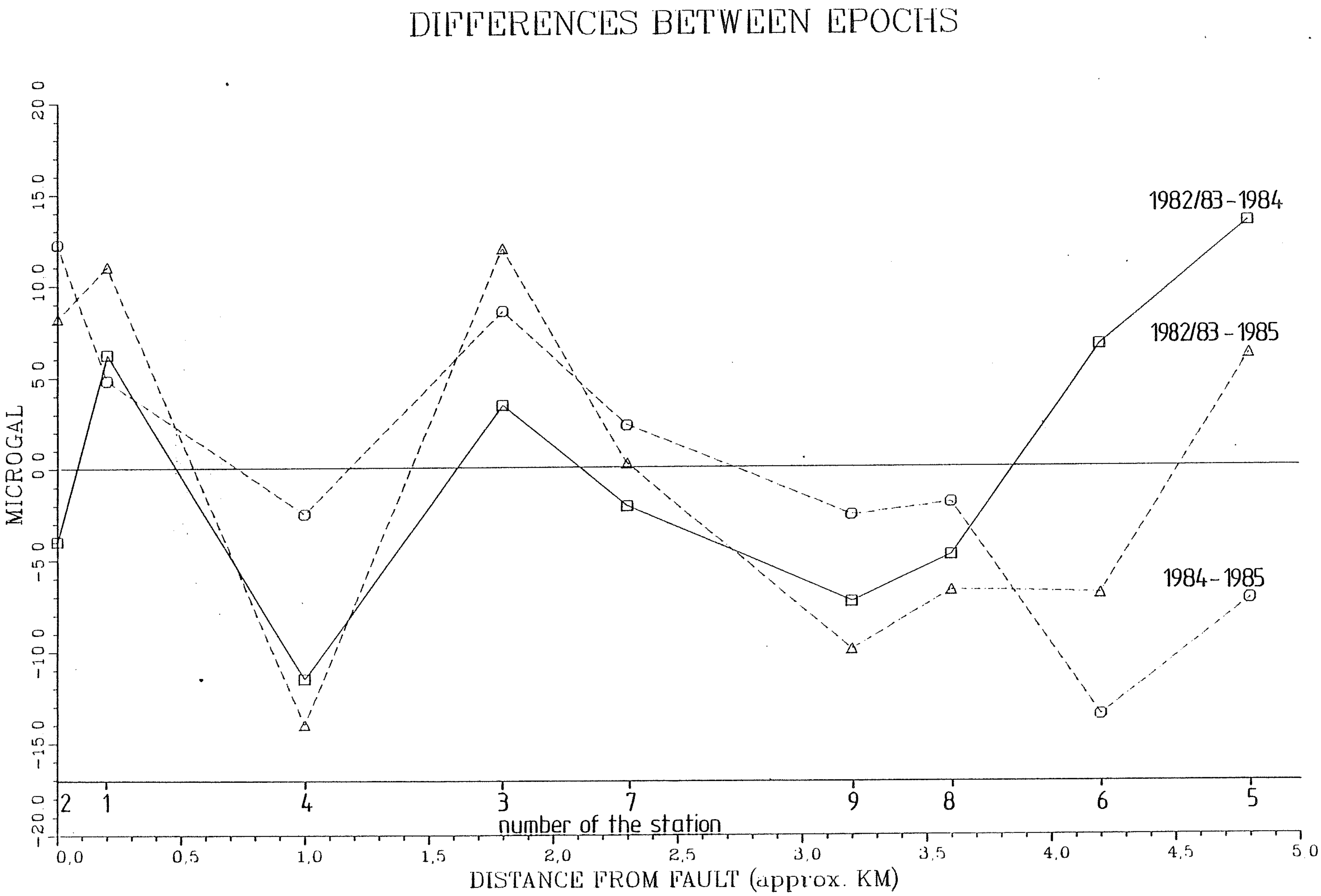


Fig. 4.2 Time-dependent changes in the gravity values

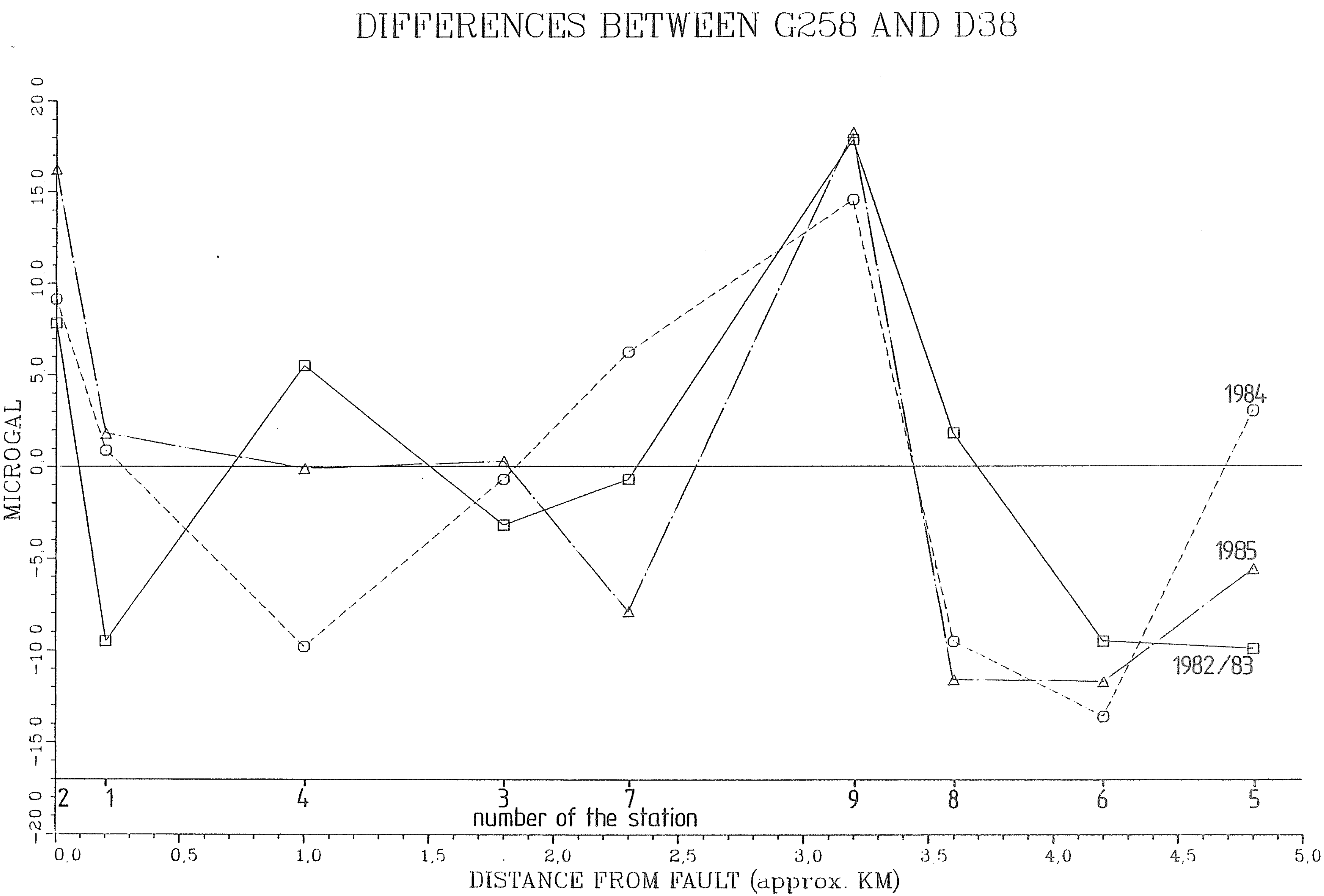


Fig. 4.3 Differences between instruments for three epochs

Relative Gravimeter Measurements at the 1985 Absolute Gravimeter Campaign in Sèvres -Preliminary results-

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Abstract

Relative gravimeter measurements conducted during the 1985 absolute gravimeter comparison in the BIPM, Sèvres, are evaluated. Results of 10 LaCoste and Romberg Model G and D gravimeters for gradient measurements at 6 sites and differences between the absolute gravimeter locations are given. Gravity differences and gradients were determined with an average m.s.e. of 0.7 and 0.9 μgal respectively.

1. Introduction

In June and July 1985 the IAG SSG 3.86 organized a simultaneous intercomparison of 6 absolute gravimeters at the Bureau International de Poids et Mesures in Sèvres. It was the subsequent campaign to that conducted in 1981 (Boulanger et al., 1983). IAG SSG 3.85 organized a campaign in parallel to determine the gravity differences between the six different stations used as well as the vertical gradients of gravity. All together 14 LaCoste and Romberg Gravity meters were employed, see Appendix A1 for the participants. It was of special interest that 6 out of these 14 were equiped with electrostatic feedback systems which are supposed to eliminate the gravimeter's periodical errors being the major source of systematic discrepancies between instruments.

2. Data evaluation

For the computions the original readings were transformed to milligal using the calibration values for scale, periodical errors or conversion from feedback-voltages to milligal as supplied by the owners of the instruments, see Appendix A.2 for a table of calibration parameters. No air-mass correction was used because of the small time differences between the readings. Tidal corrections were computed with the Cartwright-Taylor-Edden tidal potential development using the empirical tidal parameters for 7 wave groups for Sèvres as published in (Becker, Groten, 1983).

Special care was taken for the height correction. Due to the large differences between gradients in the ground floor, stations A1, A3, and the basement stations A4 to A7 of about 50 μgal, even with constant instrumental height above the floor the reduction to the station marker is different. In Tab. 2.1 the instrumental heights are given. It is assumed that in the average the gravimeter mass is about 16 cm below the top-plate. For ordinary instruments the effective height for correction therefore is about 5 cm. In Tab. 2.1 this height is transformed by the ratio of actual gradient and normal gradient (0.3086 mgal/m) to demonstrate the effects of variable gradients corresponding to changed instrumental heights. E.g. in case of D 21 the correction for the gravity difference A1 - A4 amounts to -11.1 μgal.

The adjustment is done in two steps, by first taking every set of an instrument's readings with a common drift behavior to produce adjusted gravity differences and drift estimation. In the second step these differences, together with their variance covariance matrix, are combined both for the single adjustment of one instrument and for the combined adjustment of all instruments.

Instr.		i	i-16	A1	3	4	5	6	7
1	G305	0.200	0.040	0.041	0.038	0.033	0.033	0.033	0.033
2	G298	0.214	0.054	0.055	0.052	0.045	0.044	0.045	0.045
3	G790	0.208	0.048	0.049	0.046	0.040	0.039	0.040	0.040
4	D8	0.212	0.052	.053	.050	.043	.043	.043	.043
5	G258	0.229	0.069	.070	.066	.057	.057	.058	.058
6	D38	0.234	0.074	.075	.071	.061	.061	.062	.062
7	G54	0.217	0.057	.058	.054	.047	.047	.048	.048
8	G290	0.214	0.054	.055	.052	.045	.044	.045	.045
10	D21	0.346	0.186	.189	.178	.154	.152	.156	.156
11a	G563	0.290	0.130	.132	.124	.107	.107	.109	.109
b		0.215	0.055	.056	.053	.045	.045	.046	.046

Tab. 2.1 Instrumental heights for correction to the floor assuming a gradient of 0.3086 mgal per m on every station (For G54, G290, D21, G563 mean instrumental heights are given but actual heights are used in calculations.)

As long as there are no time-dependent systematic errors, like those caused by artificial magnetic fields, the single instruments in their separate adjustments can be weighted according to their inner accuracy as obtained by the first step drift adjustments. In the combination of the various instruments systematic errors become obvious and may distort the results badly. Therefore in the combined adjustment and for taking the weighted mean value in the gradient determinations the weights were computed like

$$p_i = (m^2_{i,r} + m^2_{i,s})^{-2}.$$

Here $m_{i,r}$ indicates the r.m.s.error of a gravimeter reading obtained from single adjustments and $m_{i,s}$ stands for systematic errors. Tab. 2.2 gives the average error of the gravimeter readings and the systematic errors as estimated from the uncertainties for the calibration parameters or from the expectable effects of uncompensated periodic errors.

3. Vertical gradient measurements

All gradients have been observed at the center of the stations, the heights of the top plates of the gravimeters are given in Tab. 3.1 to 3.6. Single instruments gradient determinations have accuracies of 0.2 to 4.6 µgal, the average being about 1 µgal.

Figs. 3.1 to 3.6 show the deviations from the adjusted mean values for all instruments and all stations together with the associated r.m.s. error bars. It is seen that the non-feedback instruments in general show larger discrepances.
Especially G 54, G 290 and G 258 whose values are systematically too large, may be affected by systematic errors. D38F suffered from a failure of the feedback power supply and should not be considered in an comparison.

Instr.	inner accuracy (average, μgal)	systematic error (μgal)	total (μgal)
D8F	2.65	<1 Feedback calibration	2.83
G298F	2.20	<1 Feedback calibration	2.41
G709F	2.11	<1 Feedback calibration	2.33
G563	1.71	2 uncertainty of period.error corr.	2.63
D21	0.64	1 uncertainty of period.error corr.	1.18
G54	1.90	2 periodical errors	2.76
G290	1.70	2 periodical errors	2.62
G305	2.50	2 periodical errors	3.20
G258	3.34	2 periodical errors	3.89
D38F	2.66	1 Feedback calibration	2.84

Tab. 2.2 Root mean square errors of gravimeter readings for the weighting of gravimeters in the combined adjustment

In the computation of the adjusted gradients the weights were chosen as explained in sec. 2. The gradients are determined with an average accuracy of 0.8 μgal.

Tab. 3.7 shows the changes in the vertical gradients since the

Gradient-Measurements S è v r e s A

Instr.		Instrumental down	height up	Difference m	Number of obs.	Gradient gal/m
1	D8F	0.212	1.212	1	11	312.5±0.4
2	G298F	0.214	1.214	1	13	313.7±1.3
3	G709F	0.208	1.208	1	11	311.1±0.7
4	G563	0.406	1.406	1	8	313.7±0.9
5	D21	0.186	1.185	0.999	6	309.7±0.1
6	G54	0.217	1.031	0.814	6	314.3±0.9
7	G290	0.212	1.027	0.815	8	-
8	G305	-	-	1	6	308.2±4.6
9	G258	0.229	1.227	0.998	8	312.0±1.4
10	D38F	0.234	1.232	0.998	9	313.5±1.7
	Mean					311.8±0.6

Gradients S è v r e s A 3

1	D8F	0.212	1.212	1	15 13	296.0±0.5 296.4±1.2
2	G298F	0.214	1.214	1	11 11	290.0±0.7 291.3±1.0
3	G709	0.208	1.208	1	13 11	296.8±1.6 297.0±0.7
4	G563	0.406	1.406	1	8	292.1±0.9
5	D21	0.192	1.191	0.999	6	291.5±0.5
6	G54	0.216	1.035	0.819	6	295.7±1.3
7	G290	0.212	1.032	0.820	8	303.9±0.5
8	G305	-	-	1	6	300.4±1.3
9	G258	0.229	1.229	1	8	299.4±3.3
10	D38F	0.234	1.234	1	9	302.3±1.0
	Mean					295.3±1.2

Tab. 3.1, 3.2

Gradients S è v r e s A 4

Instr.		Instrumental down	height up	Difference m	Number of obs.	Gradient gal/m
1	D8F	0.212	1.212	1	12 11	257.4±1.1 254.4±1.58
2	G298F	0.214	1.214	1	11	255.0±1.2
3	G709F	0.208	1.208	1	13 11	252.0±1.4 255.0±0.7
4	G563	0.406	1.406	0.999	6	253.9±1.2
5	D21	0.190	1.190	1	6	254.7±0.1
6	G54	0.219	1.036	0.817	6	261.1±0.6
7	G290	0.214	1.031	0.817	8	261.8±0.7
8	G305	-	-	1	6	246.5±0.8
9	G258	0.229	1.229	1	8	256.7±2.5
10	D38F	0.234	1.234	1	8	259.9±1.5
	Mean					255.5±1.0

Gradients S è v r e s A 5

1	D8F	0.212	1.212	1	13	251.8±0.5
2	G298F	0.214	1.214	1	11 11	256.4±0.8 253.5±0.9
3	G708F	0.208	1.208	1	11	251.3±0.5
4	G563	0.406	1.406	1	6	252.5±1.0
5	D21	0.191	1.190	0.999	6	251.4±0.3
6	G54	0.218	1.035	0.817	6	253.4±0.3
7	G290	0.213	1.031	0.818	9	254.3±1.0
8	G305	-	-	1	6	245.5±1.0
9	G258	0.229	1.229	1	8	255.8±1.5
10	D38	0.234	1.234	1	8	250.1±1.7
	Mean					252.4±0.7

Tab. 3.3, 3.4

Gradients   S è v r e s   A 6

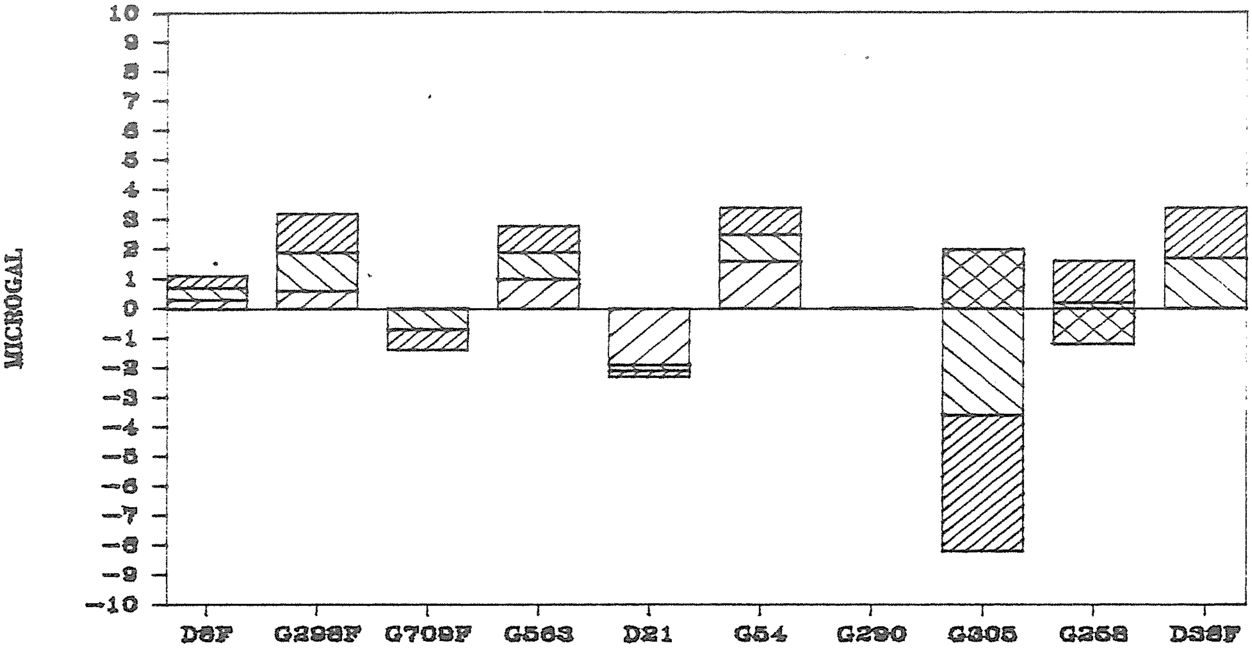
1 D8F	0.212	1.212	1	14 11	259.6±1.0 257.4±1.0
2 G298F	0.214	1.214	1	11	257.3±1.0
3 G709F	0.208	1.208	1	11	257.4±0.5
4 G563	0.190	1.189	0.999	6	256.6±1.4
5 D21	0.190	1.189	0.999	6	257.9±0.4
6 G54	0.217	1.036	0.819	8	261.3±1.4
7 G290	0.213	1.033	0.820	8	260.1±0.9
8 G305	-	-	1	6	253.2±0.7
9 G258	0.229	1.229	1	8	267.4±1.3
10 D38F	0.234	1.234	1	8	264.0±1.0
Mean					x_g=258.9±0.9

Gradients   S è v r e s   A 7

1 D8F	0.212	1.212	1	11 11	257.8±0.7 260.2±0.7
2 G298F	0.214	1.214	1	11	256.2±0.9
3 G709F	0.208	1.208	1	11 10	258.8±0.8 258.0±1.1
4 G563	0.407	1.406	0.999	6	254.7±0.7
5 D21	0.192	1.191	0.999	6	258.7±0.3
6 G54	0.218	1.036	0.818	6	263.8±1.5
7 G290	0.214	1.032	0.818	8	261.2±0.8
8 G305	-	-	1	6	260.4±0.7
9 G258	0.229	1.229	1	10	262.0±2.0
10 D38F	0.234	1.234	1	10 8	260.5±1.0 259.7±0.6
Mean					x_g=259.0±0.5

Tab. 3.5, 3.6

GRADIENT A1 : 311.8 +- 0.6



GRADIENT A3 : 295.3 +- 1.2

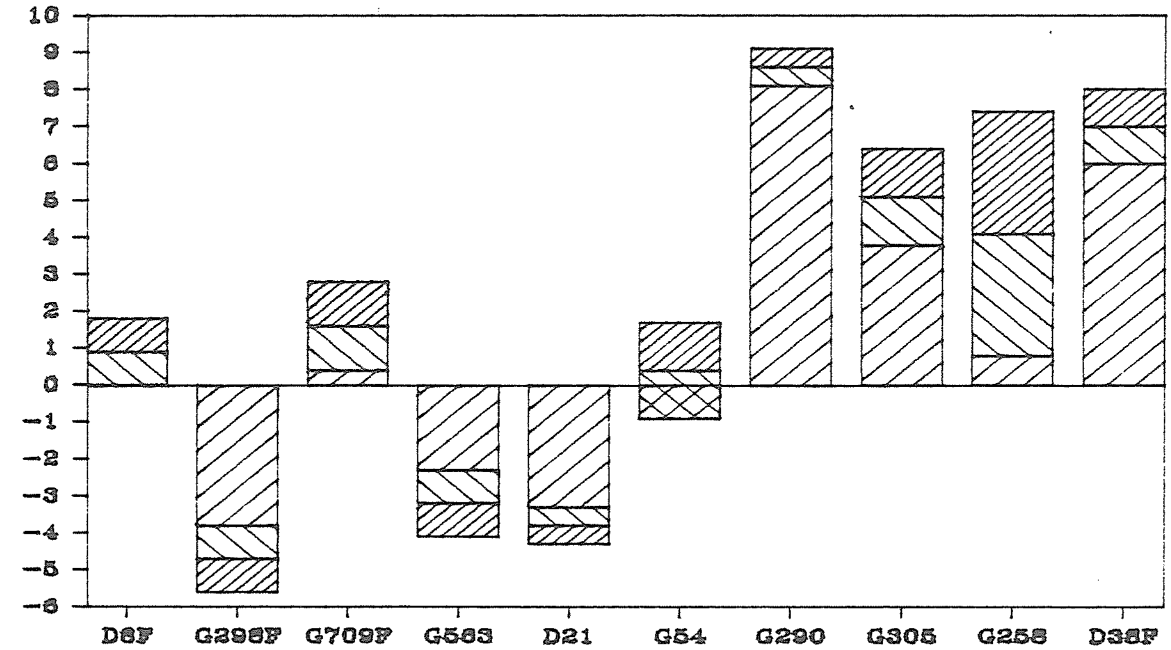
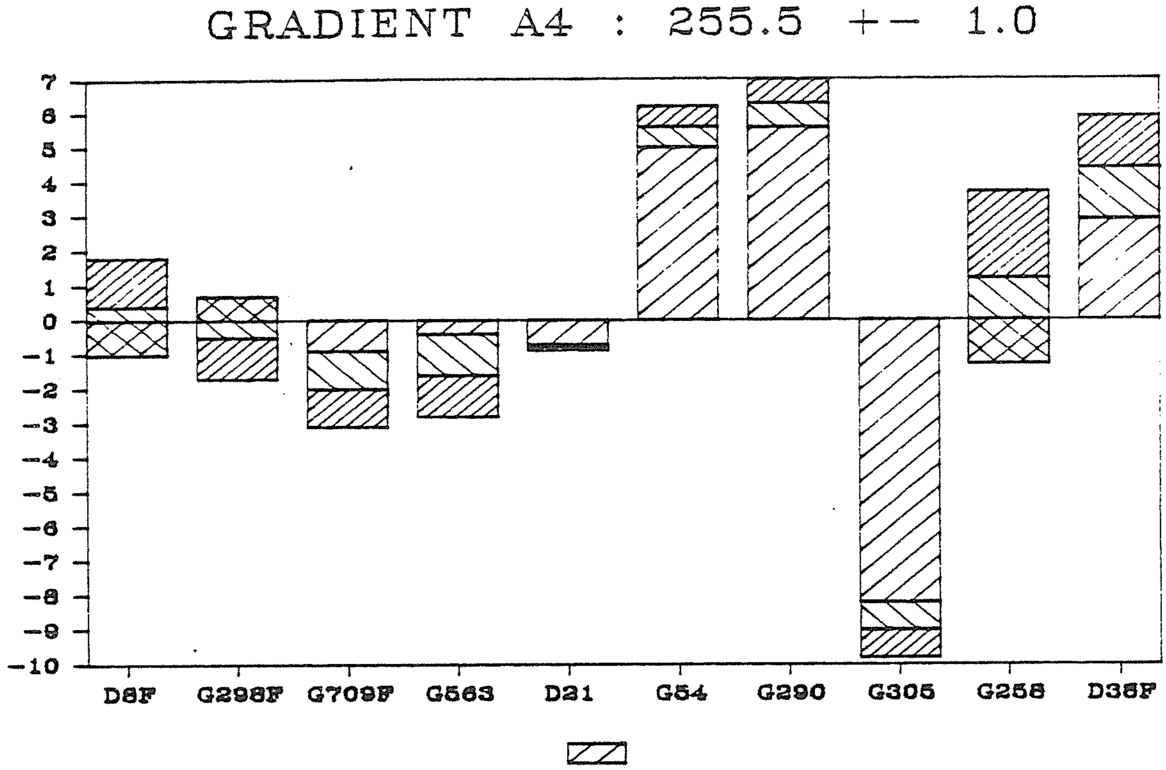


Fig. 3.1, 3.2


GRADIENT A4 : 255.5 +- 1.0
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D8F
G298F
G709F
G563
D21
G54
G290
G305
G258
D38F

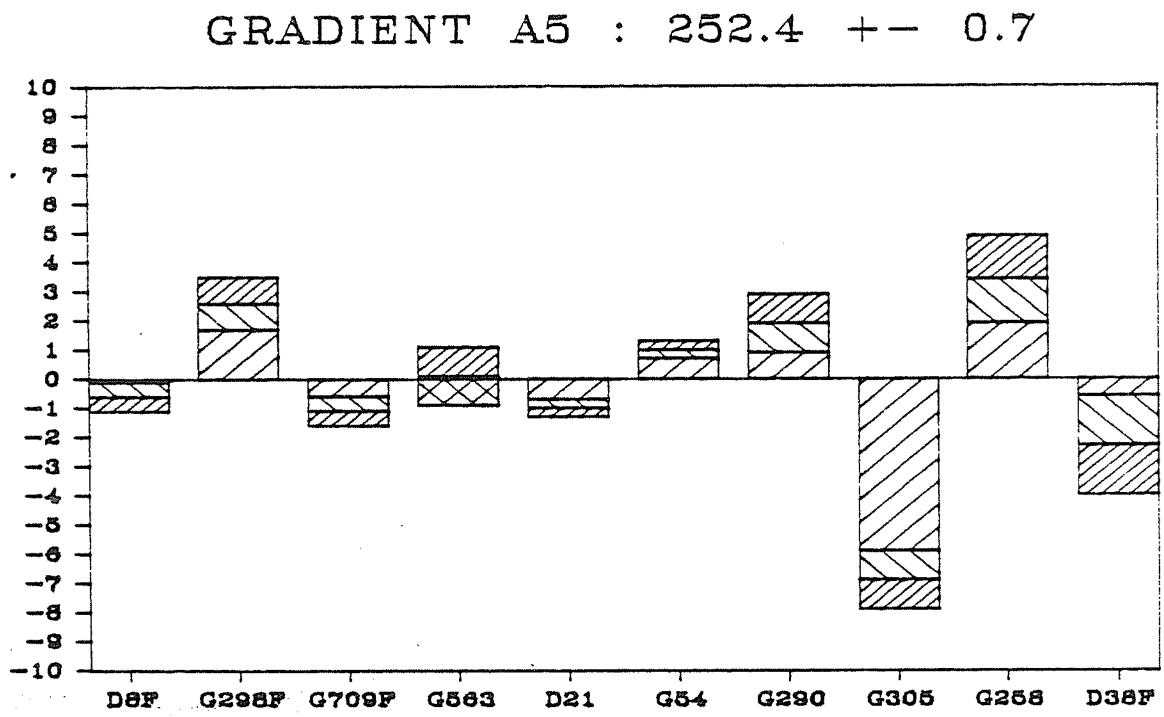
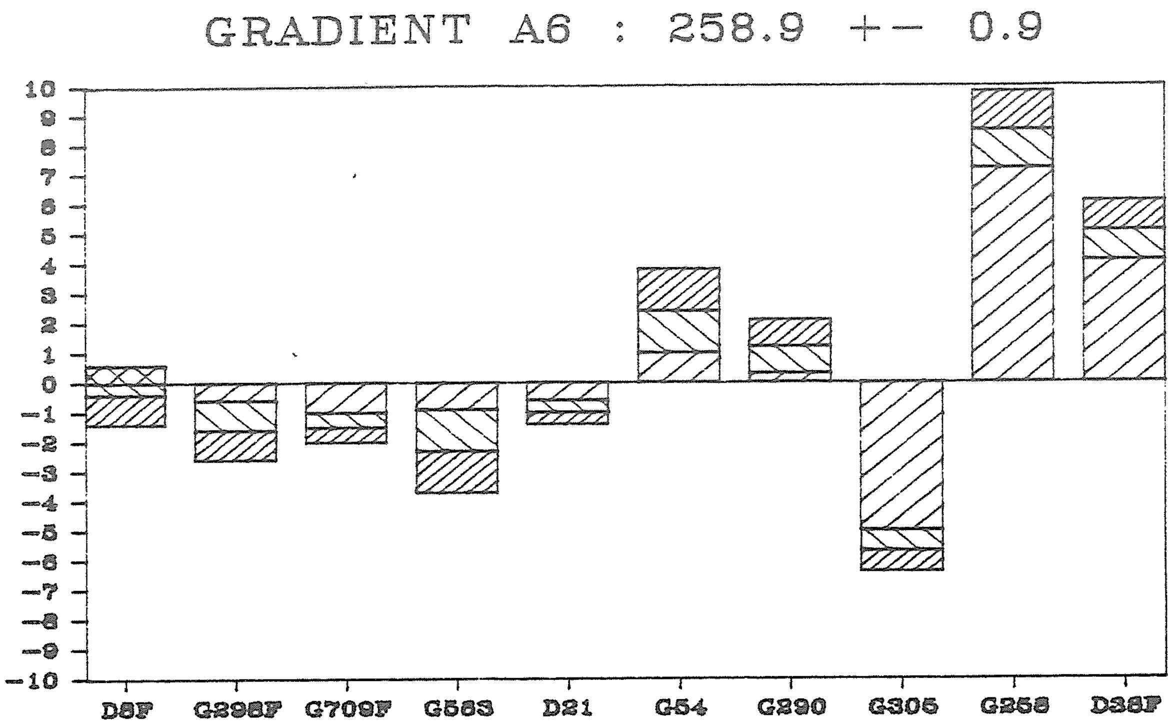

GRADIENT A5 : 252.4 +- 0.7
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D8F
G298F
G709F
G563
D21
G54
G290
G305
G258
D38F

Fig. 3.3, 3.4


GRADIENT A6 : 258.9 +- 0.9
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D8F
G298F
G709F
G563
D21
G54
G290
G305
G258
D38F

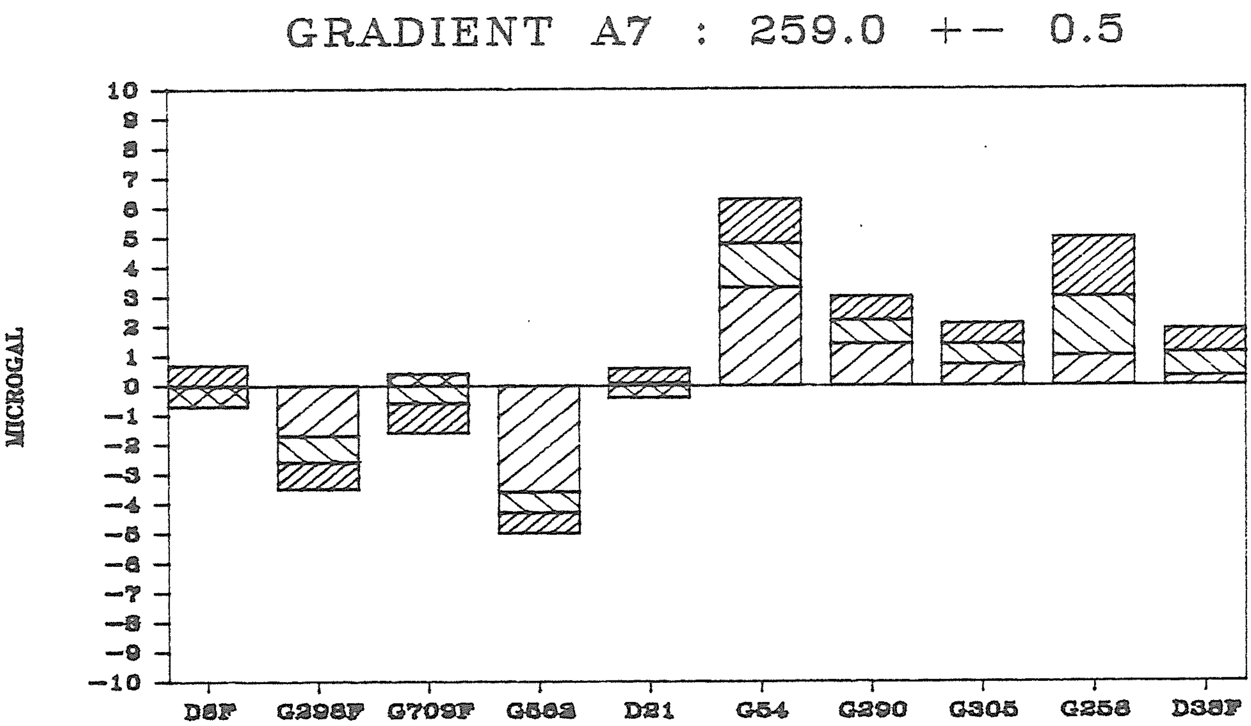

GRADIENT A7 : 259.0 +- 0.5
MICROGAL
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D8F
G298F
G709F
G563
D21
G54
G290
G305
G258
D38F

Fig. 3.5, 3.6

last campaign in October 1981. One intermediate value was taken from (Mathieu, Ogier, 1985). All gradients show an increase, especially on A1 and A6 a change of 11.2 and 7.2 µgal occured.

Station/Date	10/1981	10/1984	7/1985	Difference
A 1	-	-	311.8±0.6	-
A 3	283.6±1.6	274.7±1.3	295.3±1.2	+11.9
A 4	253.5±1.3	-	255.5±1.0	+ 1.9
A 5	250.8±1.1	-	252.4±0.7	+ 1.6
A 6	251.8±1.2	-	258.9±0.9	+ 7.2
A 7	-	-	259.0±0.5	-

Tab 3.7. Comparison of vertical gradients at different epochs

In (Boulanger, 1985) a correction for the excentric measurements at pillar A3 in 1981 was computed and our value of 1981 was decreased by 10.6 µgal/m. The result of 273 µgal/m fits quite well with the gradient of (Mathieu, Ogier, 1985). However, considering the results of the centric measurements reported here, there must have been a change in the vertical gradient of more than 20 µgal within 9 months.

4. Gravity differences between absolute sites

During this campaign all differences could be observed between the station markers of every site, no excentric measurements are included.

Instr.	1		3		4		5		6		7		—
	g	mg	g	mg	g	mg	g	mg	g	mg	g	mg	mg
D8F	-0.1	1.32	-67.9	1.15	583.7	1.93	577.8	0.91	608.8	1.34	657.8	1.12	1.3
G298F	0.6	1.0	-71.3	1.10	584.9	1.37	580.6	1.02	610.2	1.22	660.4	1.13	1.1
G709F	0.4	0.62	-67.2	0.61	583.3	0.50	577.9	0.48	610.5	0.58	658.7	0.57	0.6
G563	-4.4	1.26	-71.8	1.32	577.5	1.54	571.7	1.36	602.6	1.32	654.8	1.24	1.3
D21	1.4	0.25	-70.9	0.33	585.0	0.34	580.8	0.26	611.2	0.35	663.1	0.32	0.3
G54	0.6	1.09	-69.4	1.08	582.7	1.36	577.6	1.11	611.4	1.13	662.1	1.17	1.2
G290	1.4	1.24	-73.1	1.24	585.7	1.59	580.7	1.25	611.5	1.24	664.4	1.36	1.3
G305	-4.3	2.86	-68.6	3.19	574.4	4.90	575.9	2.73	603.2	2.86	650.3	2.67	3.3
G258	3.8	1.58	-72.0	1.42	593.7	2.73	583.4	1.75	611.7	2.07	667.0	1.55	1.9
D38F	1.2	1.89	-76.2	1.62	588.8	1.52	581.5	1.71	614.0	1.62	660.3	1.62	1.7
comb.	0.0	0.46	-70.5	0.48	583.8	0.53	578.5	0.43	609.4	0.51	659.8	0.47	0.5

Tab. 4.1 Results of single and combined adjustments

Table 4.1 and Fig.'s 4.1 - 4.6 show the results and precision of the single instruments. Tab. 4.2 shows the differences to the final combined adjustment with weights according to sec. 2. Adjustments are made as free network adjustments minimizing the norm of the normal equation matrix. For comparison the gravity values of the relative instruments are transformed to be zero in the average, the combined adjustment's gravity values are transformed using the value of zero at A1.

Instr.	Difference						
	1	3	4	5	6	7	Std.Dev.
D8F	0.1	2.7	0.0	-0.6	-0.5	-1.9	1.5
G298F	-0.6	-1.4	0.5	1.5	0.2	0.0	1.0
G709F	-0.4	2.9	-0.9	-1.0	0.7	-1.5	1.6
G563	4.4	+3.1	-1.9	-2.4	-2.4	-0.6	3.0
D21	-1.4	-1.8	-0.2	0.9	0.4	1.9	1.4
G54	-0.6	0.5	-1.7	-1.5	1.4	1.7	1.5
G290	-1.4	-4.0	0.5	0.8	0.7	3.2	2.4
G305	4.3	6.2	-5.1	1.7	-1.9	-5.2	4.8
G258	-3.8	-5.3	6.1	1.1	-1.5	3.4	4.3
D38F	-1.2	-6.9	3.8	1.8	3.4	-0.7	3.9

Tab. 4.2 Differences of single instruments and combined adjustment

In the final combined adjustment the gravity values determined with an accuracy of 0.5 μgal in the average, this means that all differences between sites are determined with an error of less than 0.8 μgal.Single instruments gained errors about 1.4 μgal in the average.

It is interesting to compare the precision as given by m_g in Tab. 4.1 to the accuracy as described by the standard deviations of the differences to the mean values. For 3 instruments, G54, G298F and D8F, these values are approximately equal. With the others there is a discrepancy. Especially D21 and G709F are of interest. G709F is equipped with electrostatic feedback and so all screw-errors are eliminated. This means that there are other effects leading to systematic errors, e.g. artificial magnetic fields, which have to be investigated. D21 is a special type of modified D-meter (see Groten, 1983) and has the highest precision of 0.3 μgal. The accuracy is limited because of the imperfections in the correction of the screw-errors by sinusoidal models with constant amplitude and phase. With the instrument it would be interesting to apply an electrostatic feedback in order to check whether the accuracy can approach the precision or if, besides the screw-errors, other effects, as indicated in G709F, are prevai ling.

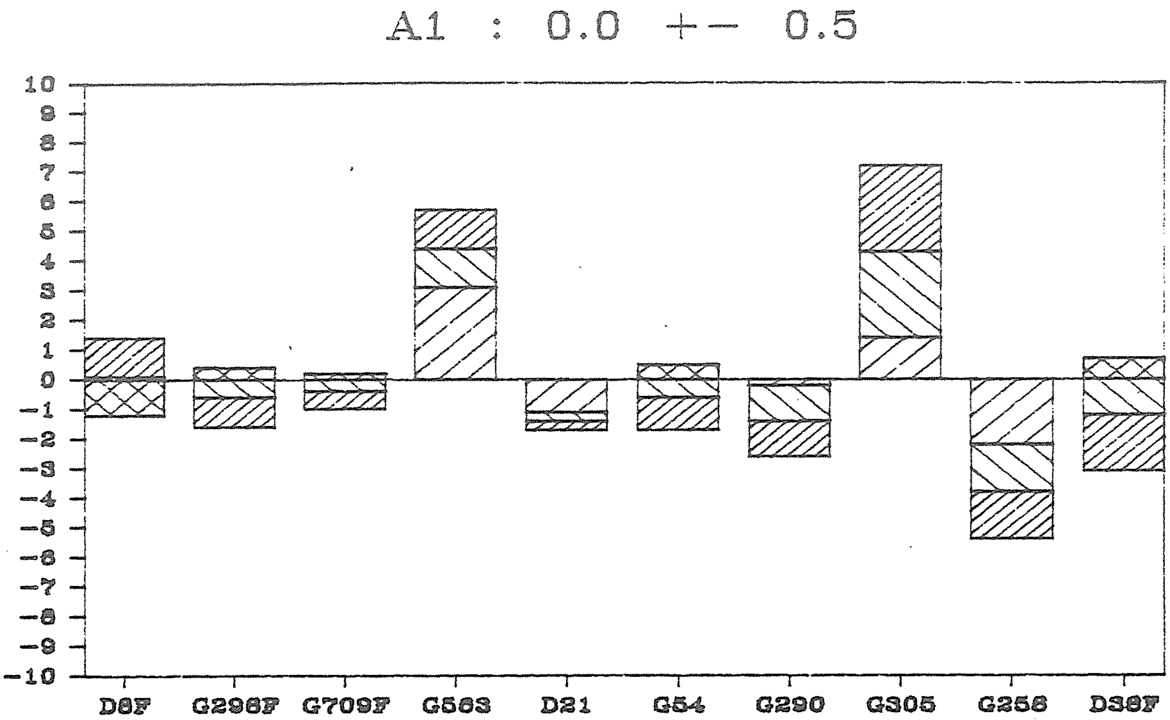
It is noteworthy that G54, which was red optically, has an accuracy almost equal to that of the feedback instruments and to D21.

Looking at Fig's 4.1 to 4.6 one can take the differences of the deviations on different pairs of stations to clear some systematic effects. E.g. for G563 it is obvious that mainly the differences between the ground floor stations A1, A3 and the basement stations show discrepances to the adjusted mean values. This can be caused by the longer transportation and possibly by shaking the instrument during the carrying through the narrow staircases. On the other hand on these larger gravity differences the screw-errors are more important. This holds for all G-meters except G54.

In general these figures as well as figures 3.1 to 3.6 for the gradients reveal that mainly station A3 and also station A4 seem to be more noisy than the others, the scatter of the results is bigger.

Tie	1981 I	1984 II	1985 III	II-I	III-I	III-II	Boulanger IV
A1-A3	-79.6	-	-70.5	-	9.1	-	-90.1
A1-A4	577.8	-	583.8	-	6.0	-	-
A1-A5	579.6	-	578.5	-	-1.1	-	-
A1-A6	606.8	-	609.4	-	2.6	-	-
A3-A4	657.4	665	654.3	11.6	-3.1	-14.7	-669.2
A3-A5	659.2	-	649.0	-	-10.2	-	-671.1
A3-A6	686.4	-	679.9	-	-6.5	-	-699.6
A4-A5	1.8	-2.0	-5.3	-3.8	-7.1	-3.3	-
A4-A6	29.0	-	25.6	-	-3.4	-	-
A5-A6	27.2	39	30.9	11.8	3.7	-8.1	-

Tab. 4.3 Gravity differences at different epochs


A1 : 0.0 +- 0.5
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D8F
G296F
G709F
G563
D21
G54
G290
G305
G256
D38F

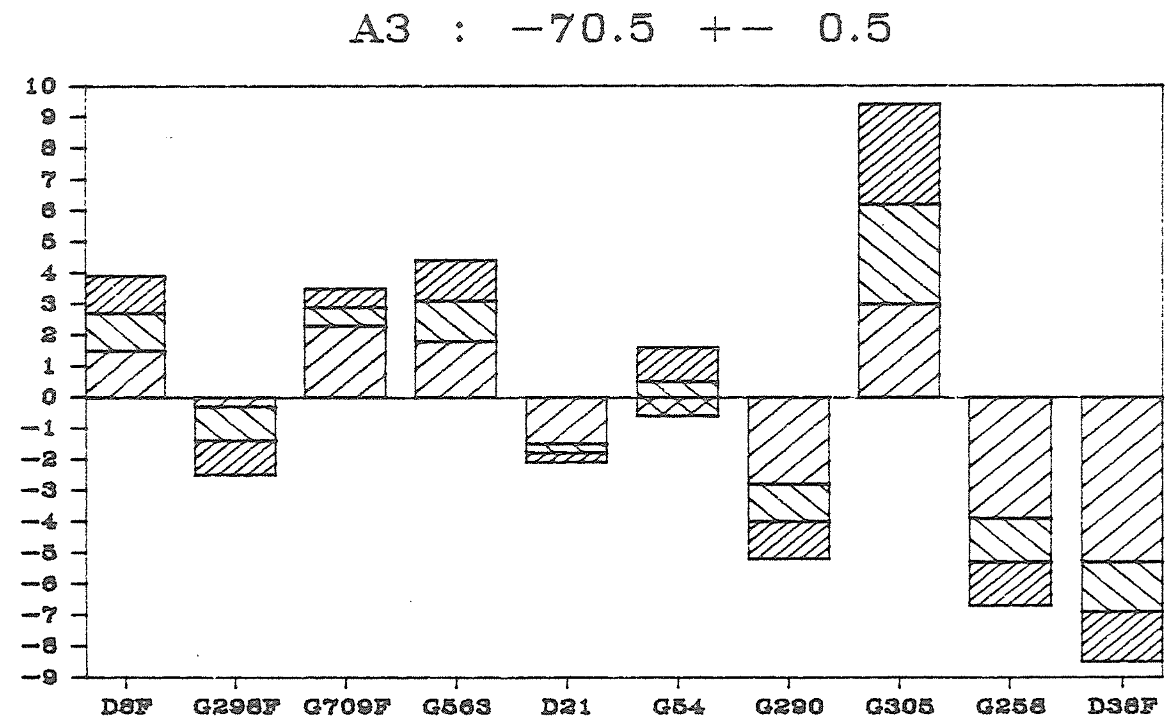
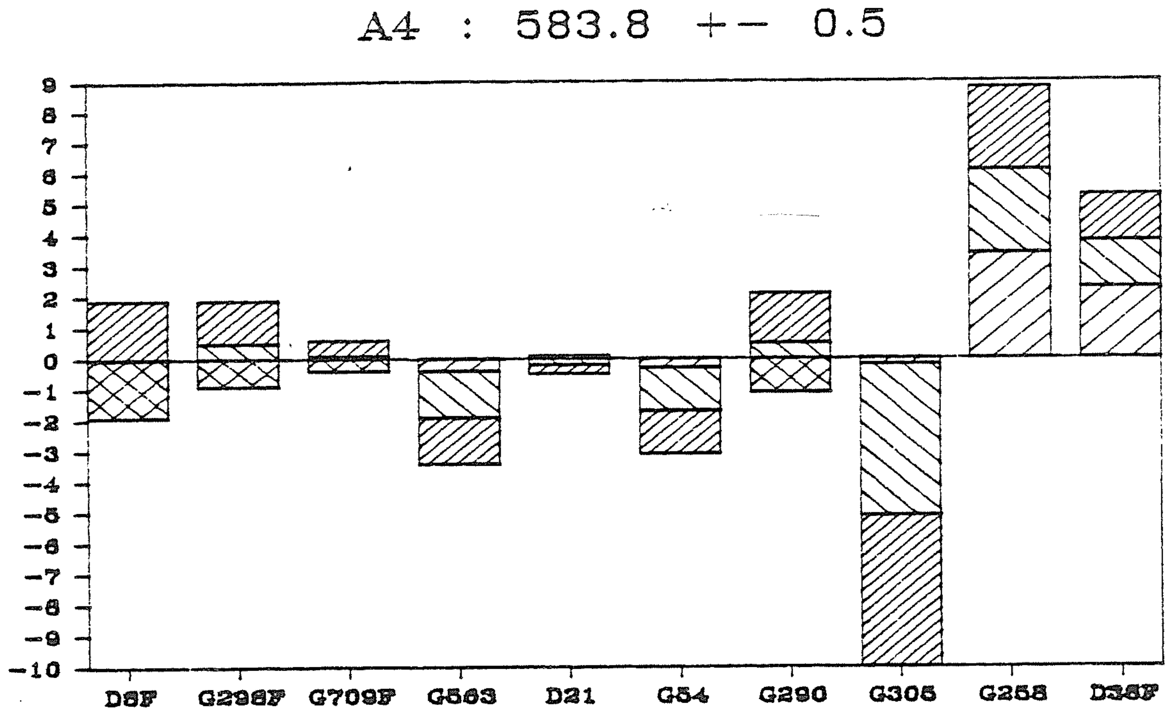

A3 : -70.5 +- 0.5
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
D8F
G296F
G709F
G563
D21
G54
G290
G305
G256
D38F

Fig. 4.1, 4.2


A4 : 583.8 +- 0.5
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D6F
G296F
G709F
G563
D21
G54
G290
G305
G258
D36F

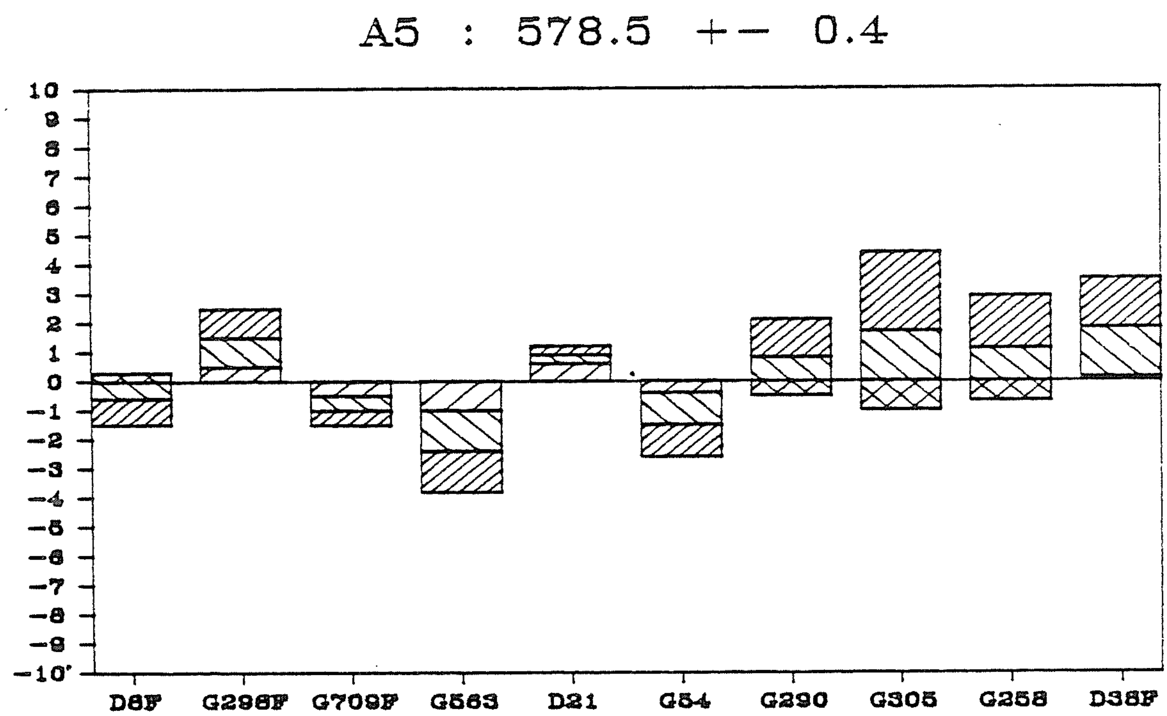
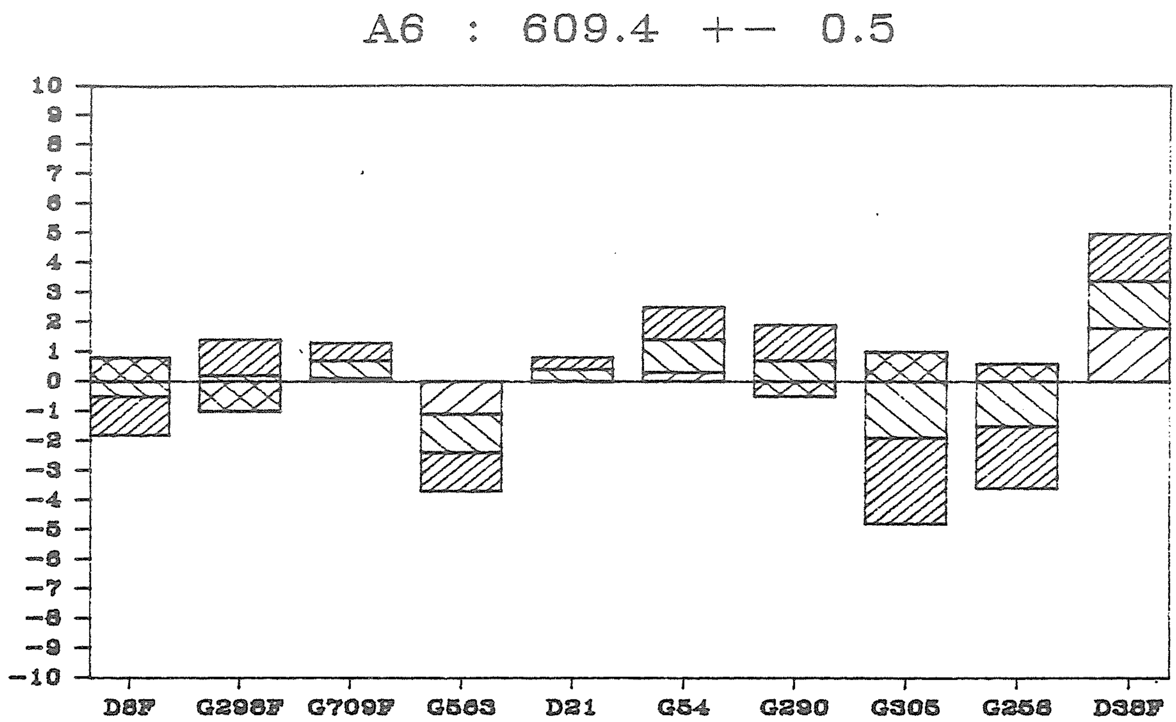

A5 : 578.5 +- 0.4
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D6F
G296F
G709F
G563
D21
G54
G290
G305
G258
D36F

Fig. 4.3, 4.4


A6 : 609.4 +- 0.5
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
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G290
G305
G258
D38F

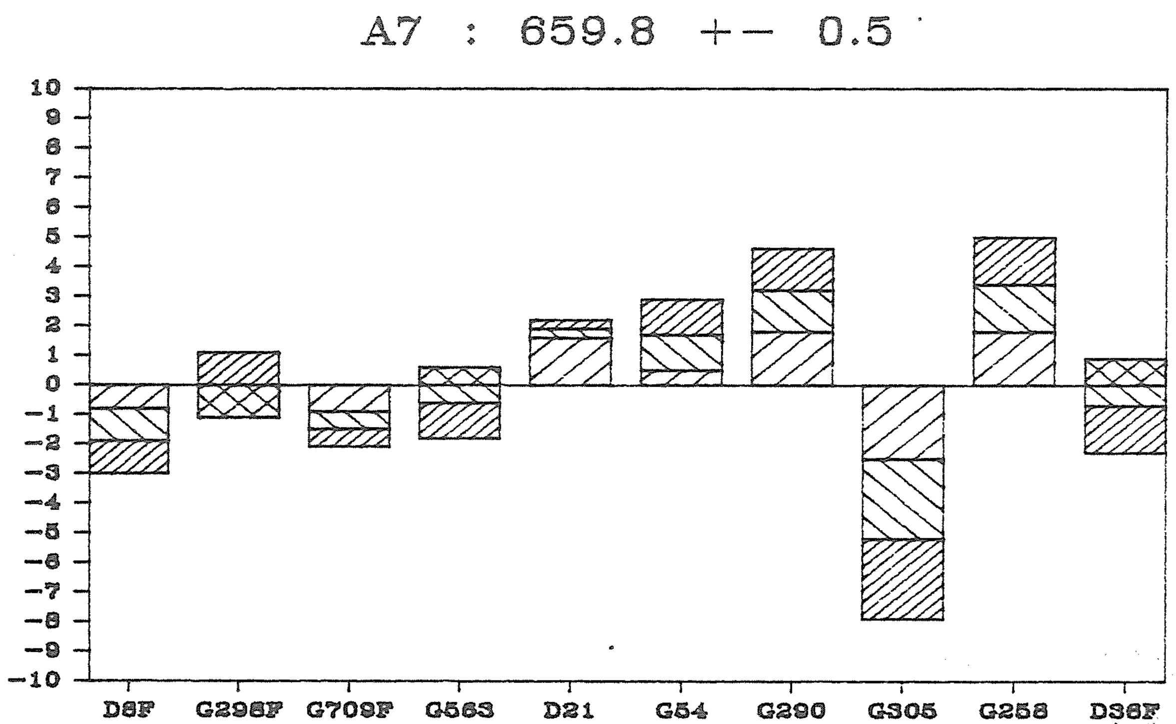
A7 : 659.8 +- 0.5
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
D8F
G298F
G709F
G563
D21
G54
G290
G305
G258
D38F

Fig. 4.5, 4.6

In Tab. 4.3 the results of different epochs are compared.The values of (Mathieu, Ogier, 1985) seem to be not directly comparable, because different gravimeters have been used.

Comparing the 1985 to the 1981 values it is obvious that changes in the differences up to 9 μgal occured. From relative measurements above it can not be decided how the absolute values changed. However, the average change in the ties to A1 is 4.15 μgal. Associating this change to A1 it could be assumed that the following changes in the values of g may have occured.

A1	A3	A4	A5	A6
4.2	+5,0	+1.8	-5.3	-1.6

Considering the changes in the gradients of Tab. 3.7 this is astonishing because e.g. on A3 and A6 the gradients increased by about 10 μgal but the difference between both stations decreased by 6.5 μgal.

In Tab. 4.3 the values of (Boulanger, 1985) including a correction to the 1981 differences to A 3 due to the excentric measurements of 11.3 μgal are included. There again is a good agreement with the 1984 value of Mathieu and Ogier, but the differences to the 1985 results are increased to about 20 μgal. This seems to be a rather large change of gravity and the source of it should be obvious.

5. Conclusions

The preliminary data evaluation including the observations of 10 LaCoste Romberg G- and D-meters resulted in adjusted gravity differencesin the 6 point network with errors less than 0.8 µgal. Gradients were determined with an average accuracy of 0.8 µgal. The values given here can be used as reference for the intercomparison of the different absolute apparatusses. Taking both the errors of the ties and of the gradients the differences of gravity at 1 m height can be determined with an r.m.s error of about 1.4 µgal. For further reduction of errors in future campaigns one should think of installing gravity stations on every site in about 1 m height for the duration of the relative measurements. In this way the errors of the gradient measurements could be eliminated to a great extent. The 1985 measurements are more accurate than those of 1981. This is mainly due to the fact that feedback instruments were used. From this preliminary relative measurements time-dependent changes of gravity between the sites can be found to be less than 10 µgal. However care must be taken because of the fact that in 1981 excentric measurements were used and that no height correction was applied.

In order to determine the actual value of gravity in Sèvres, all absolute measurements should be reduced e.g. to A1 using the results presented here. The agreement on the final value should then be found by the careful consideration of all systematic errors in the absolute measurements and a suitable weighting of these results.With respect to the present accuracy of absolute apparatusses a combined adjustment together with relative measurements seems to be not necessary.

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Appendix

A.1 Participants at BIPM in S è v r e s July 3 to July 7, 1985

Institute		Instrument	Observer
1.	Institut für Erdmessung Technische Universität Hannover	D8F with electrostatic feedback	Schnüll
2.	"	G298F with electrostatic feedback	Wenzel
3.	"	G709F "	Röder
4.	Institut für Angewandte Geodäsie, Frankfurt	G563	Richter
5.	"	D21	Beetz
6.	Land Survey of Sweden, Gävle	G290	Haller
7.	"	G54	Haller
8.	International Latitude Observatory, Mizusawa	G305	Hanada
9.	Institut für Physikalische Geodäsie, Technische Hochschule Darmstadt	D38F with electrostatic feedback	Becker
10.	"	G258	Becker
11.	Defense Mapping Agency	G131	Spita
12.	"	D79	Beruff
13.	Observatoire Royal Belgique, Bruxelles	D31F with electrostatic feedback	Poitevin
14.	"	G487F "	Zhou

A.2 Calibration Parameter

1. Feedback-Instruments

Instr.	E_1 mgal/v	E_2 $(mgal/v)^2$ 10^3
D8F*	1.0879	-6.30
G298F*	1.0567	+0.34
G709F*	0.9993	+0.49
D38F	1.2633	-0.46

$g = u * E_1 + u^2 * E_2$

g = Reading in mgal

u = Reading in Volt.

* Taken from (IFE, 1985)

2. Calibration Polynomials

Instr.	F	L 10^{-4}	Q 10^6	K 10^8
D21	1.12023	-13.37±1.5	+11.43±1.8	-2.7±0.6
G563	1.0283	0.55	-	-
G54	1.04654	0.9	-	-
G290	1.05588	1.2	-	-
G258	1.0666	0.37	-	-

$r_K = r * (F + L) + Q * r^2 + K * r^3$

r = Reading in Counter Units (=approx.mgal)

r_K= Corrected Reading in milligal

3. Periodical errors

Instr.	Period P c.u.	Ampl. A. gal	Phase O p
D 21	1.625	2.8±0.5	260±11
	3.25	1.5±0.5	65±18
	6.5	1.2±0.6	14±26
G563	1.00	1. ±1.	50±30
	7.333	5. ±1.	110±10
	36.666	4. ±1.	30±10
	73.333	12. ±1.	60±10
G54	1.00	3.6±0.9	38±14

$$r_K = r - A * \sin (360/p \; * r + \;)$$

Appendix B Review of measurements

Instrument	Date	Number of station occupations						S
		A	A3	A4	A5	A6	A7	
D8F	03.07.85	2	7		8	2	12	31
	04.07.85	2	3	1	2	2	1	11
	05.07.85	2	-	-	2	4	-	8
	06.07.85	7	10	5	11	3	2	38
G709	03.07.85	8	9	-	6	5	11	39
	04.07.85	3	2	3	2	2	3	15
	06.07.85	6	6	12	12	5	4	45
G563	04.07.85	6	4	-	6	6	4	26
	05.07.85	2	2	2	2	2	3	13
	06.07.85	4	4	2	2	3	4	19
D21	03.07.85	3	3	-	2	2	2	12
	04.07.85	3	2	-	2	2	2	11
	06.07.85	3	-	6	3	-	-	12
G54	03.07.85	2	2	-	2	3	2	11
	04.07.85	2	2	2	3	2	2	13
	06.07.85	3	3	2	2	2	2	14
G290	03.07.85	2	2	-	2	3	2	11
	05.07.85	2	2	2	3	2	2	13
	06.07.85	3	3	2	2	2	2	13
G305	03.07.85	2	2	-	2	2	3	11
	04.07.85	2	2	3	2	2	2	13
D381	04.07.85	2	2	3	2	2	2	13
	05.07.85	2	2	3	2	2	2	13
not used	(03.07.85	3	2	-	3	2	2	12)

GRAVIMETRY WITH AN ELECTROSTATIC FEEDBACK SYSTEM

by R.H. Röder, M. Schnüll and H.-G. Wenzel

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Abstract

One year experiences with an electrostatic feedback system for LaCoste-Romberg gravity meters (SCHNÜLL et al. 1984), implemented in 7 instruments, are reported. Application of the feedback system for the determination of screw errors, gravity gradients, non-linear calibration terms for model D meters and earth tide recording are described. Problems are discussed and further improvements are proposed.

1. Introduction

HARRISON and SATO 1983 have shown, that an electronic feedback system can be applied to LaCoste-Romberg (LCR) model D and G gravity meters, by simply attaching the feedback circuit to already available connections on the capacitive position indicator (CPI) board. The feedback circuit generates two voltages applied to the fixed plates of the CPI capacitor, which hold the gravimeter's beam in his zero position by electrostatic force. The electronic feedback system is a priori non-linear, because the electrostatic force is proportional to the square of the voltage applied to the capacitor's plates. By applying two bias voltages, the feedback system can be linearized, even if the zero position of the beam is not exactly centered between the capacitors's fixed plates. The major advantage of the feedback system is the independence of it's sensitivity from tilt, the much easier frequency transfer function of the feedback instrument due to the elimination of hysteresis effects of the spring, and the practical independence of the frequency transfer function from tilt. This allows the observation of small gravity differences without using the gravimeter's screw, and better accuracy of earth tide recording, because the calibration of the electronic feedback system is stable. The major disadvantage of the development made by HARRISON and SATO to linearize the feedback is, that it can be applied only for small eccentricities, i.e. small deviations of the beam's zero position from the center between the capacitor's fixed plates. In practice, eccentricities up to 50 % have been found (e.g. BECKER 1984), and thus not all LCR model G or D meters can be equipped with an electronic feedback system applying the HARRISON and SATO method.

SCHNÜLL, RÖDER and WENZEL 1984 have published an improved electronic feedback system for LCR gravity meters (abbreviated as SRW or SRW system in the following), which can compensate large eccentricities. Additionally, a better output filter circuit has been constructed, generating +/- 0.5 microgal reading precision under normal conditions at 40 sec delay time. The SRW system is operated from the gravimeter's 12 V battery, and because of it's small size (72 mm x 50 mm x 18 mm) and in order to provide thermal protection, it is installed directly in the gravimeter's box.

Meanwhile the SRW system has been successfully installed in LCR gravity meters D-8, D-14, D-23, D-38, G-79, G-298 and G-709. The range of SRW was found to be between +/- 2 mgal and +/- 10 mgal, depending on the specific LCR meter. Experiences, applications and problems with SRW systems are reported in the following.

2. Calibration and Application of SRW Electrostatic Feedback System

2.1. Calibration

The linearization of the SRW system was done by comparison of it's output voltages with gravimeter's screw readings at three positions of the SRW measurement range and adjusting the electronics. Right after that procedure a calibration was performed using at least three stations (A, B and C), selected with respect to the SRW range from the vertical calibration line in a multi-storey building, which is part of the "Gravimeter Calibration System Hannover" (KANNGIESER et al. 1982). The observation of the three possible differences AB, BC and AC five times each took approximately 1.5 hours and resulted in an accuracy of the calibration better than 0.05%. To check the parameters and to increase the accuracy, a second set of observations has been performed using three additional stations. The quadratic term was found in any case to be smaller than 0.5 microgal at +/- 1 Volt. Taking measurements symmetrically to an output voltage of zero, this term as well as it's uncertainty cancels out. In any other case it can be easily corrected in course of the data processing and there is no reason to invest more effort in the linearization of the electronics. Linear discrepancies between the mechanical measuring system and the SRW system occured in the order of several parts in 10^{-3} up to 3 parts in 10^{-2}, which means that a calibration of electrostatic feedback systems can not be performed with the gravimeter's screw as reference.

2.2 Determination of Non-Linear Calibration for LCR-D Meter

For the determination of calibration functions for LCR-D meters three different methods could be distinguished up to now:

- 1. The "Cloudcroft Junior method": Readings with an auxiliary mass added to and removed from the beam gives relative scale factors. The calibration is completed by observation of a known gravity difference in the field (KRIEG 1981).

- 2. The "single difference method": A well known gravity difference is measured at different reset screw positions (GÖTZE and MEURERS 1983).

- 3. The "calibration line method": Observations on a suitable calibration line covering the measuring range of the gravity meter are used (KANNGIESER, RÖDER and WENZEL 1983).

With the calibrated SRW system a fourth method is now available for the calibration of the mechanical measuring system of the meters. Within the SRW range, the gravimeter's screw readings can be compared with the calibrated SRW readings. In order to cover the whole range of the gravimeter's screw, numerous resets have to be carried out. We have calibrated LCR D-23 at 40 different positions of the 200 CU range of the mechanical system, shifting it along the SRW range in 5 CU intervals. This procedure lasted only 12 hours; the results can be well approximated by a third order polynomial (Fig. 2.1). The comparison with a calibration function for D-23 determined in 1984 after damaging the meter by a car accident shows an expected linear discrepancy of 0.25 % (see 2.1). To overcome this problem, two large gravity differences (70 resp. 90 mgal) were measured at the Hannover-Harz calibration line with the mechanical system at different reading positions. A common adjustment of these observations with the SRW measurements yielded in the calibration function. A comparison with the calibration function determined one year ago using a combination of "single difference" and "calibration line" method (Fig. 2.1) shows discrepancies in the 100... 200 CU range, which are probably after-effects of the car accident. Further investigations will be carried out.

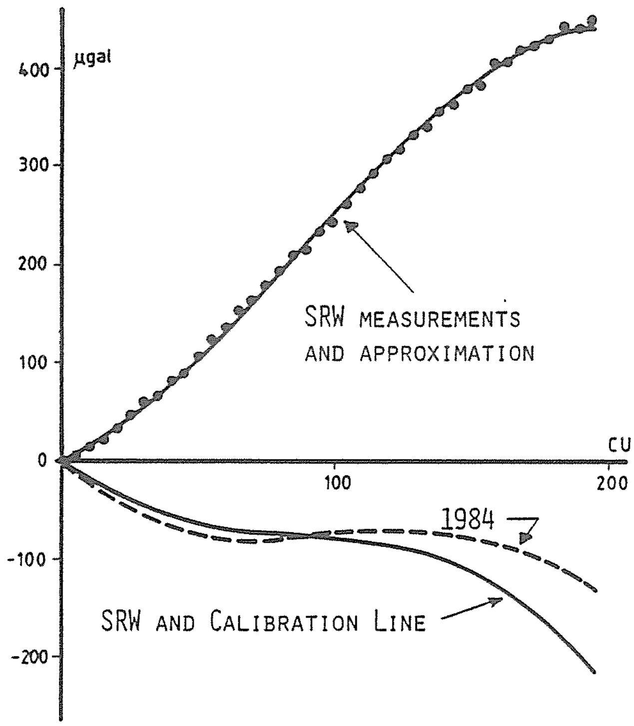

Fig. 2.1 Calibration Function of LCR D-23

2.3 Determination of Cyclic Errors

From the construction of LCR gravity meters, cyclic errors can be expected. The periods are:

- Model G: 1.00, 7.88 (7.33), 35.47, and 70.94 (73.33) Counter Units. (1 Counter Unit (CU) = 1 mgal). Values given in brackets are valid for LCR G-458 and the following G-meters.
- Model D: 0.100, 0.722, 1.625, and 3.25 CU (LACOSTE 1984).

With SRW system, these periods except of the 35.47 and 70.94 (73.33) CU period can be determined. The time required for the measurements is ten times less compared to that necessary for the "calibration line method". For model G the amplitudes and phases agreed within their r.m.s. errors with the values determined on the calibration line (see Fig.2.3.1 and 2.3.2). The results for the 3.25 CU period of D-23 varied, depending on the actual screw position (Table 2.3.1). This effect was never detected before. It can be explained by unperfect construction of the screw and may also occur for the 70.94 (73.33) CU period of model G (LACOSTE 1984). Further investigations are urgently necessary.

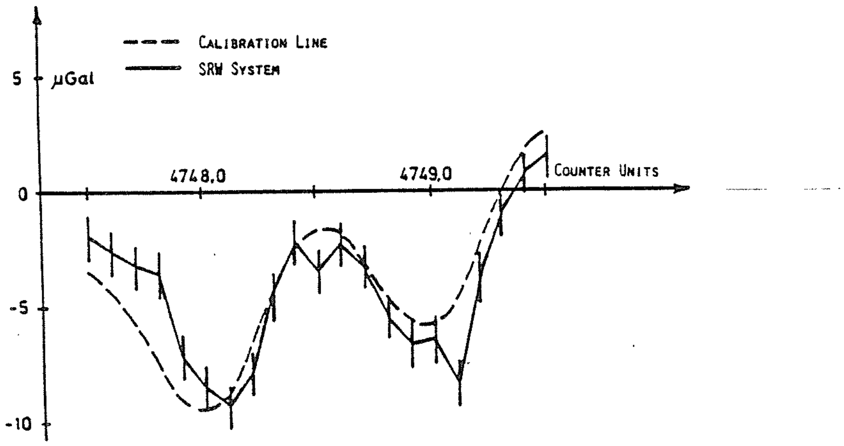

Fig. 2.3.1: 1.00 CU Cyclic Error of LCR G-79

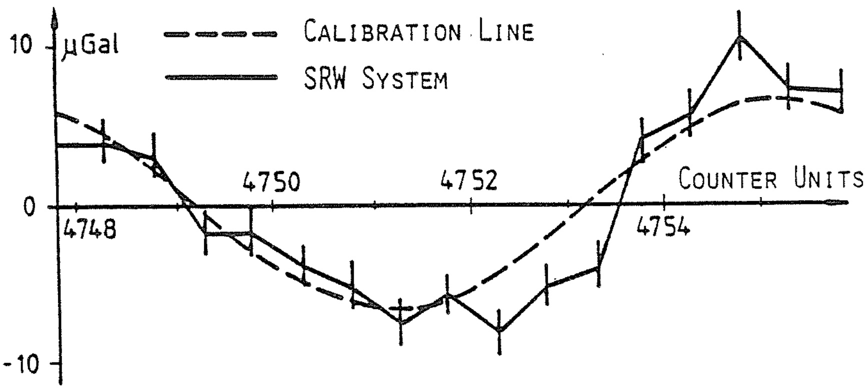

Fig. 2.3.2: 7.88 CU Cyclic Error of LCR G-79, (1.00 CU Error Removed)

Screw position [CU]	Amplitude [Microgal]	Phase [Deg]
5	1.5 + 0.9	272 + 25
50	2.9 + 0.9	240 + 13
100	2.8 + 1.2	269 + 17
150	4.8 + 0.7	223 + 6
195	5.2 + 0.9	190 + 7

Table 2.3.1: 3.25 CU Cyclic Error of LCR D-23 at Different Screw Positions

2.4 Determination of Gravity Gradients

The accurate measurement of small gravity differences and vertical gravity gradients is necessary for the combination of absolute and relative observations. Comparison of vertical gradients repeatedly measured in conventional manner showed, that several microgal errors can occur, even if a large number of measurements has been carried out (SCHNÜLL et al. 1984). Remeasurements in the absolute stations 21639A Hamburg and 21520G Braunschweig with several LCR-meters each time (Tab. 2.4.1) yielded deviations up to 11 resp. 24 microgal compared to those determined in course of the absolute measurements (CANNIZZO et al. 1978). From numerous test measurements in Hannover with 6 LCR gravity meters under good environmental conditions and correction of all known instrumental errors it is concluded that the accuracy of vertical gradients from one conventional observation set is not much better than +/- 5 microgal, whereas gravity gradients observed with different SRW system in the same stations agreed within +/- 1...2 microgal (Table 2.3.1). The time required for a set of 10 SRW measurements (gravity differences) was typically 45 minutes.

------ Conventional observations ------				----- SRW observations ------		
Station	Date	Instr.	Gradient [Microgal/m]	Date	Instr.	Gradient [Microgal/m]
21639 A	2/77	D-18	274 + 3	6/85	D-8	287.1 + 0.4
Hamburg	7/77	G-79,G-85	284 + 5	6/85	D-23	285.4 + 0.5
		G-87,G-432		6/85	D-23	286.7 + 0.5
	2/83	D-14,D-23	285 + 2	6/85	G-298	287.5 + 0.6
		G-79		6/85	G-709	286.9 + 0.7
	10/83	G-79,G-298	283 + 2			
		G-709			Mean:	286.7 + 0.4
21520 G	2/77	D-18	267 + 3	6/85	D-8	284.7 + 0.4
Braun-	7/77	G-79,G-85	296 + 5	6/85	G-298	285.8 + 0.8
schweig		G-87,G-432		6/85	G-709	285.3 + 0.5
	2/83	D-14,D-23	280 + 4			
		G-79			Mean:	285.3 + 0.4
	10/83	G-79,G-298	291 + 1			
		G-709				

Table 2.4.1: Gravity Gradients

2.5 Gravimetric Earth Tide Observations

As a first test, gravimetric earth tide recording with SRW installed in LCR gravity meter D-14 has been performed from April 9 to April 28 1985. The instrument was simply installed on concrete pillar No. 102 of station Hannover and connected to a digital voltmeter with 5 1/2 digit resolution. A mini computer performed the readout of the voltmeter, the data proces-

PROGRAM ETG CHOJNICKI-WENZEL

GRAVIMETRIC EARTH TIDE STATION NO. 0709 HANNOVER W.GERMANY
52.387N 9.712W H55M P2M VERTICAL COMPONENT
INSTITUT FUER ERDMESSUNG UNIVERSITAET HANNOVER
GRAVIMETER LACOSTE-ROMBERG NO. D14 PROF. TORGE HANNOVER
1985.04.09 - 1985.04.28
INSTALLATION . R.H.ROEDER/H.-G.WENZEL
MAINTENANCE H.-G.WENZEL
INSTRUMENTAL PHASE LAG NOT CORRECTED FOR 0.06 DEG O1, 0.12 DEG M2
AIR PRESSURE NOT CORRECTED

NUMBER OF DAYS 17.1

ESTIMATION OF NOISE BY LEAST SQUARES METHOD
INFLUENCE OF AUTOCORRELATION NOT CONSIDERED

ADJUSTED TIDAL PARAMETERS

NR.	FROM	TO	WAVE	AMPL. MYGAL	SIGNAL/ NOISE	AMPL.FAC.	PHASE LAG DEG
1	129	193	Q1	6.7	172.4	1.1724	1.00
						0.0068	0.40
2	194	219	O1	34.7	640.8	1.1535	0.41
						0.0018	0.11
3	220	241	M1	2.6	76.7	1.1044	-2.74
						0.0144	0.83
4	242	274	P1S1K1	48.1	711.8	1.1388	0.18
						0.0016	0.09
5	275	296	J1	2.8	78.9	1.1834	0.52
						0.0150	0.85
6	297	333	OO1	1.5	89.0	1.1883	1.22
						0.0133	0.77
7	334	374	2N2	1.0	64.8	1.1670	0.58
						0.0180	1.03
8	375	398	N2	6.3	171.7	1.1846	2.46
						0.0069	0.40
9	399	424	M2	33.2	697.8	1.1862	1.55
						0.0017	0.10
10	425	441	L2	0.9	33.1	1.1190	2.41
						0.0338	1.94
11	442	488	S2K2	15.5	566.7	1.1900	0.48
						0.0021	0.12
12	489	505	M3	0.4	30.2	1.1460	0.76
						0.0380	2.18

MEAN SQUARE ERROR 0.351 MICROGAL DEGREE OF FREEDOM 386

Table 2.5.1: Adjusted Tidal Parameters from LCR-D14

sing (calibration, smoothing by numerical filtering, computation of reference tide and drift, adjustment of tidal parameters), and data recording on floppy disc.

The adjusted tidal parameters from 17 day observations, applying CHOJNICKI 1973 analysis method, are given in Table 2.5.1. The standard deviation of 0.35 microgal for hourly readings is much better than ever obtained in station Hannover with non-feedback LCR gravity meters and analog recording (0.56 ... 0.75 microgal, see TORGE and WENZEL 1977), although air pressure correction has not yet been applied to the LCR-D14 observations. The adjusted tidal parameters from 17 days LCR-D14 observations are compared in Table 2.5.2 with mean values for station Hannover obtained from 9 different gravity meters with totally 1936 observation days (TORGE and WENZEL 1977). The agreement is better than 1% and 0.5 degree, which is quite good considering the short observation period.

Wave Group	Mean Value		LCR-D14		Difference	
	Ampl. Fact.	Phase [Deg]	Ampl. Fact.	Phase [Deg]	Ampl. Fact.	Phase [Deg]
O1	1.1594	-0.08	1.1535	0.41	0.0059	-0.49
	0.0026	0.10	0.0018	0.11		
P1K1	1.1485	0.03	1.1388	0.18	0.0097	-0.15
	0.0023	0.12	0.0016	0.09		
M2	1.1906	1.60	1.1862	1.55	0.0044	0.05
	0.0014	0.06	0.0017	0.10		
S2K2	1.1925	0.37	1.1900	0.48	0.0025	-0.11
	0.0022	0.15	0.0021	0.12		

Table 2.5.2 : Comparison of LCR-D14 Earth Tide Results with Mean Values from Nine Gravity Meters with totally 1936 Observation Days for Station Hannover

3. Problems and Further Improvements

3.1 Gravity Meter with Large Asymmetry

HARRISON and SATO 1983 and BECKER 1984 claimed that it is not possible to linearize gravity meters with large eccentricity of the beam plate at CPI zero position applying the HARRISON and SATO method. Seven SRW systems have been installed successfully in LCR gravity meters using the method described in SCHNÜLL et al. 1984. Two of the instruments had a large eccentricity (delta/d up to -0.413). In order to get a better knowledge about the differences between these two methods and to optimize the adjustment of the individual SRW systems, a computer program has been written. It simulates the plate drive circuits, which are similar in both electronics. The program gives a plot of the two plate voltages U1 and U2 and the relative feedback force F as function of the feedback voltage e (see SCHNÜLL at al. 1984, Fig. 2.1).

Fig. 3.1.1 shows the behavior of a non-linearized SRW feedback in a LCR gravity meter with a delta/d of -0.413. In Fig. 3.1.2 the HARRISON and SATO method was used to linearize the instrument. Besides a wide range of linearity, there is a small range where the beam will be still zeroed by the feedback force F, but there is no linearity with e. This range always appears and depends on the delta/d of the specific instrument. In addition there is a 20% offset and 20% asymmetry of range.

Fig. 3.1.3 shows the same instrument linearized with the SCHNÜLL et al. method. There is linearity over the whole range and no offset - but 20 % asymmetry of range and a quite small range of F. In Fig. 3.1.4 the feedback is optimized for maximum range of F. There is linearity over the whole range, no asymmetry and the maximum range of F - but an offset of about 40 % .

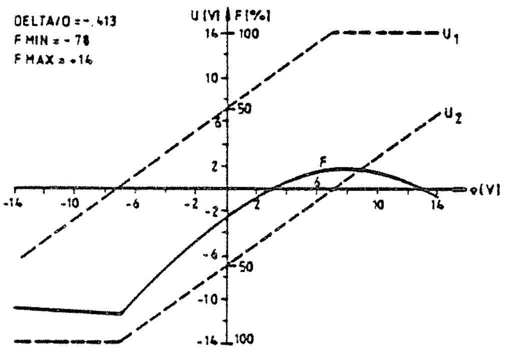

Fig. 3.1.1

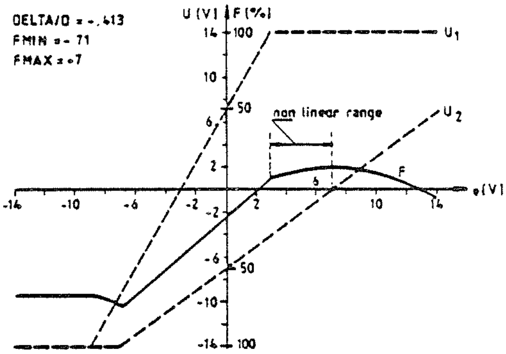

Fig. 3.1.2

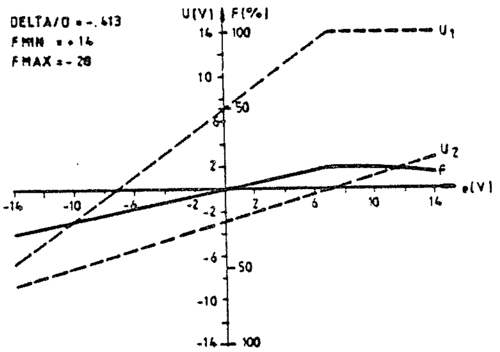

Fig. 3.1.3

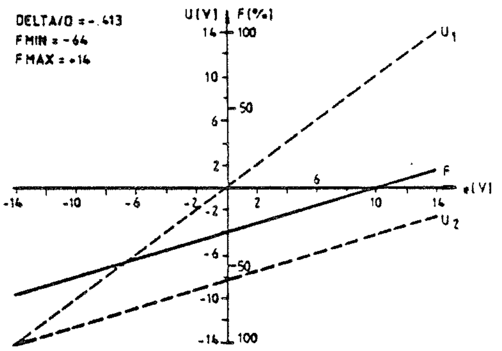

Fig. 3.1.4

From the computer simulations, we conclude:

- even LCR gravity meters with large eccentricities can be linearized.
- the maximum feedback range can be achieved under acception of an offset, but the offset may cause trouble for the handling of "sticking" instruments.
- the offset can be avoided under acception of an asymmetric and smaller feedback range, but asymmetry causes more expense for the calibration.

3.2 Long Term Stability

Because a variation of the calibration factors of the feedback systems up to $5*10^{-3}$ has been detected, the stability of the electronical parts has been investigated. By using a heater box the working condition (50 o C) of the electronic circuit was simulated. Following variations were found after one week:

+/- 1...$2*10^{-3}$ for the voltage regulators 78L05 and 79L05,
+/-1...$2*10^{-3}$ for the trimpots,
- $2*10^{-3}$ for the metal film resistors.

The trimpots can be replaced by metal film resistors. The influence of the metal film resistors is small, because they are drifting all in the same direction and the circuit compensates their drift. So the most critical parts are the voltage regulators. Tests with several other regulators or voltage references showed, that the specification given in the data sheets (if they are given at all) are mostly too optimistic. Only one exception was found with the LM399 reference diode, which has less then $3*10^{-6}$ /week long term drift. In order to avoid time variations of the SRW linearity, both plate drives should use the same voltage reference.

3.3 Differential Input

Older CPI cards have an unprotected differential output and can be damaged by connecting to battery ground. Next version of SRW electronics will have an differential input circuit.

3.4 Over-voltage Protection

The most users of LCR gravity meters charge the battery in parallel to the instrument. So the high charging voltage (up to 15 V) exceeds the maximum input voltage of the PID 25B DC-DC converter and may damage it . The use of a 12 V PCD 1220 constanter between the battery and the gravity meter and an additional over-voltage switch-off in the SRW circuit will solve this problem in the future.

3.5 Range

The range of SRW implemented in 7 instruments, was found to be between +/- 2 and +/- 10 mgal, due to the different physical properties of LCR instruments. For some special applications, a +/- 2 mgal range is too small. A version of SRW with a four times larger range is planned for the future.

3.6 Voltmeter

To utilize the full range of todays and future SRW systems, voltmeters with an accuracy of at least 0.01% should be used. Battery powered, hand-held voltmeters with an accuracy of better than 0.05 % are not available at present, which restricts some field applications of SRW.

Conclusions:

The experiences with SRW feedback systems have shown, that a remarkable improvement for the determination of small gravity differences could be achieved. There exist still problems, expecially in the long term stability of the calibration due to aging of the electronic parts, which hopefully will be solved in the future. A new version of SRW feedback electronics, which has been modified regarding all possible improvements described in 3.2 ... 3.4, is currently under test.

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AN ESTIMATION ON THE NEEDED NUMBER OF STATIONS IN THE INTERNATIONAL ABSOLUTE GRAVITY BASE NET

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ABSTRACT

Authors demonstrate by model computations that about 36 absolute gravity stations in a global distribution of 6o^{o}x3o^{o} are needed at minimum to determine the global features of the assumed time variations of the earth's gravity field. More reliable numeric results can be achieved by a 3o^{o}x3o^{o} net of 84 absolute stations and a spherical harmonic expension to degree and order 6,6. About 126 stations in a 3o^{o}x2o^{o} distribution and a computation to 8,8 give very good global results which can be improved only in regions by detailed local researches beside the global one. Computerprogram for future computation of the IAGBN observations has been developed.

1. Introduction

One of the main goals of the geodynamic researches is the investigation on the recent crustal /or plate/ movements of the earth. The determination of these is based - according to the recommendation No 11 of the International Association of Geodesy, Hamburg 1983 - on the observed time variation of the absolute gravity and that of the height above sea level in stations favourably distributed around the globe.

The Special Study Group 3.87 IAG has got the task of the development of such a new world absolute gravity base net for monitoring of the time variation of the earth's gravity field with determination of its geodetic effects such as

- the variation in the gravity potential,
- the vertical displacement of the equipotential surfaces,
- changes in the direction of the local vertical i.e. the variation in the astronomic coordinates,
- the ratio between gravity and height variation, etc.

The first step of the solution of this task is the network design [Boedecker 1983-85]. For this aim appropriate model computations for the time variation of the earth's gravity field can be useful in estimating the needed number and distribution of the stations to be observed.

2. Basic formulae

After having observed and reobserved the stations of the IAGBN we shall have observations δg_i for gravity variations and δH_i for variations in height of the stations for a future period of time, elapsed between the epochs of the observations with i=1,2,..j, being j the number of IAGBN stations. From these two sets of data the boundary values

$$\left[\delta g - \frac{\partial g}{\partial H} \delta H\right]_i \doteq \left[\delta g + \frac{2g}{R} \delta H\right]_i \qquad /1/$$

can be constructed.

The time variation of the earth's gravity field can easily numerically be described by the variation δW in the geopotential as a function of the location $\vec{r}=\vec{r}$ /r, ϑ , λ / of the station, being r, ϑ , λ the spherical coordinates. This function can be given in two different forms with the approximation $r \doteq R$ for the earth's surface, either as Stokes' integral formula for time variations /as for example in [Biró 1983]/

$$\delta W / \vartheta , \lambda / = \frac{R}{4\pi} \iint_{\sigma} \left[\delta g - \frac{\partial g}{\partial H} \delta H\right] S[\psi] \, d\sigma \qquad /2/$$

or as a series of spherical harmonics [Thông 1985.b, Biró and Thông 1985]

$$W / \vartheta , \lambda / = \frac{kM}{R} \sum_{n=2}^{\infty} \sum_{m=0}^{n} \left[\delta \overline{C}_{nm} \cos m\lambda + \delta \overline{S}_{nm} \sin m\lambda\right] \overline{P}_{nm}[\cos \vartheta] \qquad /3/$$

being R the mean earth's radius, $S[\psi]$ the Stokes' function, σ the unit sphere, kM the geocentric gravitational constant, $\overline{P}_{nm}$ the fully normalized associated Legendre function of degree n and order m finally $\delta\overline{C}_{nm}$ and $\delta\overline{S}_{nm}$ the time variations of the fully normalized spherical harmonic coefficients of the geopotential.

Stokes' /2/ integral formula can practically be solved for δW with the observed boundary values /1/ by numeric integration for the surface of the unit sphere i.e. for the earth's surface. The practical use of the spherical harmonic expansion /3/ needs the knowledge of the variation in the harmonic coefficients. These latters can practically be determined with the observed boundary values /1/ by the least square solution of the observation equations

$$\left[\delta g - \frac{\partial g}{\partial H}\delta H\right]_i = \frac{kM}{R^2}\sum_{n=2}^{k} /n-1/ \sum_{m=0}^{n}\left[\delta\overline{C}_{nm}\cos m\lambda_i + \delta\overline{S}_{nm}\sin m\lambda_i\right]\overline{P}_{nm}[\cos\vartheta_i] \qquad /4/$$

being k a finite number of degree and $/k+1/^2-4 \leq j$ in order not to have more unknowns as equations.

With known variation in geopotential the geodetic effects of the time variation of the earth's gravity field can be computed as [Biró at al.1986]

$$\begin{bmatrix} \delta\Phi \\ \delta\Lambda \\ \delta N \end{bmatrix} = \begin{bmatrix} \delta\Theta_{\Phi} \\ \dfrac{1}{\cos\Phi}\,\delta\Theta_{\Lambda} \\ \dfrac{1}{g}\,\delta W \end{bmatrix} \qquad /5/$$

being $\delta\Phi$, $\delta\Lambda$ the time variation in the astronomic latitude and longitude, δN the variation in the equipotential surfaces /i.e. in the geoidal undulations/,

$$\begin{bmatrix} \delta\Theta_{\Phi} \\ \delta\Theta_{\Lambda} \end{bmatrix} = \frac{1}{g} \begin{bmatrix} +\dfrac{1}{R}\,\dfrac{\partial}{\partial\vartheta}\,\delta W \\ -\dfrac{1}{R\sin\vartheta}\,\dfrac{\partial}{\partial\lambda}\,\delta W \end{bmatrix} \qquad /6/$$

the N-S and the E-W components of the variation in the direction of the local vertical.

The time variation in gravity is

$$\delta g = -\left[\frac{\partial}{\partial r}\,\delta W + \frac{2}{R}\,\delta W\right] + \frac{\partial g}{\partial H}\,\delta H\,. \qquad /7/$$

The true surface movement $\delta\vec{v}$ for geodynamic researches can be computed as

$$\delta\vec{v} = \begin{bmatrix} \delta v_1 \\ \delta v_2 \\ \delta v_3 \end{bmatrix} = \begin{bmatrix} R\,[\,\Phi_2 - \Phi_1 - \delta\Phi\,] \\ R\,[\,\Lambda_2 - \Lambda_1 - \delta\Lambda\,]\,\cos\Phi \\ H_2 - H_1 + \delta N \end{bmatrix} = \qquad /8/$$

$$= \langle R,R,1\rangle \begin{bmatrix} \Phi_2 - \Phi_1 - \delta\Theta_\Phi \\ [\Lambda_2 - \Lambda_1]\cos\Phi - \delta\Theta_\Lambda \\ H_2 - H_1 + \delta N \end{bmatrix}$$

with δv_1, δv_2 the horizontal components and δv_3 the vertical component of the true surface movement, Φ_1, Φ_2; Λ_1, Λ_2 and H_1, H_2 the astronomic latitude, longitude and height above sea level of the station in epochs 1 and 2.

3. Model computations

In the lack of observations simulated gravity variations has been computed by an accepted realistic physical model. /The variation in height has been neglected in the first approximation./ The principal idea of the model for gravity variation is given by [Barta 1979] assuming that the angular velocity of the displacement of the deep seated mass inhomogenities is the same as the westward drift of the earth's magnetic field /i.e. o,2 %/a/. The deep seated inhomogenities can be separated from the geopotential either by the filtering effect of the increasing height above the earth's surface or by the decomposition of the spherical harmonic expansion of the geopotential into parts $n < 6$ and $n \geqq 6$ [Kaula 1972]. One gets nearly the same result on both way [Thông 1985 a] .

With simulated gravity variations the time variation of the gravity field and its geodetic effects /5/, /6/ and /7/ have been computed on both ways i.e. by using Stokes' /2/ integral formula [Weisz 1985, Biró at al. 1984] and the spherical harmonic expansions /3/ and /4/[Thông 1985.c] . The results have been compared to that of the model and root mean square deviations have been computed indicating the reliability of our computations. Time variations $\delta \dot{N}$, $\delta \dot{\Theta}_{\Phi}$, $\delta \dot{\Theta}_{\Lambda}$ and $\delta \dot{g}$ have been computed with different numbers and configurations /distributions/ of simulated stations.

The results are demonstrated in Table 1 and in Figures 1-4.

4. Conclusions

The magnitudes of the geodetic effects of the time variation of the earth's gravity field as computed by the modell assumed are $|\delta \dot{g}| < 300$ μgal/a, $|\delta \dot{N}| < 82$ cm/a and $|\delta \dot{\Theta}| < 0{,}1''$/a, maxima and minima of $\delta \dot{g}$, $\delta \dot{N}$ and $\delta \dot{\Theta}_{\Lambda}$ are near to the equator and the global distributions of them are nearly periodical in the longitude.

Numeric results computed by spherical harmonics are more reliable with the same number and global distribution of the simulated observations as that by Stokes' integral formula.

Therefore the former is more economic i.e. it needs less observed station for aiming a presumed reliability and it will be suggested for the future computations of the IAGBN. Computer program is ready for use.

The characteristic features of the global distribution and generally the order of magnitude of the vertical displacement of the equipotential surface at sea level can be determined by the repeated observation of a world-wide net consisting of about 36 absolute gravity stations /Variant 8/.

More reliable numeric results can be achived by an absolute gravity net consisting of about 84 stations in a constant $30^{\circ} \times 30^{\circ}$ distribution around the globe /Variant 6/.

A world-wide net of 126 stations in a $30^{\circ} \times 20^{\circ}$ distribution /Variant 3/ gives very good numeric results, which practically can not be improved even if 500 more stations would be observed. Anyway stations should be selected on and near to the equator. A higher reliability can be achieved only in regions by detailed local researches beside the global one.

Even if the figures of our numeric results were overestimated, a tenth or a hundredth part of the computed variations would be enough to be significant and the study of their global distribution can help us to a favourable choice of the locations of the IAGBN stations anyway.

Our computer program can be used for the future computations of the global geodetic effects of the time variation of the earth gravity field as soon as the results of the observation and the first reobservation of the IAGBN will be available.

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Table 1

Variant	Distribution	Number of stations	Stokes's integral $m_{\delta N}$ cm/a	Spherical harmonic expansion: Degree and order	$m_{\delta N}$ cm/a	$m_{\delta g}$ gal/a	$m_{\delta\Theta_\Phi}$ $1''.1o^{-3}$/a	$m_{\delta\Theta_\Lambda}$ $1''.1o^{-3}$/a
1	1o°x1o°	612	3	8,8	2,o	5,5	-	-
2	2o°x2o°	162	7	8,8	2,o	5,5	o,o	o,o
3	3o°x2o°	126	-	8,8	2,o	6,5	o,9	o,6
4	6o°x1o°	1o8	-	8,8	19,o	8o,o	17,5	18,8
5	4o°x2o°	9o	-	7,7	6,5	42,3	8,o	9,2
6	3o°x3o°	84	11	6,6	5,6	38,8	4,9	9,2
7	4o°x4o°	45	15	6,6	13,1	65,o	9,7	17,5
8					9,1	46,3	7,9	11,4
9	6o°x3o°	36	28	5,5	1o,5	52,7	9,o	13,3
1o			-		1o,9	53,4	8,8	13,7
11		36	-	5,5	19,7	8o,2	14,3	23,8
12	6o°x4o°	27	-	4,4	17,2	84,8	11,6	23,3

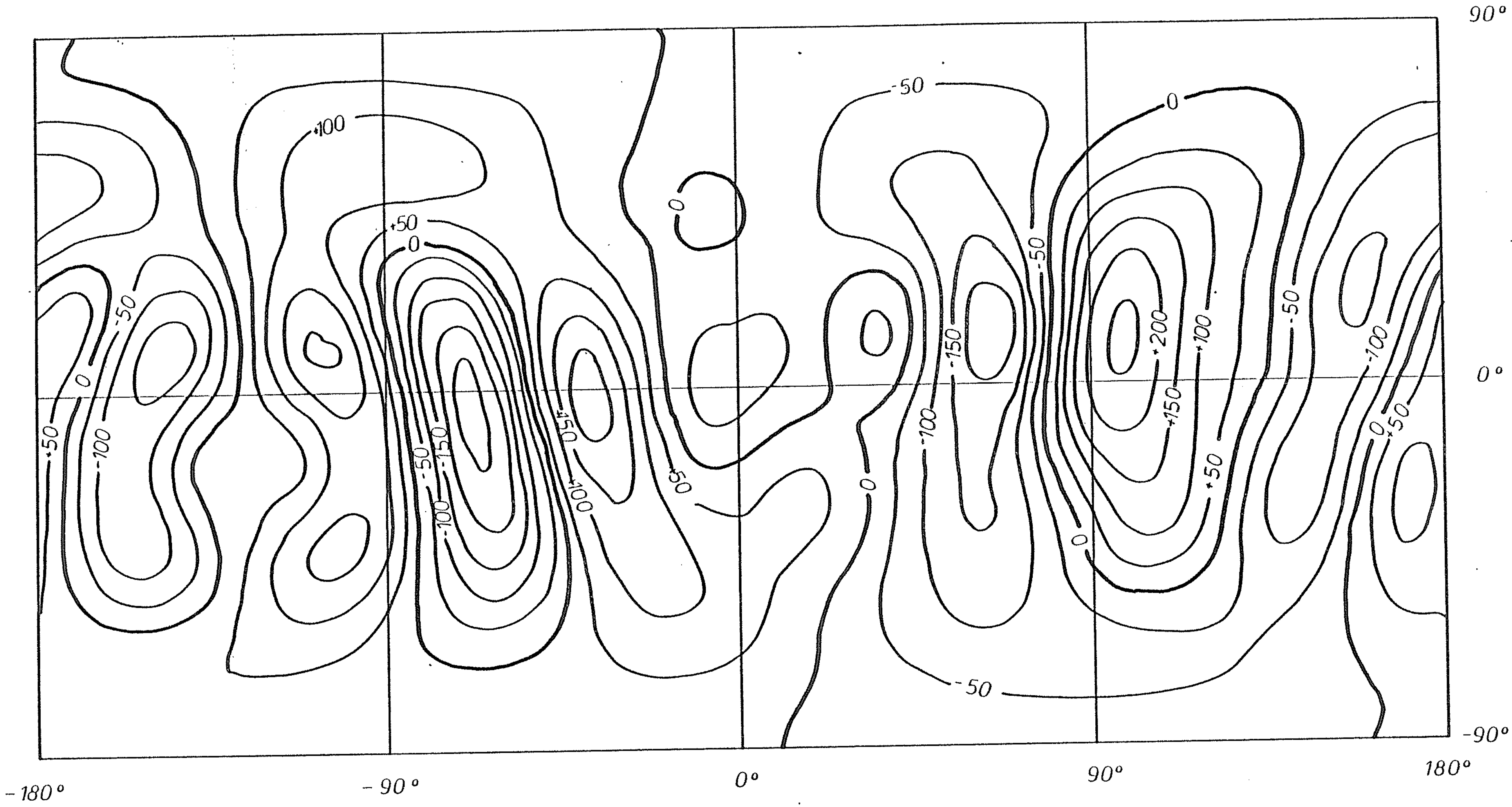

Figure 1. Gravity variation as computed by the model. Contour intervals 50 microgals/year (i.e. 50.10^{-8} ms^{-2}/a)

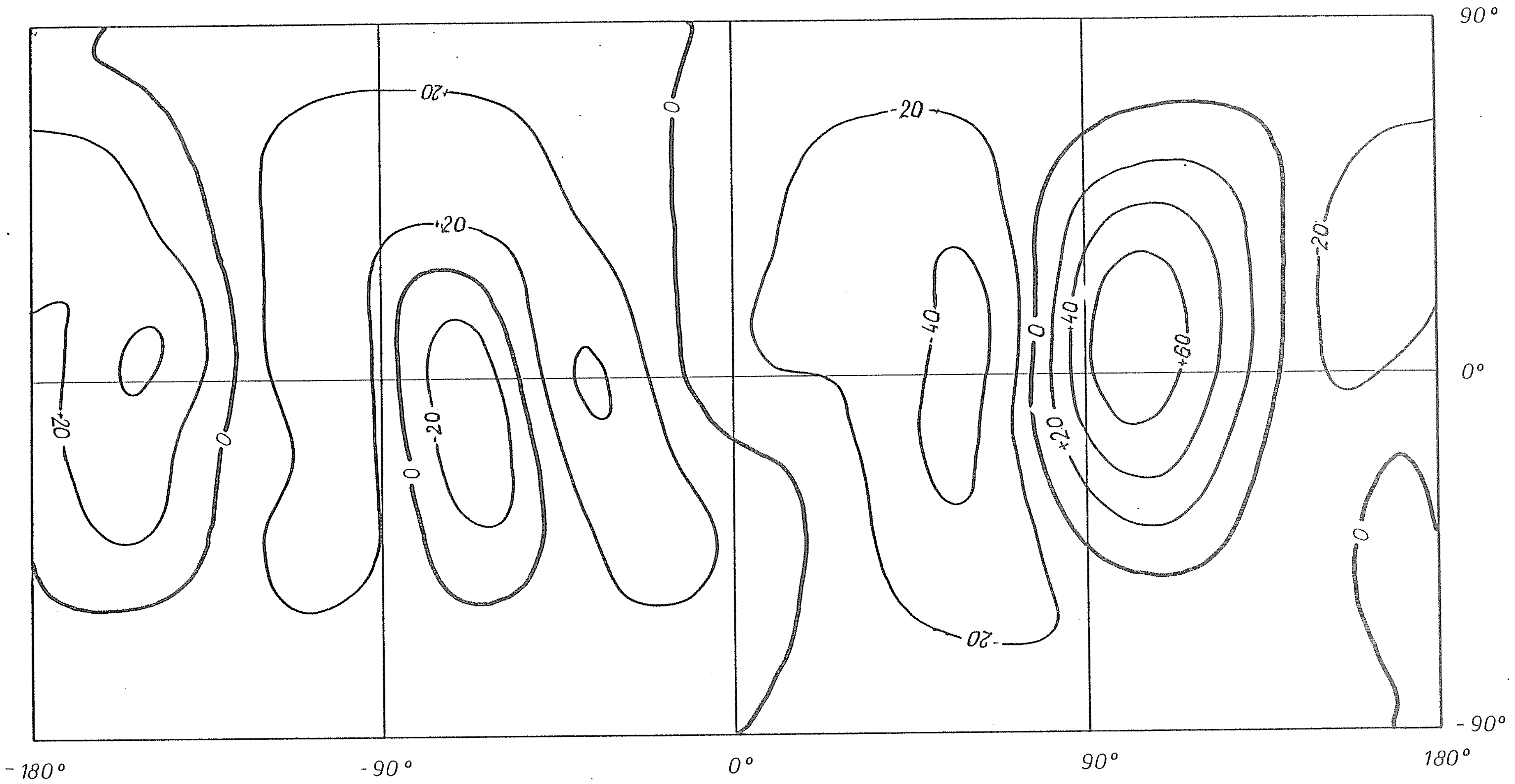

Figure 2. Time variation in the undulations of the geoid according to Barta.

Contour intervals 20 cm/year

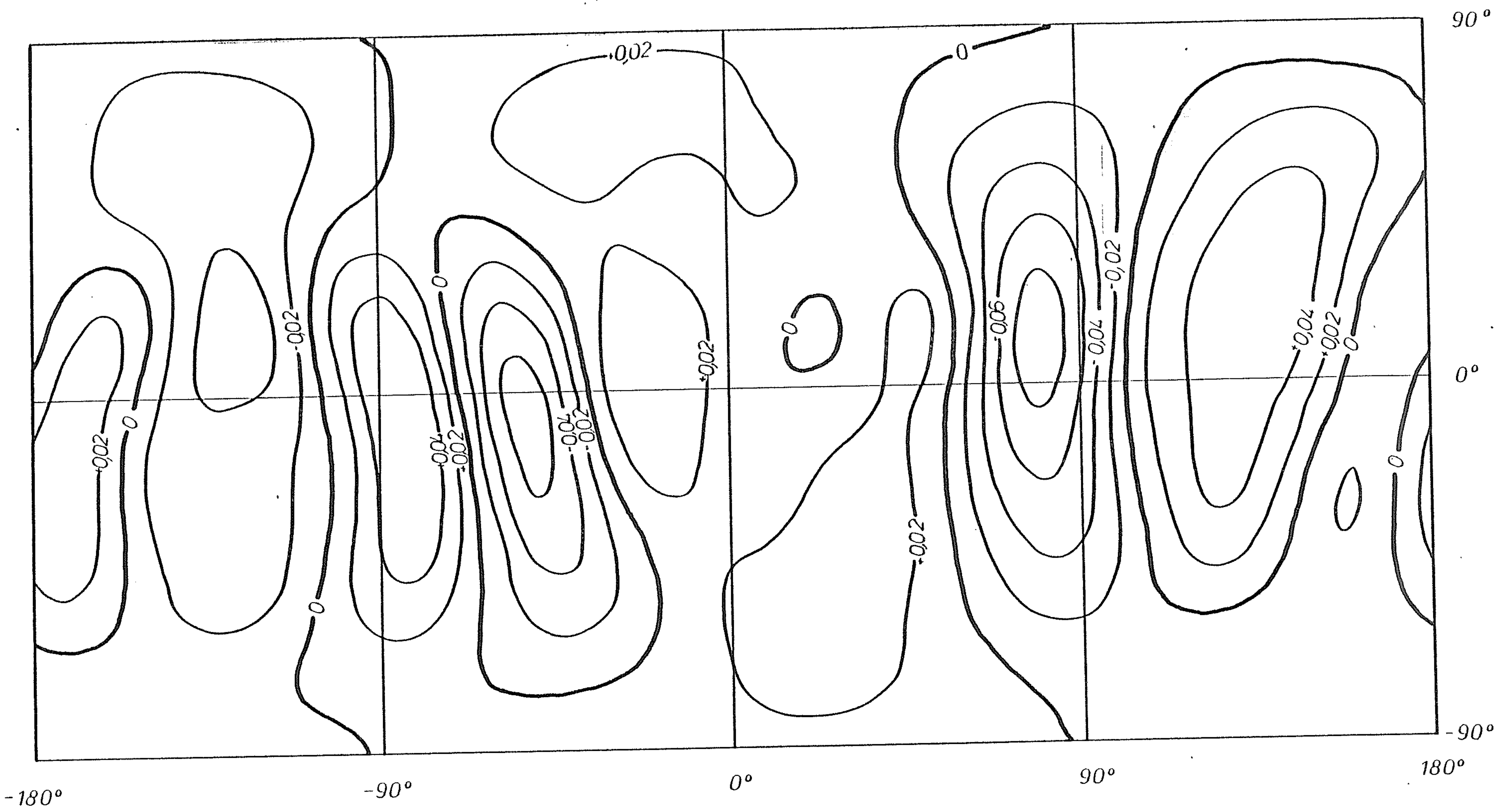

Figure 3. Variation in the direction of the local vertical as computed by the model(E-W component). Contour intervals 0,02 arcseconds/year

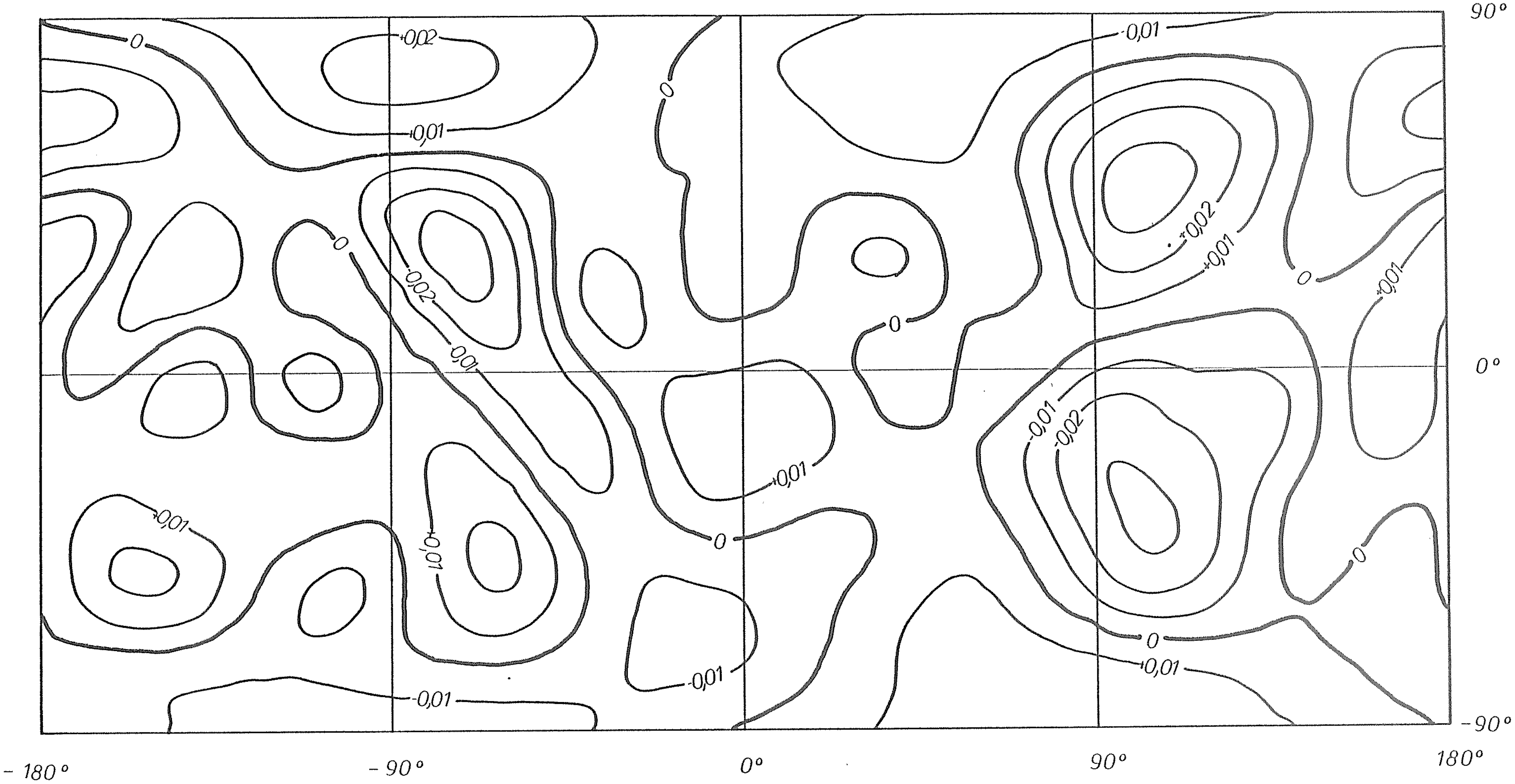

Figure 4. Variation in the direction of the local vertical as computed by the model (N-S component). Contour intervals 0,01 arcseconds/year

RESULTS OF ABSOLUTE GRAVITY SURVEYS IN TOHOKU DISTRICT, JAPAN

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ABSTRACT

We have recently succeeded in measuring the acceleration due to the earth's gravity with an accuracy of $5X10^{-8}$ m/s^2 (5 μgal) using the transportable absolute gravimeter completed at the International Latitude Observatory of Mizusawa. The instrument is based on laser interferometry which measures the acceleration of a freely falling cat's eye with a rubidium frequency standard as a reference of time and an iodine stabilized He-Ne laser as a reference of length. We have already made absolute gravity surveys at five stations in Tohoku district, and in a few years we will increase the number of stations to ten or more. The gravity values so far obtained by the absolute measurements were smaller by about $1X10^{-6}$ m/s^2 (100 μgal) than those referring to the IGSN71 system.

1. INTRODUCTION

We have recently completed a transportable absolute gravimeter after about five years of improvements and experiments. The study of the absolute gravity measurements with the transportable apparatus in the International Latitude Observatory of Mizusawa have two main purposes: one is to detect the secular gravity changes produced by plate motions, particularly by plate subductions, and another is to detect the long period gravity changes produced by polar motions. About ten absolute gravity stations were chosen in Tohoku district which is situated in a typical subduction zone, and the first survey was carried out at Sendai at the beginning of 1984 (Hanada et al, 1984). The absolute gravity surveys will be repeated every two or three years in each station hereafter. Recently we have also started the fixed point observations at the Esashi Gravity Station in order to detect the gravity changes produced by the polar motions.

Measurements with an accuracy of a few parts in 10^9 or better are necessary for these purposes. At the start, the accuracy of the measurement with the transportable absolute gravimeter is not so good, since not all the causes for the error can be removed. We have recently developed a new data-handling system which enables the data reduction within ten minutes, in order to improve the efficiency of the experiments, and could thoroughly investigate probable error sources one by one. As the result of the experiments, it became clear that the main cause for the error was electrostatic forces which act between a glass cat's eye and its teflon pocket. The accuracy of the measurement was rapidly improved after replacing the teflon pocket by metallic one and coating the side of the cat's eye with gold. It is possible to carry out the experiment with an accuracy of $5X10^{-8}$ m/s^2 or better if the condition is appropriate. This means that our instrument has attained the world level (Murata, 1978; Sakuma, 1984; Ooe et al, 1982; Zumberge et al, 1982; Alasia et al, 1982; Feng et al, 1982; Arnautov et al, 1983). Some features of the instrument and the results of the measurements recently made are discussed below.

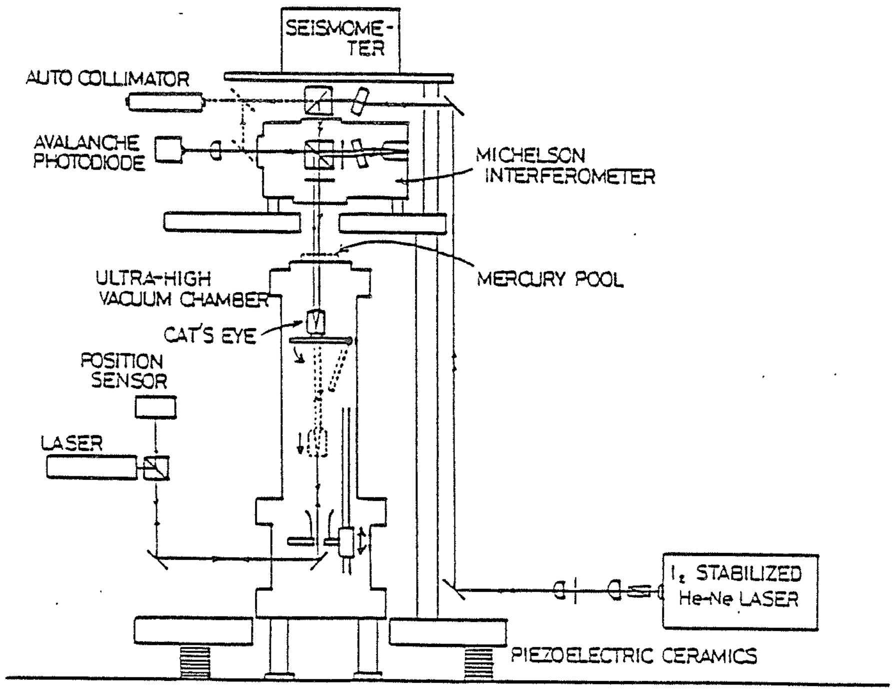

Fig. 1. Schematics of the absolute gravimeter.

2. THE INSTRUMENT

The transportable absolute gravimeter (Tsubokawa type) developed at the International Latitude Observatory of Mizusawa is almost the same in principle as that developed in the Earthquake Research Institute, University of Tokyo (Murata, 1978). Figure 1 illustrates the principle of the instrument. A Michelson interferometer determines the momentary positions of the cat's eye, which freely falls about 30 cm inside a ultra high vacuum chamber. We use a rubidium frequency standard as the reference of time and an iodine stabilized He-Ne laser as the reference of length.

This instrument employs a very small and simple-shaped cat's eye consisting of only one plano-convex lens with a single spherical incident surface. This is, however, so simple that its optical characteristics is not exactly ideal. The rotation of the cat's eye around its horizontal axis during 30 cm fall must be as small as possible lest a reflected laser beam should affected by its spherical aberration (Hanada and Tsubokawa, 1983). Therefore we have developed a dropping mechanism which uses a magnet and piezoelectric ceramics and succeeded in reducing the rotation of the cat's eye during the fall to within ten seconds of arc(Tsubokawa et al, 1976; Hanada et al, 1978). The time sequence of the mechanism is as follows (see figure 2).

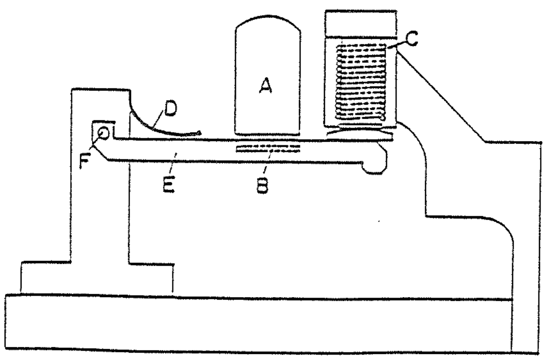

Fig. 2. The dropping mechanism.
A: cat's eye, B: piezoelectric ceramics, C: magnet, D: spring, E: launcher, F: rotation axis.

1) The launcher is fixed by the magnet.
2) The cat's eye is set on the piezoelectric ceramics.
3) The excitation current for the magnet is cut off at t_0.
4) The piezoelectric ceramics are discharged 0.1 ms after t_0 and they contract rapidly about 0.7 μm.
5) The cat's eye floats in the space and begins to fall.

6) The launcher separates from the magnet 0.2 - 0.3 ms after t_0 due to coercive force, then begins to revolve downward around the axis being accelerated by the flat spring lest it should recontact with the cat's eye.

The rotation of the cat's eye is monitored by an optical lever. A two-dimensional position sensor (type C1454-05, Hamamatsu) measures the incident point of the laser beam which are reflected at the back of the falling cat's eye. The signals detected by the position sensor can be displayed on a CRT.

The light source of the Michelson interferometer is the iodine stabilized He-Ne laser, which has been developed in our observatory with the help of the National Research Laboratory of Metrology (Tanaka, 1975; Tsubokawa, 1977). The wave length of this laser was compared with that of National Research Laboratory of Metrology in March, 1983, and both were proved to be agreed with each other within one part in 10^{10}. The iodine stabilized He-Ne laser has a modulation of about 5 MHz in optical frequency, which corresponds to one part in 10^8 of the wavelength, in order to control the cavity length. This modulation affects the fringe signals, however the fringe error does not exceed one part in 10^8.

We must reduce the diameter of the laser beam to within 1 mm, since the effective diameter of the cat's eye is only 2 mm. It is very difficult to form collimated beams of such a small size. In our system, light emitted from the iodine stabilized He-Ne laser, whose diameter is about 1.5 mm, is expanded 5 times first, and collimated with a 10 μm pinhole and two aspherical lenses, whose diameters are 80 mm and 10 mm, respectively.

An avalanche photodiode (type NDL1102, NEC) detects the fringe signals generated by the Michelson interferometer and converts them into electrical ones. These electrical signals, whose frequency increases linearly in time from 0 to about 8 MHz during the 30 cm fall, are stored in IC memories in the time span of 2 μs at every 1 ms with an analog-to-digital converter (Model 6500 Waveform Recorder, Biomation). Each portion of the signals consists of 1024 data recorded at sample rates of 2 ns. Finally, 250 parts of the digitized signals are stored in a cassete memory and used for further analysis. We determine the fringe phase at every 1 ms, which corresponds to the fractional part of the fringe number, and construct the falling distance at every 1 ms using the second-difference of succesive fringe phases (Murata, 1978; Tsubokawa, 1984). The gravity value is determined by a least square method with 250 sets of the relation between the falling distance and the time.

The bandwidth of the amplifier including the avalanche photodiode is better than 100 MHz, which is wide enough to detect the fringe signals. The amplifier's bandwidth was checked by inputing light signals produced by a laser modulater (type 1250C, Isomet), whose frequency varies linearly in time from 0 to 20 MHz, and measuring them with the same system as the actual absolute gravity experiment.

Ground vibrations such as pulsations and microseisms and mechanical ones produced by the dropping mechanism cause errors in the length measurements by the Michelson interferometer. The Michelson interferometer has no mechanical connection with the ultra-high vacuum chamber, in which the dropping device is attached, in order to avoid the effects of the mechanical vibrations. A long period vertical-component seismometer (PELS 73v, VTC Corp.) which is set on the top plate of the absolute gravimeter detects these vibrations and we make corrections for quadratic component of them. When the ground vibrations are strong, piezoelectric ceramics, which are attached to the feet of the absolute gravimeter, can reduce the effects of them to less than one-tenth. This stabilization is controlled by another seismometer which is set on the pier.

3. RECENT OBTAINED RESULTS

The plan of absolute gravity surveys in Tohoku district was started in 1984. The absolute stations were chosen after considerations of uniformity of distribution, permanency, traffic convenience, facilities, existence of other geophysical observations etc. Figure 3 shows the locations where the absolute gravity measurements have already been made. We show the results from the absolute gravity surveys so far performed in the following section.

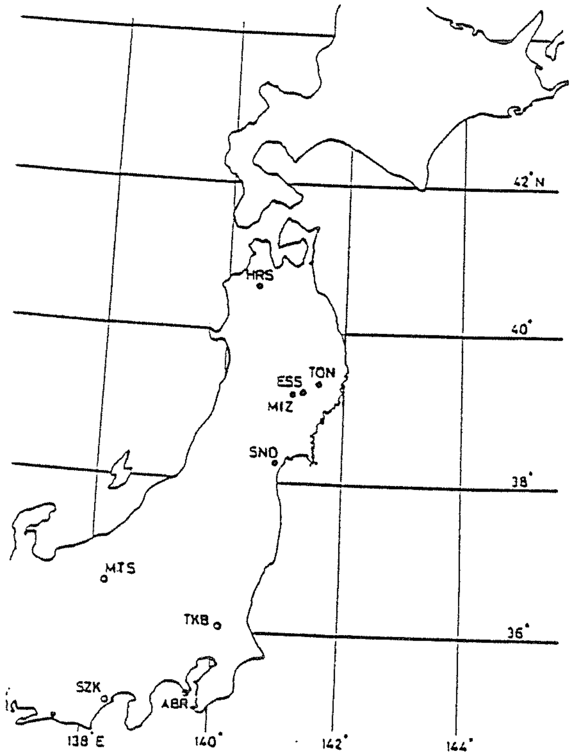

Fig. 3. Locations of the absolute gravity stations in Japan. Solid and open circles indicate the station where the absolute gravity measurements have been made by the International Latitude Observatory of Mizusawa and by other institute, respectively. HRS: Hirosaki, TON: Toono, ESS: Esashi, MIZ: Mizusawa, SND: Sendai, MTS: Matsushiro, TKB: Tsukuba, SZK: Shizuoka, ABR: Aburatsubo.

It takes about one day to aquire the first data if there is no trouble during transport by a small truck. When somethig becomes wrong with the dropping mechanism, we introduce air in the vacuum chamber in order to repair it. In this case, another one day is required. About a week is usually prepared for the entire operation, which includes unloading, assemblage, data acquisition, disassemblage and reloading. Measurements with LaCoste and Romberg gravimeters are also made during the survey in order that the gravity values at the absolute stations may be connected with those referring to the IGSN71 system (International Gravity Standardization Net 1971). The scale values of the LaCoste and Romberg gravimeters employed were calibrated at the IGSN71 stations in Circum-Pacific zone (Nakagawa et al., 1983).

3.1 RESULTS AT ESASHI

The absolute gravity measurements at the Esashi Gravity station, which was completed at the end of 1983, were made for the period from November 6 to 16, 1984. The site for the measurements is shown in figures 4 and 5. Two granite piers which will be used for comparisons with other absolute gravimeters are equipped inside the building. Figure 6 shows the histogram of the results. We have succeeded in measuring the absolute gravity values with the accuracy of

5×10^{-8} m/s^2 (5 μgal) at this station. This is due not only to the improvements of the instrument but to the quiet environment. This station is in an out-of-the-way place and is on a solid foundation composed of granite. The arithmetic mean of 71 measurements after corrections of the tidal and the vibration effects etc. is

$$g = 9801216.61 \pm 0.05 \ \mu m/s^2.$$

On the other hand, the value obtained with the LaCoste and Romberg gravimeter referring to the IGSN71 system is

$$g = 9801217.77 \ \mu m/s^2.$$

The value obtained with the absolute gravimeter is approximately 1.0×10^{-6} m/s^2 (100 μgal) smaller than that referring to the IGSN71 system.

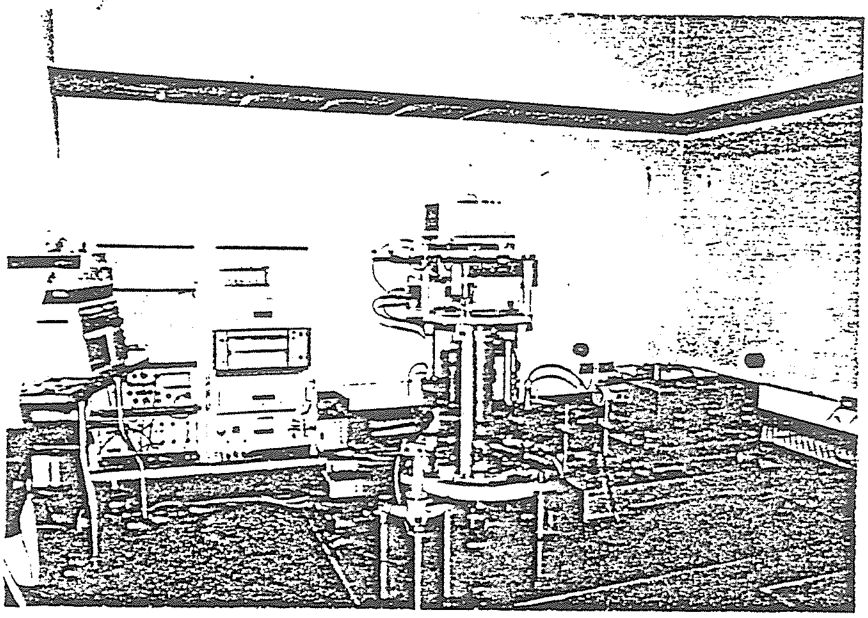

Fig. 4. Photograph showing the instrument at the Esashi Gravity Station.

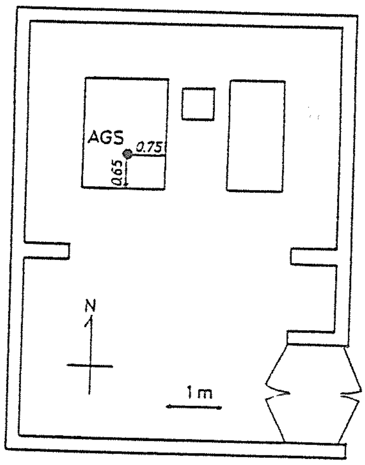

Fig. 5. The Esashi Gravity Station.
AGS: The absolute gravity station.
Latitude: 39°08'53" N
Longitude: 141°20'07" E
Altitude: 370 m.

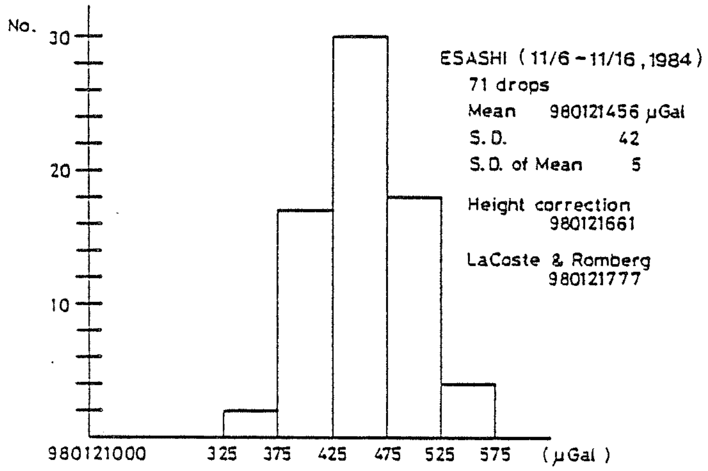

Fig. 6. Histogram of measured gravity values at Esashi.

3.2 RESULTS AT HIROSAKI

We made the absolute gravity measurements at the Second Seismograph Room (Room No.130), Faculty of Science, Hirosaki University for the period from November 29 to 30 and from December 3 to 5,1984. The site for the measurements is shown in figure 7. Figure 8 shows the histogram of the results obtained. A traffic noise was very large here, since this station is near a main street. To make matters worse, there were heavy seas in that time, which also increased the ground noise. We made the measurements mainly early in the morning, in order to be free from the traffic noise. The effects of ground pulsations, however, could not be avoided in such hours. We could measured the absolute gravity values with the accuracy of $1.5X10^{-7}$ m/s^2 (15 μgal) even in such a condition. The arithmetic mean of 50 measurements is

$$g = 9802610.70 \pm 0.15 \ \mu m/s^2,$$

and the value referring to the IGSN71 system is

$$g = 9802612.63 \ \mu m/s^2.$$

There is also the difference between them. Figure 9 shows the relation between the measured gravity values, which do not include the vibration corrections, and the effects of ground vibrations. There is good correlation between them. This figure also shows that we can reduce the effects of the long period vibrations, such as pulsations, to within 10 percent under present conditions. More precise vibration measurements or more effective stabilization are required for further advanced absolute gravimetry.

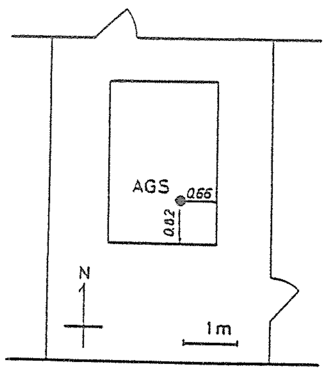

Fig. 7. The absolute gravity station (AGS) in the Second Seismograph Room, Faculty of Science, Hirosaki University.
Latitude: 40°35'06" N
Longitude: 140°28'30" E
Altitude: 50 m.

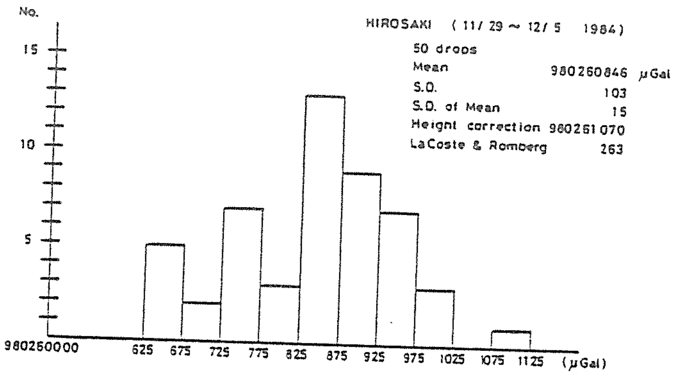

Fig. 8. Histogram of measured gra vity values at Hirosaki.

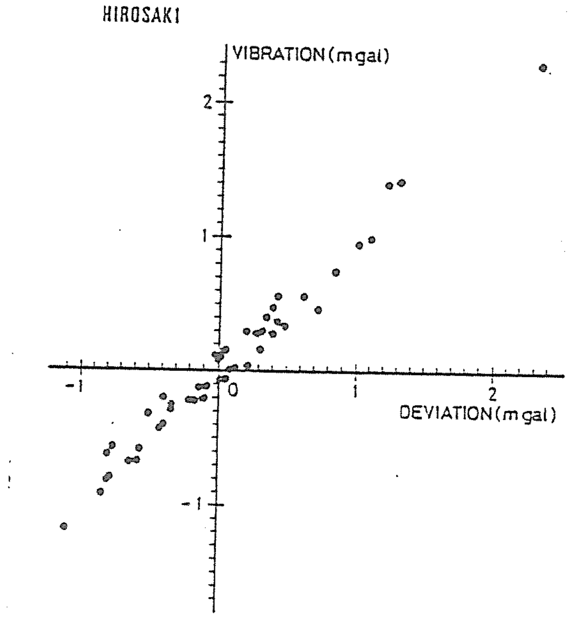

Fig. 9. Relation between the measured gravity values at Hirosaki and the effects of the ground vibrations.

3.3 RESULTS AT MIZUSAWA

The absolute gravity measurements with the transportable apparatus at

Mizusawa were made for the period from February 2 to March 11, 1985. The site for the measurements was in the room where the station type absolute gravimeter is set up as shown in figure 10. The traffic noise was very large also here, since this station is near an express highway and is not on the firm ground. The effects of traffic noise exceeded 1 mgal at all times. The arithmetic mean of 56 measurements is

$$g = 9801462.07 \pm 0.12\ \mu m/s^2,$$

and the value referring to the IGSN71 system is

$$g = 9801463.86\ \mu m/s^2.$$

There is also the difference between them. Figure 11 shows the histogram of the results obtained.

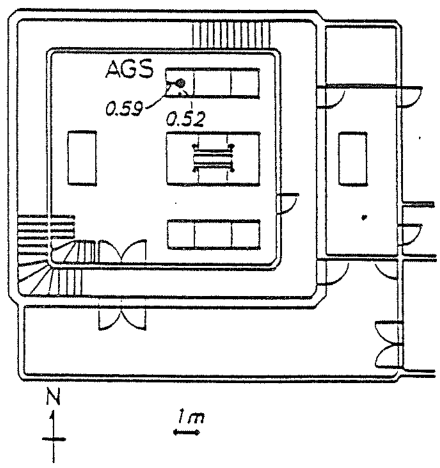

Fig. 10. The absolute gravity station in the International Latitude Observatory of Mizusawa. AGS means the absolute gravity station for the transportable apparatus.
Latitude: 39°08'08" N
Longitude: 141°07'54" E
Altitude: 60 m.

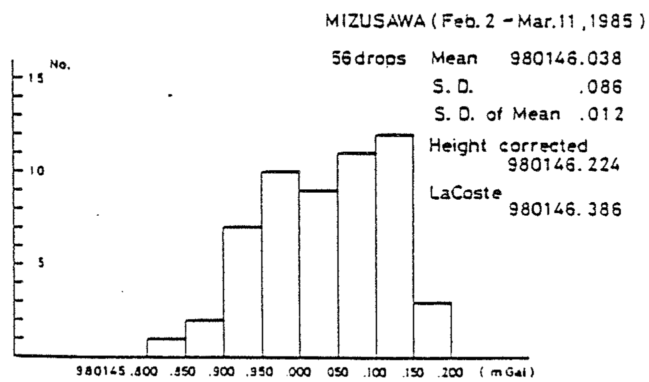

Fig. 11. Histogram of the measured gravity values at Mizusawa.

3.4 RESULTS AT TOONO

The absolute gravity survey at the Kitakami Seismological Observatory, Faculty of Science, Tohoku University (Toono city) was made for the periods from March 18 to 20 and from March 25 to 28, 1985. The site for the measurements was in a garage (figure 12) and the base was not enough tough, so that the mechanical vibrations produced by the dropping devise traveled through the base into the Michelson interferometer and greatly affected the measurements. We placed a stone table in the bottom of the absolute gravimeter in order to reduce the vibrations. Figure 13 shows how the stone table could reduce the mechanical vibrations. It also decreased the amount of scatter in measured values. The arithmetic mean of 29 measurements, which were made with the stone table, was

$$g = 9801320.54 \pm 0.19 \ \mu m/s^2,$$

and the gravity values referring to the IGSN71 system was

$$g = 9801320.68 \ \mu m/s^2.$$

Figure 14 shows the histogram of the results obtained.

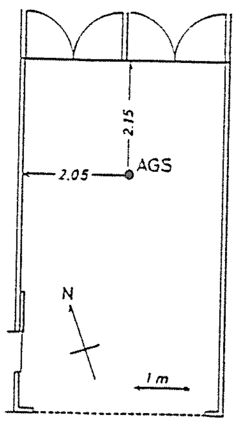

Fig. 12. The absolute gravity station (AGS) in the Kitakami Seismological Observatory, Faculty of Science, Tohoku University (Toono city).
Latitude: 39°23'12"N
Longitude: 141°33'56"E
Altitude: 376 m.

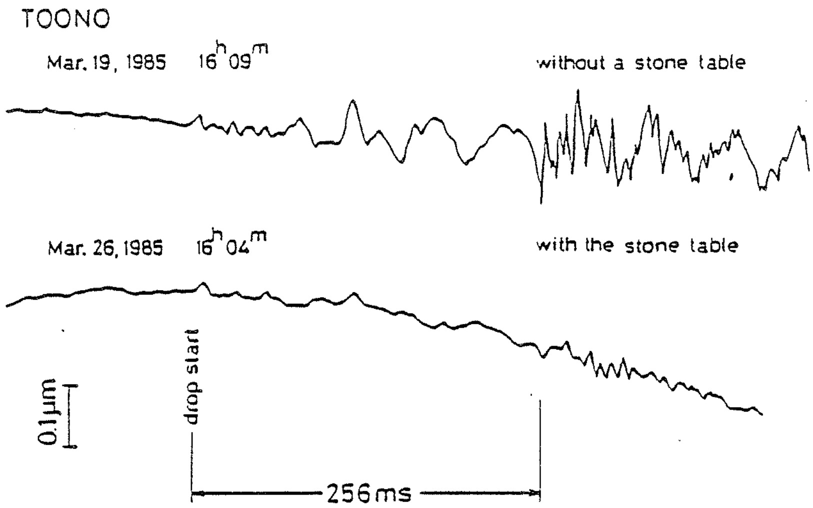

Fig. 13. Traces of the mechanical vibrations during free falling of the cat's eye observed on the top plate of the absolute gravimeter. Lower and upper traces show the cases when the stone table was used and when it was not used, respectively.

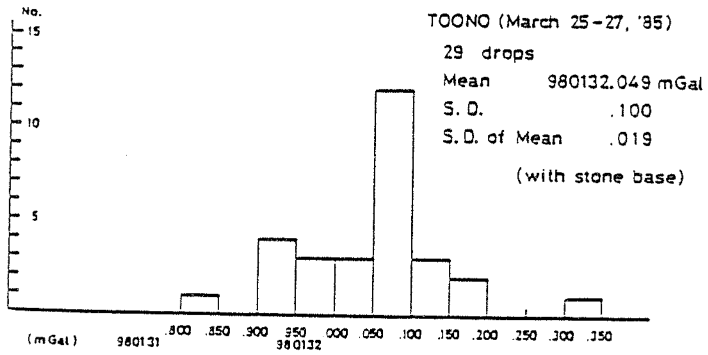

Fig. 14. Histogram of the measured gravity values at Toono.

4. DISCUSSION

We have just started the plan of absolute gravity surveys in Tohoku district, therefore we cannot yet discuss about the gravity changes which may be detected in the near future. Now we compare the gravity values so far obtained by absolute measurements with those referring to the IGSN71 system, in order to investigate the reliability of both the absolute measurements and the IGSN71 system. There are other four stations where absolute gravity measurements have already been made with other transportable absolute gravimeters in Japan, i.e. Matsushiro (Murata, 1978), Aburatsubo (Hanada et al., 1979), Shizuoka (Endo et al.,1981) and Tsukuba (Murakami and Tajima, 1982). After all we have nine absolute gravity stations in Japan (see figure 3). Figure 15 shows the differences between the gravity values obtained by the absolute measurements and those referring to the IGSN71 system. The results of the absolute measurements are smaller by about 100 μgal than the IGSN71 system as a whole, and there is a trend that the difference expands as the gravity value increases. We will carry out the absolute gravity surveys at more stations in order to discuss in detail about these discrepancies. It is also very important to make a comparison of different types of absolute gravimeters, since it will increase reliability of absolute gravity values. Fortunately, we have three different types of absolute gravimeters in Japan and can easily make comparisons of them. Calibration of the absolute gravimeters is the problem to be solved in the near future.

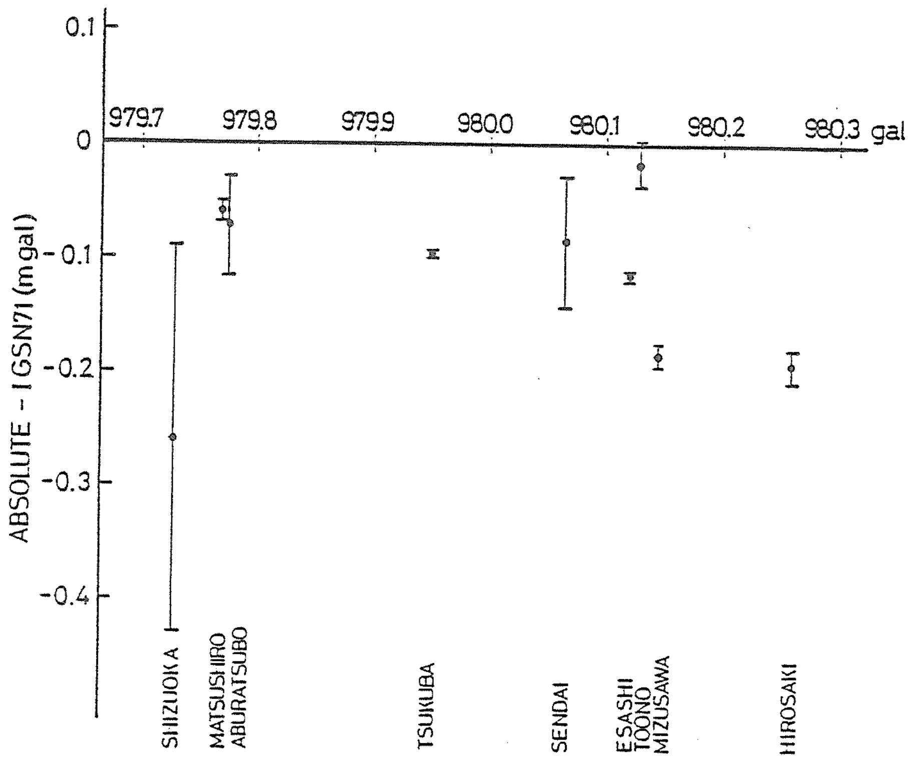

Fig. 15. Comparisons of the gravity values obtained by the absolute measurements with those referring to the IGSN71 system.

5. CONCLUSIONS

We have succeeded in measuring the acceleration due to the earth's gravity with the accuracy of 5 parts in 10^9 using the transportable absolute gravimeter. The following points should be improved for further advanced absolute gravimetry.

1) Reduction of the measurement time.
2) Removal of the effects of vibrations.
3) Automatization.
4) To make a smaller and lighter instrument.

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G. Boedecker

On the Design of the International Absolute Gravity Basestation Network (IAGBN)

July, 1985

Foreword

This paper is not intended as a thorough study of the whole problem, but should list as completely as possible the keywords for the discussion of the problem.

Objectives of IAGBN

In general, (global) gravity measurements are usefull for

- metrology
- Earth model (geoid) computation
- levelling
- satellite orbit determination
- geophysical investigations of density structures of the Earth
- geophysical prospecting
- monitoring of gravity changes for geodynamic reasons

Therefore, a worldwide network of absolute gravity base stations serves for

- zero order reference net to subordinate observations
- monitoring gravity variations because of large scale geodynamic mass redistribution
- instrument testing and calibration

These objectives require different net designs for the IAGBN. Because highest quality is required for monitoring gravity variations with time, this will to a great extent set the rules for the net design.

In general, any mass redistribution at the surface or within the Earth produces a gravity variation at stations on Earth through different mechanisms, as visualized in fig. 1:

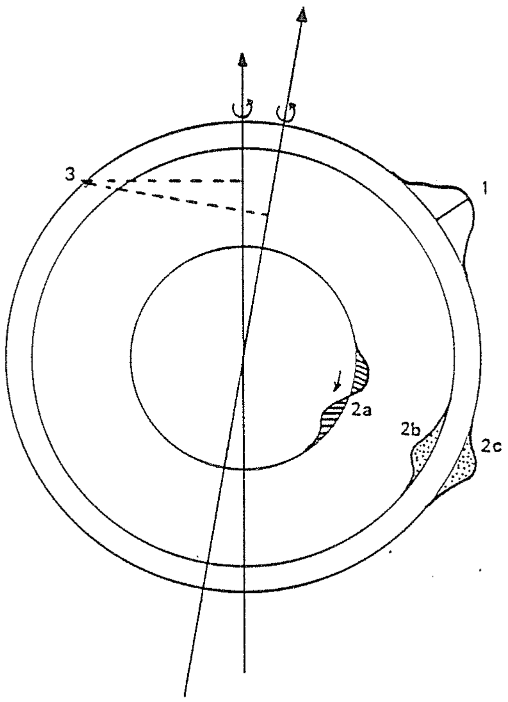


Figure 1

1 Position change including height change of the observation point

2 Deformation of a density contrast surface, i. e. mass redistribution, in particular at the core/mantle, the asthenosphere/lithosphere or the lithosphere/atmosphere boundary surfaces resp.

3 Change of the Earth's spin vector, which is caused by a mass redistribution and generates a change of centrifugal acceleration.

Height change probably plays a predominant role for the regional gravity changes in Iceland (TORGE, 1982), which typically range from a few to 100 μGal/a.

BIRO and collaborators (e.g. 1985) study on the basis of BARTA's (1963) ideas the gravity effect of a rotating core; from simulation studies they get possible gravity changes of the order of 300 μGal/a. As also the authors admit, this seems to be an order of magnitude too big, but the possibility of gravity changes through a rotating core deserves greatest interest.

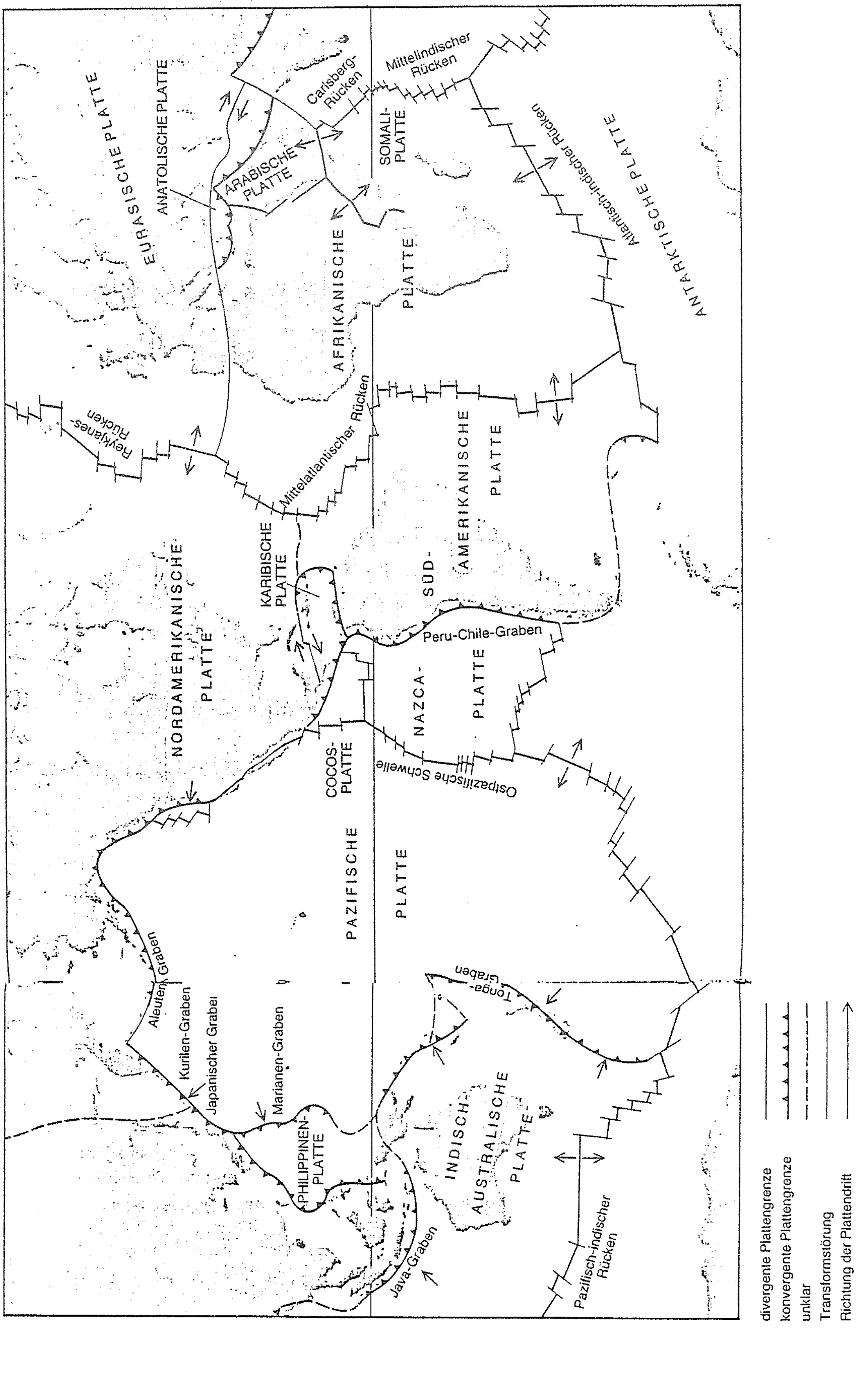


Figure 2: Tectonic plate boundaries.
After FRANCHETEAU (1983)

RICHTER (1983) presents a study on the gravity effect of the order of a few microgal due to polar motion, which he determined from observations done by a super conducting gravity meter.

The total effect of global gravity variations seems to be below 10 μGal/a as a suggested by repeated absolute gravity observations at Moscow, Novosibirsk and Potsdam in the period 1975-1980 (BOULANGER/PARIISKY/PELLINEN 1981). This is also confirmed by ELSTNER (1980), who did a theoretical study on possible gravity variations and their spectral distribution.

The conception about the variations of crust and mantle with time has been influenced very much by plate tectonic models (MINSTER & JORDAN 1978) in the past decade, c. f. fig. 2. Studies on plate motions chiefly concentrated on horizontal motions (e.g. NASA 1983). Vertical motions and gravity changes were taken into consideration at the plate boundaries only. Since a few years intraplate tectonics gained increasing interest. A considerably advanced view offer the publications of Anderson, Dziewonski and Woodhouse(ANDERSON/DZIEWONSKI 1985, WOODHOUSE/DZIEWONSKI 1984, DZIEWONSKI 1984) on the 3D seismic tomography of the Earth, from which they gain heat distribution and convection currents in lithosphere and asthenosphere (fig. 3).

Considerations for Global IAGBN Net Design

In order to serve as a reference net to subordinate gravity observations, station locations have to consider the structure of existing gravity base networks, traffic lines and accessability. The location should not prevent the intended users from using the stations!

In order to maintain historical continuity such stations should be taken into consideration, where absolute measurements were carried out in the past even if they exhibit some drawbacks as to their geological stability etc.

Also such stations should be taken into consideration, where for some reason or the other absolute instruments owners wish to observe. An unfavoroubly located station with plenty of observations is better than an ideally located station with no observations. Those stations specifically can serve for instruments intercomparisons etc.

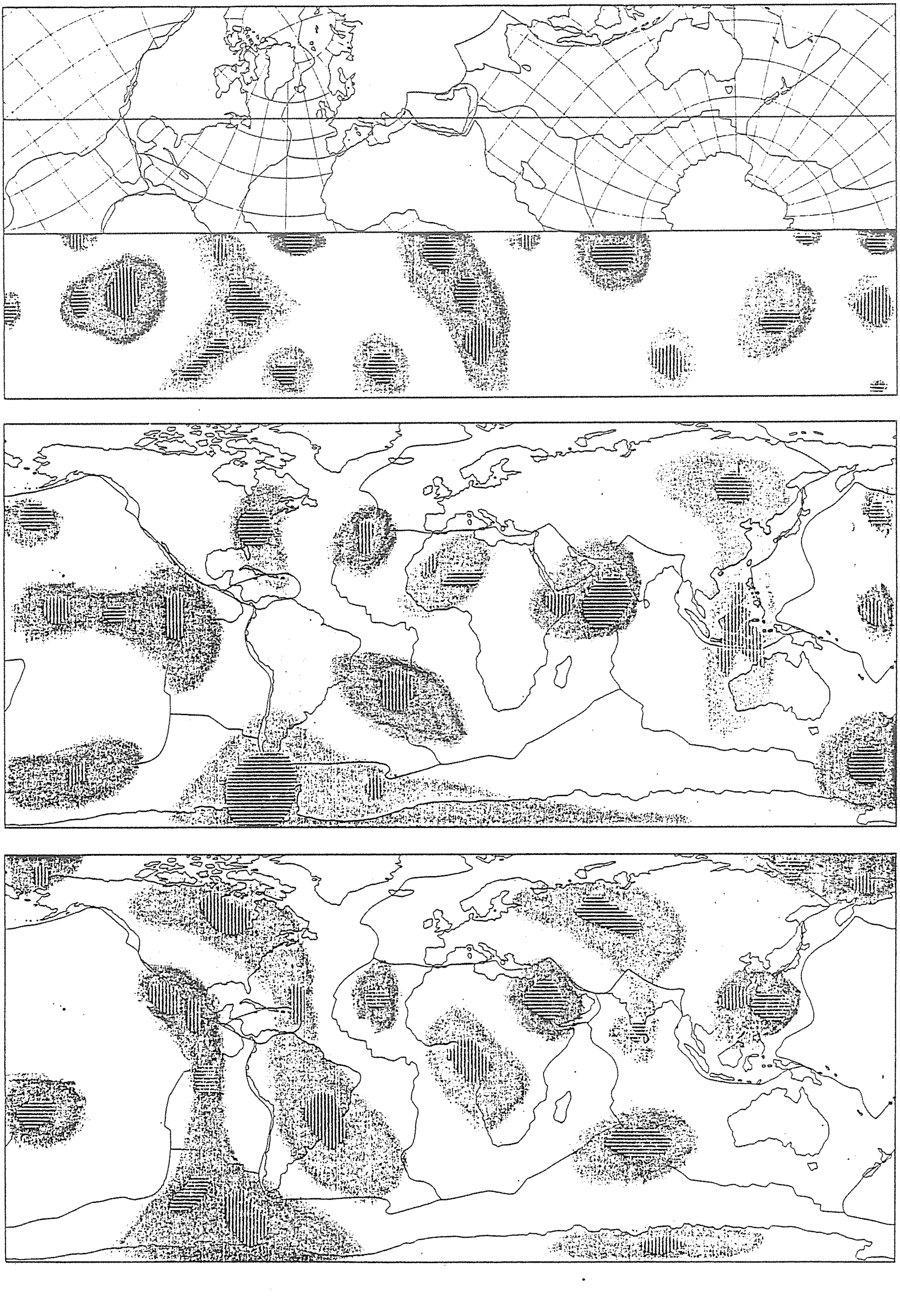


Figure 3: Hot (dark grey) and cold (light grey) anomalies in the mantle (ANDERSON & DZIEWONSKI 1984),Hatching indicates horizontal or vertical convection currents.
Above: profile, depth 0-350 km,
Middle: Depth 250 km
Below: Depth 100 km

Station establishing furthermore is restricted because of political reasons and because the necessary infrastructure for establishing and maintenance of the station is not developped sufficiently yet. On the other hand, the willingness and active support of a country to host a station certainly should be appreciated.

The majority of stations, however, should be distributed and located in view of scientific considerations. It is suggested, that the total number be of the order of 50 stations. MATHER (1978) did simulation studies on the bases of 54 stations with equal area distribution, PARIISKY (1978) discusses a set of 26 stations. BIRO et al. (1985) mention 36 stations as a minimum, 84 stations as a good and 126 as a very good coverage. Given a probable excess station density in Europe and several station failures, the total number of stations should better be of the order of 100, but because of the importance of observation repetition intervals of a few years such a high number seems to be unrealistic. Given that the effects of the Earth's spin vector changes (fig. 1) and of the effects of core rotation (BIRO et al. 1985) is maximum at mid and low latitudes, an increased station density at these latitudes should be supported. The findings on vertical convection currents by Dziewonski and others (e.g. ANDERSON/DZIEWONSKI 1984) should carefully be considered for station selection.

An important point is also the coordination with preparational works for establishing a station set to serve as a conventional terrestrial reference system through the respective IAG/IAU COTES working group (BENDER 1981, MUELLER 1983). Also the MERIT campaign (e.g. WILKINS (ed.) 1980) has to be taken into account. This coincides with the necessity to co-locate as many stations as possible with space geodetic sites. As has been pointed out by numerous authors (e.g. STRANG VAN HEES 1977, BIRO 1983) for regional investigations, geodynamic gravity variations monitoring has to be combined with geometric monitoring (for regional studies: levelling) in order to conclude on the geophysical models. This reasoning can be extended to the global case (BOEDECKER 1984). As to the co-location with space geodetic sites one point has to be made: Currently geometric geodynamics monitoring concentrates on horizontal plate motions monitoring. The respective groups performing the observations should be urged to put more emphasis on vertical motions at station selection and observations. In a SSG 3.87 letter dated January 18, 1985, space geodetic sites were compiled (fig. 4). - In order to put most stations on stable geological units, fig. 5 shows the global pattern of the ages of continental crust. Fig. 6 contributes information on seismic risk areas, which should be avoided.

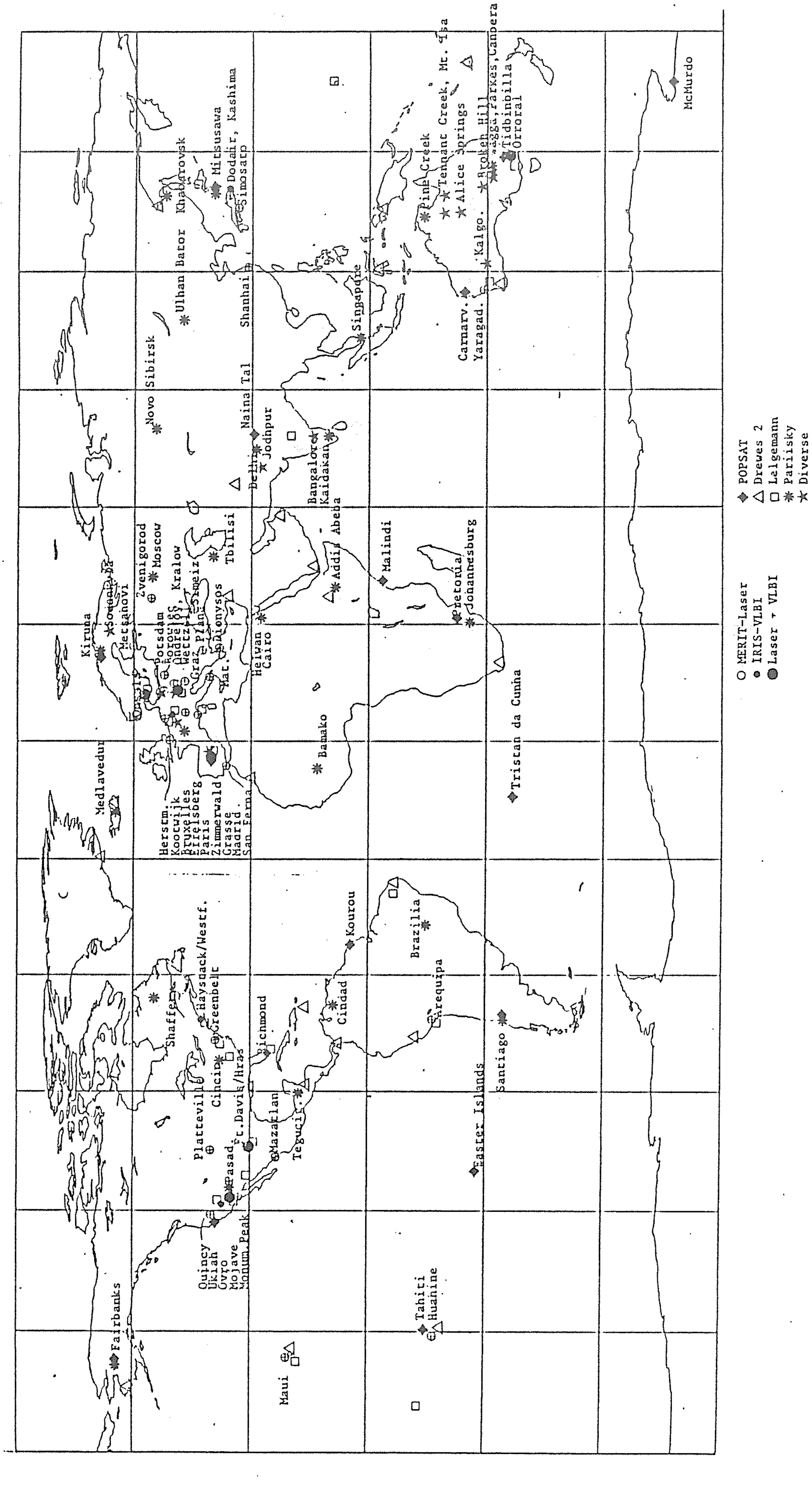


Figure 4: IAGBN station site candidates from various sources

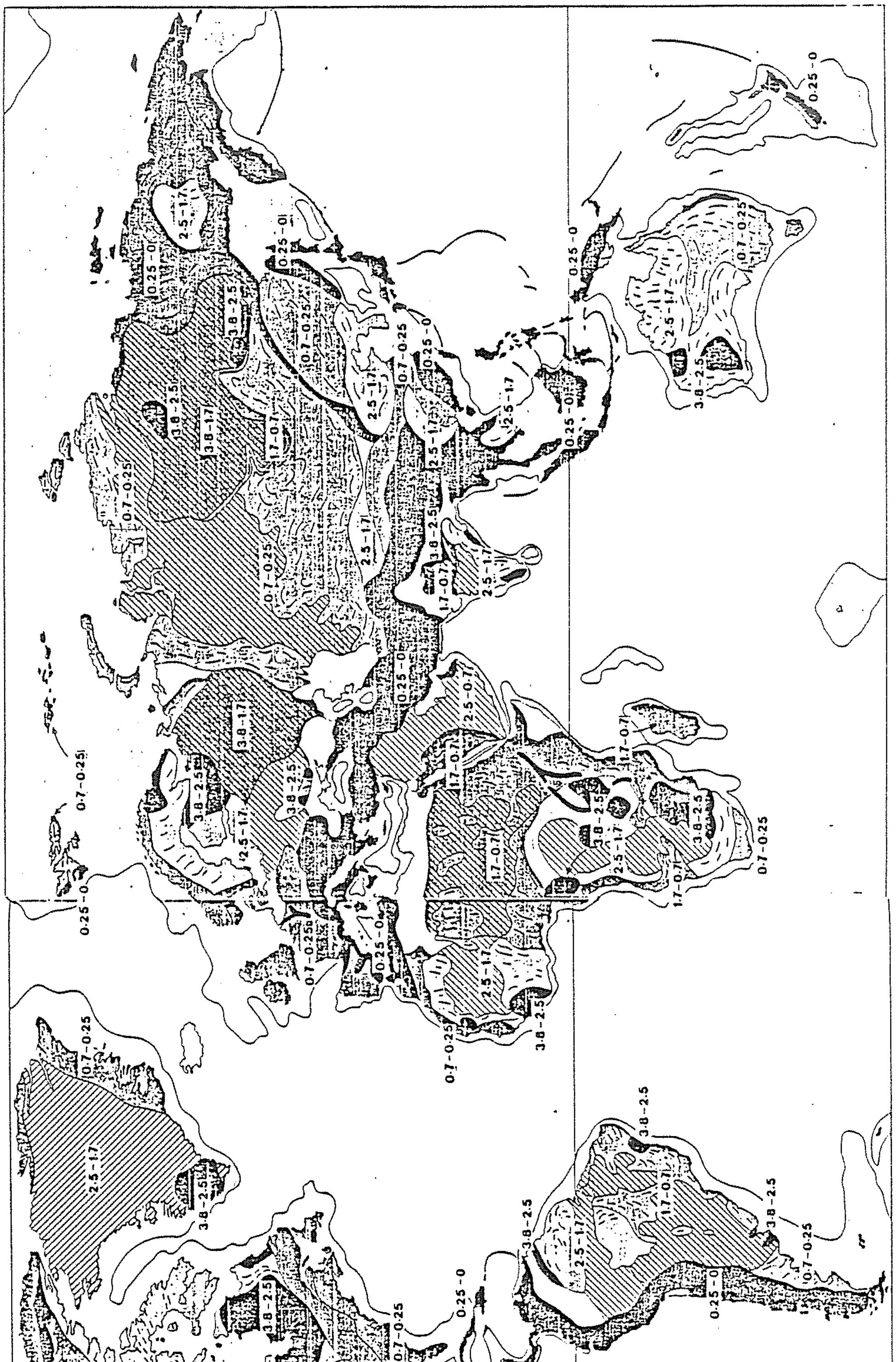


Figure 5: Age of continental crust in 10^9 years (after BURCHFIEL 1983)

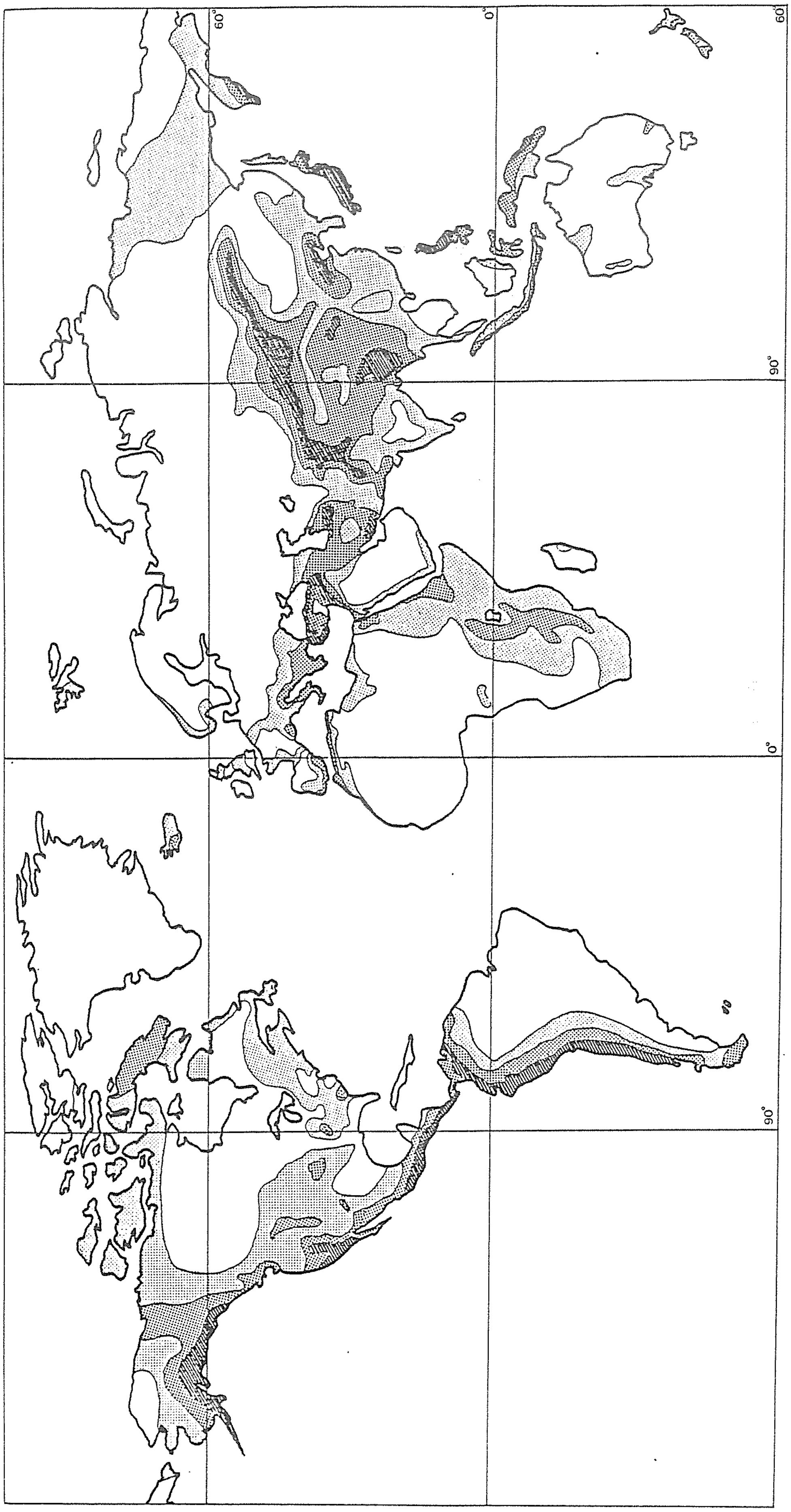


Figure 6: Seismic risk areas (dark = high risk; after a map produced by the insurance company "Münchner Rückversicherung")

The reduction of absolute gravity observation requires precise values for the Earth tide parameters. Because of past difficulties to model local effects particularly along the ocean coasts, a former version of site selection criteria (UOTILA 1982) provided for a station distance of 300 km from the oceans. The indirect tidal effect of the oceans, however, is not merely a function of distance, as was pointed out by DUCARME (1983). Thus it is more appropriate for the station site to require a minimum indirect oceanic tidal effect. Because the International Centre of Earth Tides, ICET, has numerically proven the possibility to model these effects quite precisely in most parts of the world, a restriction for the site location should be formulated through the guideline 1.4 of the site selection criteria (see below). The Earth tide reduction should be computed by or along the procedures of the ICET. More generally, in order to separate different (time-) spectral components of gravity variations, a co-location of IAGBN-sites with Earth tide registration stations should be aimed at, e.g. the stations of the Trans World Tidal gravity profiles (MELCHIOR, DUCARME, VAN RUYMBEKE, POITEVIN 1984), especially if equipped with a superconducting gravity meter (RICHTER 1983).

Local Net Structure and Station Environment

Important selection criteria are listed in the "Site Selection Criteria" (UOTILA 1982), see appendix A. These viewpoints will be augmented in the sequel.

It is very important to reduce and/or monitor disturbing effects. Besides minimizing seismicity and local temperature effects it is essential to reduce groundwater variation impact through station location on non-porous bedrock. If this is not possible in few exceptions, at least some data should be collected as to the variation of porous water or free groundwater table variations.

According to RABBEL/ZSCHAU (1985) wandering cyclones/anticyclones cause gravity variations up to an order of 20 μGal. Thus care must be taken to collect data about the air pressure development in the environment of the station in order to avoid observations during critical periods and to reduce for anomalous atmospheric pressure to a standard atmosphere according to IAG 1983 resolution no. 9 (TSCHERNING (ed.) 1984, p. 317).

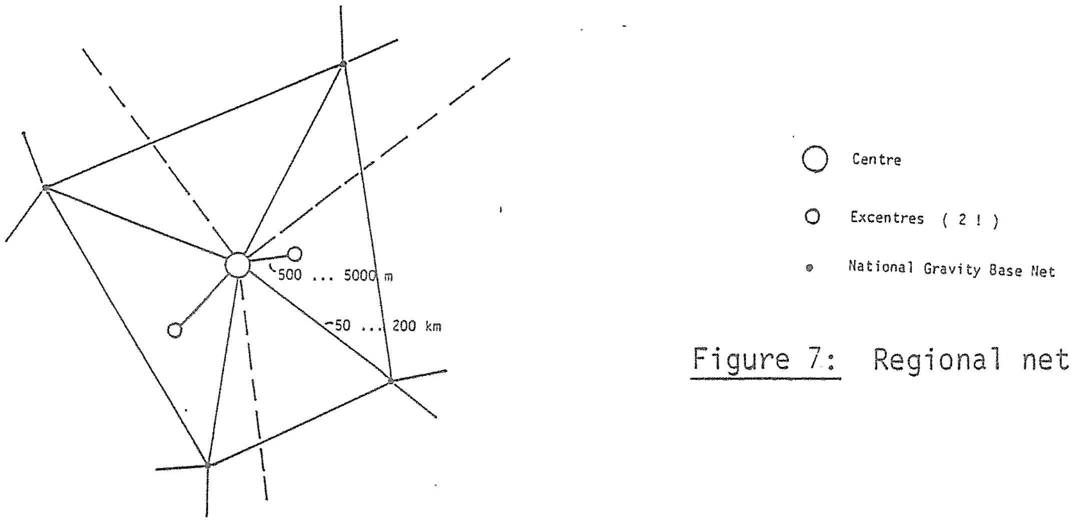


Figure 7: Regional net structure

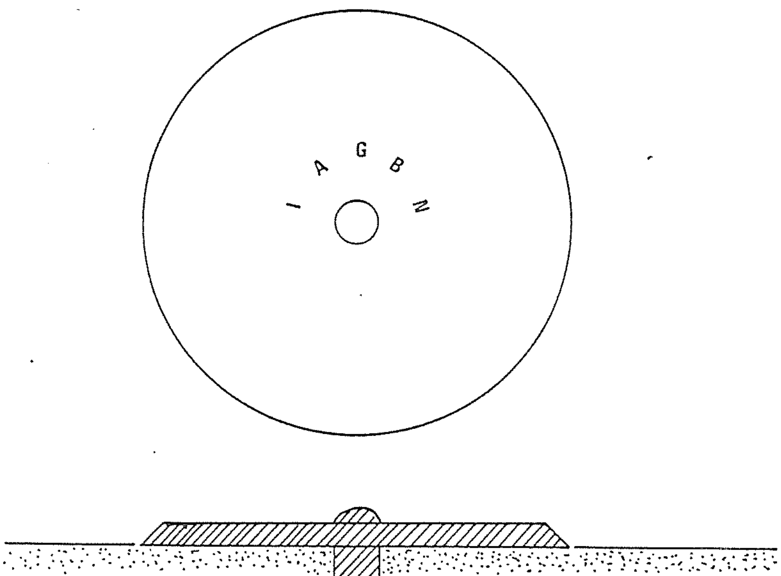
For several reasons it is important to bind the IAGBN stations to excentres and national/regional gravity networks (c.f. fig. 7):

- Base-station for subordinate networks
- Security against destruction
- Recognition of purely local phenomena, improvement of regional representability.

Station Monumenting and Description

From experiences with IGSN71 and the new German gravity base net (DOERGE/REINHART/BOEDECKER 1977, BOEDECKER/RICHTER 1981) it is strongly recommended that stations be monumented not e.g. by an excentric sign at the wall but by a centred metal disc stuck directly on the floor including an unambiguous local height reference. For an example c.f. fig. 8. The description should, besides coordinates and sketches, also include information how to access the station, photographs of the interior and exterior of the building in order to identify possible reconstructions, as also earth tide and atmosphere reduction parameters.

Figure 8: Monumentation of IAGBN station



Procedures, Observation Campaigns

It is suggested to start observations in 1986 and to repeat with intervals of 4 years.

In view of ongoing discrepancies between different instruments, it is suggested, that for the first observation campaign each station be observed simultaneously by two instruments. "Simultaneously" in this sense means within a time span of a few weeks. Furthermore as many instruments as possible should be intercompared. Thus an observation schedule as scetched in fig. 9 seems to be appropriate.

Station	Gravity Meter A	B	C	D
1	x	x		
2	x		x	
3	x			x
4		x	x	
5		x		x
6			x	x
7		x		x
8	x		x	
9		x	x	
10	x			x

Figure 9: Absolute observation scheme, example

After site selection has been completed at the Paris, July 1985, meeting, site preparation should start immediately.

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Appendix A

International Absolute Gravity Basestation Network

Purpose:

The absolute sites will be used to provide stable locations for the continued testing of absolute gravity devices, to monitor possible changes in gravity as a function of time, etc. and to form a strong network of absolute stations for definition of the International Gravity Standardization Datum.

Site Selection Criteria:

1. General Location:

1.1. Geology:

Site to be located on stable crystalline rock, preferably Precambrian or Paleozoic in age. The preferred location of maximum stability is the continental shield area of Precambrian rocks. The next preferred locations are on discordant plutons such as batholiths. The stations shall be at least 50 kilometers from active fault systems.

1.2 Seismic Hazard:

Sites shall not be located high seismic risk area. They shall be located areas comparable to zones 0 to 2 of the seismic risk map of the U.S.A.

1.3 Tidal Reduction:

Site location shall admit the determination of the tidal gravity reduction including all side effects as ocean loading etc. to an accuracy level of $\pm$ 2 μGal

1.4 Local Gravity Variations with Time:

It has to be assumed that gravity changes through possible mass changes from lake water table variations, groundwater table variations, large construction works are either to be monitored or are reliably below 2 μGal.

2. Other General Specifics:

2.1 Irregular Noise:

Irregular noise level should be low, preferably no greater than five (5) micro gal when measued by a gravity meter at peak periods.

2.2 Electromagnetic Interference:

The site shall not be located near devices that generate electromagnetic interference with absolute or relative gravity measuring instruments.

2.3 Access to Site:

Access to the site should be relatively easy, without excessive cost and available to international measuring teams with their absolute gravity measuring devices.

2.4 Excentres:

Excentres shall be established at acceptable sites in the vicinity of the absolute station. When the absolute station is not located on bedrock, excentres should be established preferably on bedrock and the height difference of excentre stations with respect to the absolute site be determined by high precision levelling.

2.5 Linkage to Regional Networks:

In order to serve as zero order stations to subordinate networks and to make possible gravity variations monitoring representative for a region, the stations have to be tied into national and regional networks.

2.6 Geometric Position Monitoring:

Consideration should be given to location of as many sites as possible in the vicinity of stations where high accuracy geocentric positions can be determined.

2.7 Levelling:

Sites should be tied to national levelling nets and relevelling to current mean sea level should be enabled wherever possible.

3. Additional Local Specifics:

3.1 Build Stability:

A stable, permanent builidng will be chosen for the measurements. The building should be over ten years old preferably, in order to ensure that settling has already occured. The building should be far enough away from disturbances caused by railroad or vehicular traffic.

3.2 Room Selection:

The room chosen will be in the lowest level of the builidng to ensure maximum stability. It should not be near heavy machinery, power transformers or other equipment that would cause vibrations or an electromagnetic field. The room should have at least 2 x 3 meters of space to accomodate the equipmant. There should be additional rooms to allow easy access by the personnel conducting the measurements and to allow dissipation of heat generated by the equipment.

3.2.1 Measuring Surface:

The surface on which the absolute apparatus sits shall be bare concrete, terrazo, marble, or other similar hard floor covering.

3.2.2 Temperature:

The room chosen for the measurements should not have external temperature or temperature variation that would adversely affect instrument performance. A climatically controlled room is preferred.
The ideal temperature for the room is 18 to 24 degrees of Celsius with only a two (2) degrees of Celsius variation during measurements.
In order to avoid air currents, ventilation outlets and air ducts must not be located adjacent to the apparatus or must be blocked off. Furnace rooms should not be used because of excessive heat. Attention must be paid to the year round temperature of the room, not just the temperature during one season.

3.2.3 Lighting:

The room must have provision for maintaining semidarkness during absolute observations to accomodate absolute isntruments with external laser sources.

3.2.4 Electric Power Requirement:

Two kilowatts of power are generally required. This normally requires two separate circuits tu supply the necessary power. Two 20-ampere circuit breakers will be adequate. A thorough analysis must be made of the electrical panel of the selected building as one or two separate circuits may have to be added.

Geodetic Aspects of Gravity Measurements in Africa

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(May, 1985)

0. Foreword

Many aspects of gravity measurements in Africa have been compiled in an earlier report on this topic by AJAKAIYE/FUBARA/RUHUKYA (1977). I shall recall these arguments and add some more recent IAG-resolutions and new arguments.

1. Utilization of Gravity Values

The following list (fig. 1) presents an overview of the various applications where gravity values are essential. In some respect the requirements of geodesy are most challenging: Geoid determinations require a good coverage and perfect homogeneity, geodynamic studies call for utmost precision.

Utilization of Gravity Values

	Application	Type	Accuracy	Limitation
Metrology:	Standard of force (Mercury-barometer electric current standards)	Point gravity	± 1 ... 0.1 mGal absolute	
Geophysics:	Local studies	Point anomalies, Bouquer type	± 0.1 ... 1 mGal relative	Topographic reduction
	Regional studies	Mean anomalies, Bouquer type	± 1 mGal relative	Topographic reduction & representation
Geodesy:	Global geoid	Mean anomalies, Free air type	± 1 mGal absolute	Representation & Earth model requirement
	Height	Point gravity	± 10 mGal absolute	Levelling accuracy
	Geodynamics	Points gravity	± 3 μGal absolute	Environmental effects

Fig.1: Utilization of Gravity Values

2. Geodetic Applications of Gravity Values

2.1 Global Geoid/Earth Model/Hight Reference

In order to define the height of a point on the surface of the Earth one may either use the height above the ellispoid, perhaps derived from satellite positioning, or the height above "mean sea level", more precisely the height above the geoid, derived from levelling. In order to compare or combine these two height concepts, we have to know the separation of the two reference surfaces, namely the ellipsoid and the geoid (fig. 2). Instead of the geoid and orthometric height above geoid we also could use the "normal height" of the socalled telluroid above the ellipsoid plus height anormaly. Because the differences of the two concepts, geoid plus orthometric height versus normal height of the telluroid plus height anormaly are mainly of academic interest, we shall stick to the convenient geoid-orthometric height concept.

The separation of the geoid from the ellipsoid depends on the mass distribution within the Earth. Because mass anomalies lead to anomalous gravitation and consequently to gravity anomalies, the geoid can be computed from global gravity anomalies. After MORITZ (1975) we need to have a global gravity base net of $\pm$ 0.1 mGal standard deviation in order to obtain a global geoid to decimeter accuracy. Because the mass anomaly likewise attracts an Earth satellite, we also can analyse the orbit as observed by satellite geodesy, particularly by means of laser ranging.

The current geoid determination combines laser ranging data and terrestrial gravity data. Because of the different height levels of the two sensors - terrestrial gravity meter on the surface of the Earth versus satellites in several hundreds to a few thousands of kilometres height - the satellite derived geoid features exhibit longwave details down to about 5000 km. Shortwave information on the oceans may be derived from satellite altimetry, on land areas only from terrestrial gravimetry. Figure 2 also visualizes that we have to know the geoid in order to fit an optimal mean earth ellipsoid Furthermore from figures 2 and 3 we can see, that improving gravity anomaly knowledge means improving satellite orbit determination and consequently also point positioning by satellite methods.

As shwon in fig. 4 there are still large gaps of terrestrial gravity anomalies in Greenland, Antarctica, the Soviet Union, Latin America and Africa, which need to be closed. This data set has been employed in the most recent GRIM3 Earth model (REIGBER et al. 1985).

As to the station density, only 1 station per $1^{\circ} \times 1^{\circ}$ may be sufficient for global geoid studies, if this point anomaly represents the block mean value. Because of the variation of local free air anomaly, representation error normally is much bigger than observation error. In order to reduce this error source and in view of local geoid studies station spacings of some tens of kilometres would be appropriate, depending on the ruggedness of topography and crustal density.

2.2 Height Determination by Spirit Levelling

Heights above mean sea level from spirit levelling are derived from

$$H = \frac{C}{\bar{g}}$$

$$C = \int g \, dh$$

where

H	height above sea level
C	geopotential number
g	gravity value along levelling line
$\bar{g}$	mean gravity value below station

Omitting the discussion about different height systems, we always need gravity values along (spirit) levelling lines. Thus for a precise height system we need to have some idea about gravity. Accuracy requirements are not demanding, i. e. accuracies of only some 10 mGal at point spacings of about 10 ... 100 km depending on ruggedness of the gravity field (c.f. RAMSAYER 1963).

2.3 Geodynamics/Gravity Changes

In all cases where a density contrast surface moves or where a mass changes density e.g. through heat impact, gravitational attraction changes and consequently observed gravity values change. Thus a wide spectrum of geodynamic processes can be investigated through monitoring gravity changes with time. As can be explained through conservation laws of physics, mass transfer at one place of the Earth causes a change of the Earth's rotation vector (spin velocity and direction) and consequently through centrifugal acceleration again gravity (BOEDECKER 1984) (fig. 5).

ELSTNER (1980) presents the (time-) spectral distribution of gravity variations. MATHER (1972) gives a thorough discussion on the extension from three- to fourdimensional geodesy including gravity variations. BOULANGER (1983), after a wide summary report concludes, that global gravity variations are of the order of a few microgal per year. In contrast, BIRO at al. (1984), on the basis of Barta's ideas, computed possible gravity variations two orders of magnitude higher. RICHTER (1983) showed, that gravity effects of polar motion throught centrifugal acceleration of the order of a few microgal can be verified by superconducting gravity meter recordings. In any case utmost attention has to be paid to purely local disturbances as e. g. groundwater variations, nearby construction works etc.

Easier than the observations of global gravity variations are, of course, local and regional nets with tens to hundreds of kilometres traverses or nets in active regions, because they reach typically a few to some tens of a microgal per year (e.g. TORGE 1982, c. f. BOULANGER 1983). In order to separate gravity changes from vertical motions of the observation point, repeated levellings have to be carried out. In global nets geometric information cannot be obtained from levelling anymore. It is necessary, to utilize information from global geometric networks such as satellite laser or VLBI-station networks, which can provide cm-accuracy. Thus the collocation of as many high precision gravity stations with geometric stations as possible is necessary (c.f. BOEDECKER 1984).

3. Referring IAG 1984 Resolutions

RESOLUTION N° 8

The International Association of Geodesy,

recognizing that the study of many geophysical phenomena in the 200 – 2000 km range of wavelength is severely handicaped by large gaps in the available surface gravity coverage, especially over land,

urges all countries to release their land gravity measurements to the scientific community via the International Gravity Bureau ; if national interests prevent the release of detailed data, national agencies are requested to release $1° \times 1°$ mean values of free air gravity anomalies and elevations, which are of fundamental importance for global scientific pursuits.

RESOLUTION N° 9

The International Association of Geodesy,

recognizing the high level of accuracy of both absolute and relative gravity measurements recently attained,

considering the necessity to adopt standard corrections to gravity observations in order to allow intercomparisons between measurements at different epochs of time,

recommends :

1. that the *tidal correction* applied to the gravity observations follow the final recommendations of the Standard Earth Tide Committee as presented at the XVIII IUGG General Assembly,

2. that the *atmospheric pressure corrections* refer to a common Standard Atmosphere, the sensitivity coefficient being $0.3 \, . \, 10^{-10}$ m s^{-2} / Pa (0.3 microgal / mbar), unless it is determined by special investigations, in which case the value used must be published together with the results. The closed formula for the computation of this Standard Atmosphere will be published in a future issue of the Bulletin d'Information du Bureau Gravimétrique International with the corresponding numerical tables and the programming code.

3. that the *gravity gradient corrections* be published with the adopted local gradient and / or the adopted height difference so that the original values may be recovered.

RESOLUTION N° 10

The International Association of Geodesy,

recognizing that techniques of repeated relative gravity measurement have achieved increased accuracy and have been applied :

1. as a fast and efficient tool to detect and investigate gravity changes associated with recent crustal movements,

2. in combination with other techniques such as levelling and VLBI to give a deeper insight into the underlying dynamic processes,

3. as an element in earthquake prediction research, and

noting the success of recent campaigns in various parts of the world,

recommends that high priority be given to this research.

RESOLUTION N° 11

The International Association of Geodesy,

recognizing that the physical interpretation of time variations of the natural coordinates, height above sea level, and astronomic latitude and longitude, requires knowledge of the time variation of the earth's gravity field, and

considering that this latter can be determined by a world–wide net of gravity stations with repeated precise observations of absolute gravity and height above the current mean sea level,

recommends that efforts be made to observe and reobserve a large number of such stations favourably distributed around the globe.

RESOLUTION N° 16

The International Association of Geodesy,

recognizing the need for the uniform treatment of tidal corrections to various geodetic quantities such as gravity and station positions, and

considering the reports of the Standard Earth Tide Committee and S.S.G. 2.55, Predictive Methods for Space Techniques, presented at XVIII General Assembly,

recommends that :

1. the rigid Earth model be the Cartwright – Tayler – Edden model with additional constants specified by the International Centre for Earth Tides,

2. the elastic Earth model be that described by Wahr using the 1066 A model Earth of Gilbert and Dziewonski,

3. the indirect effect due to the permanent yielding of the Earth be not removed, and

4. ocean loading effects be calculated using the tidal charts and data produced by Schwiderski as working standards.

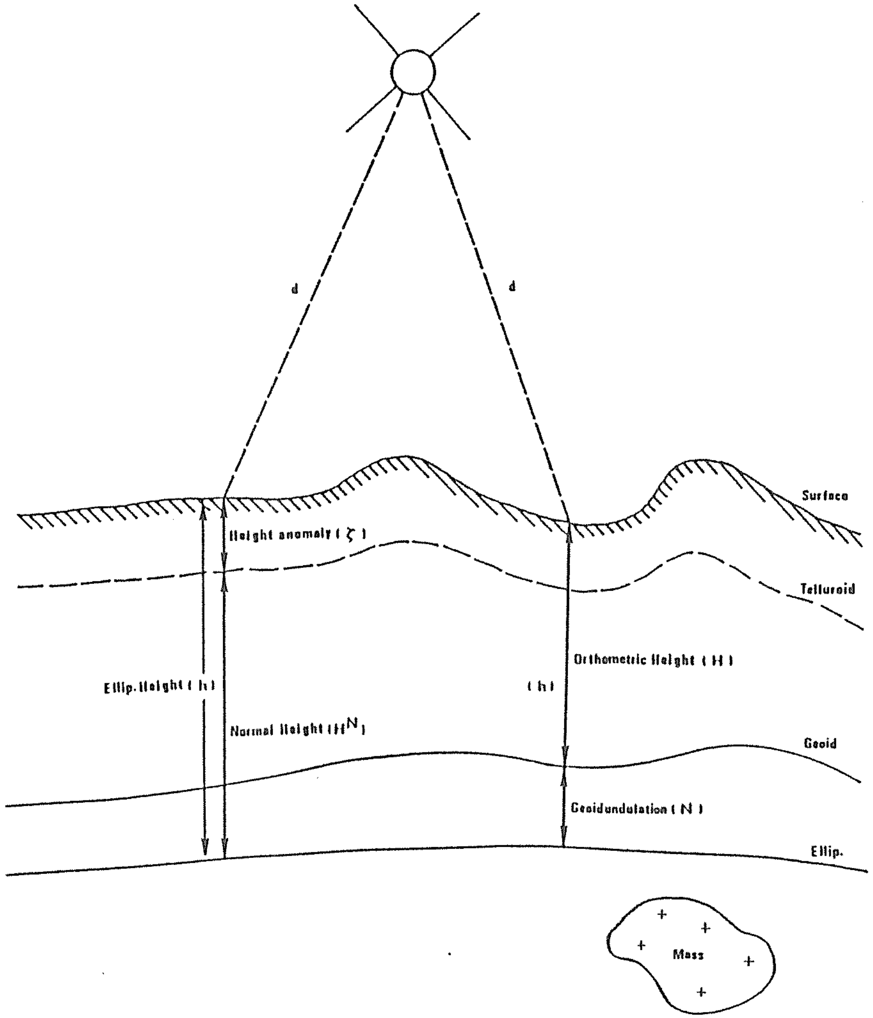


Figure 2: Height Reference

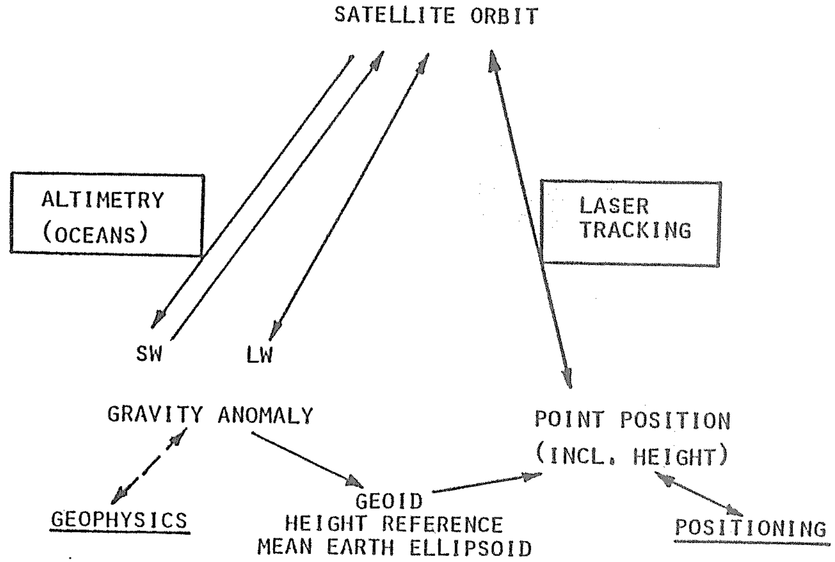
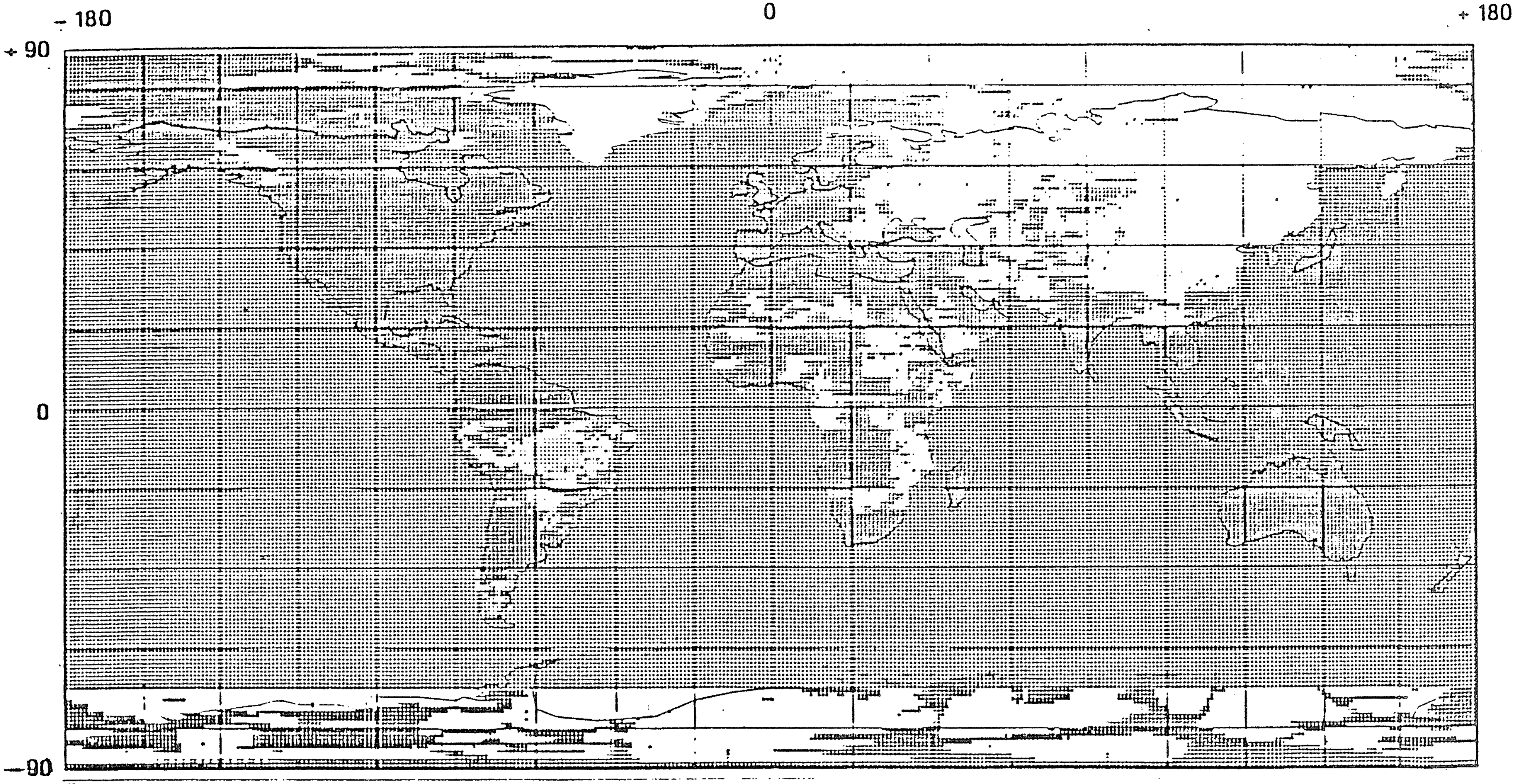


Figure 3: Some Interrelations around Gravity Anomalies

VERTEILUNG UND HERKUNFT DER 1 x 1° FREILUFTANOMALIEN



ÜBERDECKUNG 87,7 % DAVON 61,0 % AUS ALTIMETRIE △
28,1 % TERRESTRISCHE BEOB. □
10,9 % GEOPHYSIK. PRÄDIZIERT —

Fig. 4: Free Air Anomaly Quality Distribution

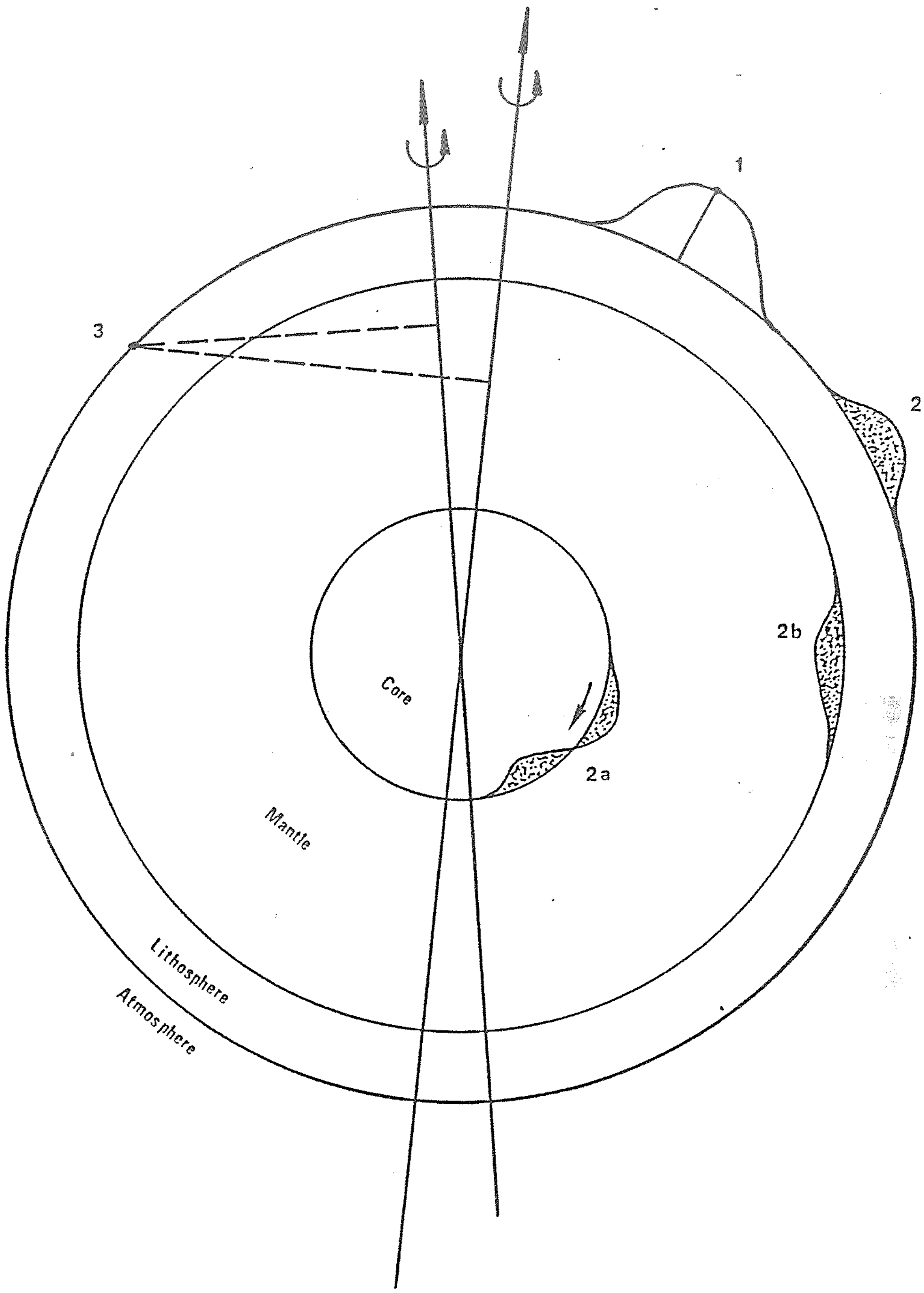


Figure 5: Geodynamic Gravity Changes: Schematic diagram of some possible sources of interest for gravity changes such as height variation of observation station (1), gravitation variation through mass change e.g. at core/mantle (2a), mantle/lithosphere (2b), crust (2c), or centrifugal acceleration variation (3).

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PART III

CONTRIBUTING PAPERS

DETECTION OF REGIONAL BIAS IN 1°X1° MEAN TERRESTRIAL GRAVITY ANOMALIES

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Abstract

This paper compares the terrestrial gravity field in two ways. The 1°x1° mean terrestrial anomalies are first compared to corresponding values derived from the NASA GEML2 field which is complete to degree 20. Much of the difference is due to the neglected higher degree terms in the potential field expansion. We then computed a spherical harmonic expansion of the terrestrial data and differenced this expansion with the GEML2 field. The resultant differences in the space domain were then plotted when the residuals exceeded 20 mgals. Most of the large residual values occur for geophysically predicted 1°x1° mean anomalies. This is preliminary evidence that such anomalies have systematic errors.

1. INTRODUCTION

Gravity anomalies on the surface of the earth can be determined from terrestrial data and from satellite observations. It is possible to compare such values recognizing the different wavelengths that each type is sensitive to (Rapp, 1978). A comparison of the two gravity fields, in a proper way, might reveal systematic errors in the terrestrial data that should be corrected. Such error could be due to incorrect gravity base station systems, or an incorrect vertical (height) datum. Height datum errors propagate into the anomalies since heights are required for the computations of the anomalies.

The satellite implied anomalies can be derived from potential coefficients inferred from the orbital motion of the satellite. Such coefficients are independent of base station networks or height datum.

The terrestrial data, Δg_T, to be used in this analysis is a set of 1°x1° mean free air gravity anomalies described by Rapp (1983) and is referenced to GRS67. These values have accuracies that range from ± 1 mgal to ± 65 mgals. The potential coefficients used are those of GEML2 (Lerch et al., 1982). They are complete to degree 20 with additional terms to degree 30, order 28.

2. COMPUTATIONS

All the GEML2 fully normalized potential coefficients ($\bar{C}_{nm}$ and $\bar{S}_{nm}$), up to degree 30 were used to compute the Δg_S implied by this model using the following:

$$\Delta g_s(r, \bar{\phi}, \lambda) = - \delta g + \frac{GM}{r^2} \sum_{n=2}^{30} (n-1) \left(\frac{a}{r}\right)^n \sum_{m=0}^{n} (\bar{C}^*_{nm} \cos m\lambda + \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm} (\sin\bar{\phi}) \quad (1)$$

In equation (1) the gravity anomalies are computed at a point on the ellipsoid with geocentric coordinates r, $\bar{\phi}$, λ. The $\bar{P}_{nm}(\sin\bar{\phi})$ are the fully normalized associated Legendre function; the $\bar{C}^*_{nm}$ values are the GEML2 values of $\bar{C}_{nm}$ minus the even degree zonal coefficients implied by an ellipsoid whose flattening was that of GRS67. GM is the geocentric gravitational constant and a is the nominal equatorial radius associated with GEML2 coefficients. δg is the atmospheric correction term (Balmino, 1983) that is to make the potential coefficients implied anomalies consistent with the terrestrial anomalies. δg is slightly dependent on elevation but a nominal value of 0.87 mgal was used here.

The values of Δg_s were computed at the center of the 1°x1° blocks. Figure 1 shows the location of those blocks where the absolute difference between Δg_s and Δg_T exceed 50 mgals. These differences are primarily caused by neglected higher degree terms in the GEML2 coefficient set. The differences can also be caused by errors in the terrestrial data. Statistical information on the two data sets is given in Table 1.

A more meaningful comparison of the two gravity fields could be made by comparing them when they have the same spectral content. In essence we could construct a smooth terrestrial field by first expanding the terrestrial data into a spherical harmonic expansion and then computing the "smoothed" anomalies from the expansion. The surface spherical harmonic expansion of the anomalies can be represented in the following form:

$$\Delta g(\phi, \lambda) = \sum_{n=o}^{\infty} \sum_{m=o}^{n} (\bar{A}_{nm}\cos m\lambda + \bar{B}_{nm}\sin m\lambda)\bar{P}_{nm}(\sin\phi) \tag{2}$$

where $\bar{A}_{nm}$ and $\bar{B}_{nm}$ are fully normalized harmonic coefficients. Given a global field of Δg values the coefficients of (2) can be computed from the following

$$\begin{Bmatrix} \bar{A}_{nm} \\ \bar{B}_{nm} \end{Bmatrix} = \frac{1}{4\pi} \iint_{\sigma} \Delta g(\phi, \lambda) \begin{Bmatrix} \cos m\lambda \\ \sin m\lambda \end{Bmatrix} \bar{P}_{nm}(\sin\phi)d\sigma \tag{3}$$

Since the terrestrial data is not global, the GEML2 implied gravity anomalies were used to fill in the empty areas. Then equation (3) was implemented to obtain the harmonic coefficients to degree 30. Inserting these coefficients into equation (2) one obtains smoothed terrestrial gravity anomalies, $\Delta g_{T'}$.

TABLE 1. Statistical Information on Gravity Anomalies Used. (Units are mgals)

	Δg_T	Δg_S	$\Delta g^*_{T'}$	$\Delta g_{T'} - \Delta g_S$
n	44513	64800	64800	64800
MEAN	0.0	-0.9	-0.1	0.8
RMS	28.6	14.3	15.4	7.3
MIN	-282	-52.5	-58.0	-34.6
MAX	365	45.8	65.5	45.8

* based on an expansion to degree 30.

The magnitude of $\Delta g_T'$ varied from -58 to 66 mgals. The root mean square value of $\Delta g_T'$ was ±15.4 mgals which is quite similar to that obtained from the GEML2 coefficients (i.e. ±14.3 mgals). Statistical information on the difference between Δg_s and $\Delta g_T'$ is given in Table 1. Figure 2 shows the location of the 946 blocks where the absolute value of the difference ($\Delta g_T' - \Delta g_s$) exceeds 20 mgals.

Equations (1) and (2) can be computed very efficiently with a computer program based on the idea of (Rizos, 1979). A CPU time of 5.6 seconds was required to compute Δg's on a regular grid of 1°x1° over the Earth, from coefficients up to degree and order 30.

Equation (3) can be computed very efficiently with the computer program HARMIN (Colombo, 1981) based on the use of fast Fourier Transform. A CPU time of 6.0 seconds was required to compute $\bar{A}_{nm}$ and $\bar{B}_{nm}$ up to degree and order 30.

3. ANALYSIS

Of the 44513 anomalies in the January 1983 terrestrial file, 6361 of them have been estimated by geophysical prediction techniques (Wilcox, 1974). Some of the substantial differences between $\Delta g_T'$ and Δg_s occur in areas having geophysically predicted anomalies. Such areas are "circled" in Figure 2. There seems to be a clear bias in some of the predicted anomalies. However many of the geophysically predicted anomalies in South America, south east Africa, Greenland, the Soviet Union and China do not show a bias.

The discrepancies in the northern part of India must clearly reflect error in our terrestrial data. The inconsistency of data sources in this area was described in Rapp (1983).

The isolated discrepancies in the other areas of Figure 2 indicate areas in which the terrestrial data needs to be carefully checked. Unfortunately some of the areas are not well surveyed gravimetrically because of various accessibility problems.

Clearly an effort is needed to improve our terrestrial data base, especially in areas identified in Figure 2. However many of the areas shown are in regions where gravimetric data is not released so that no checking will be possible. On the other hand new data sources are becoming available in regions of currently poor coverage that will improve the situation.

4. Acknowledgement

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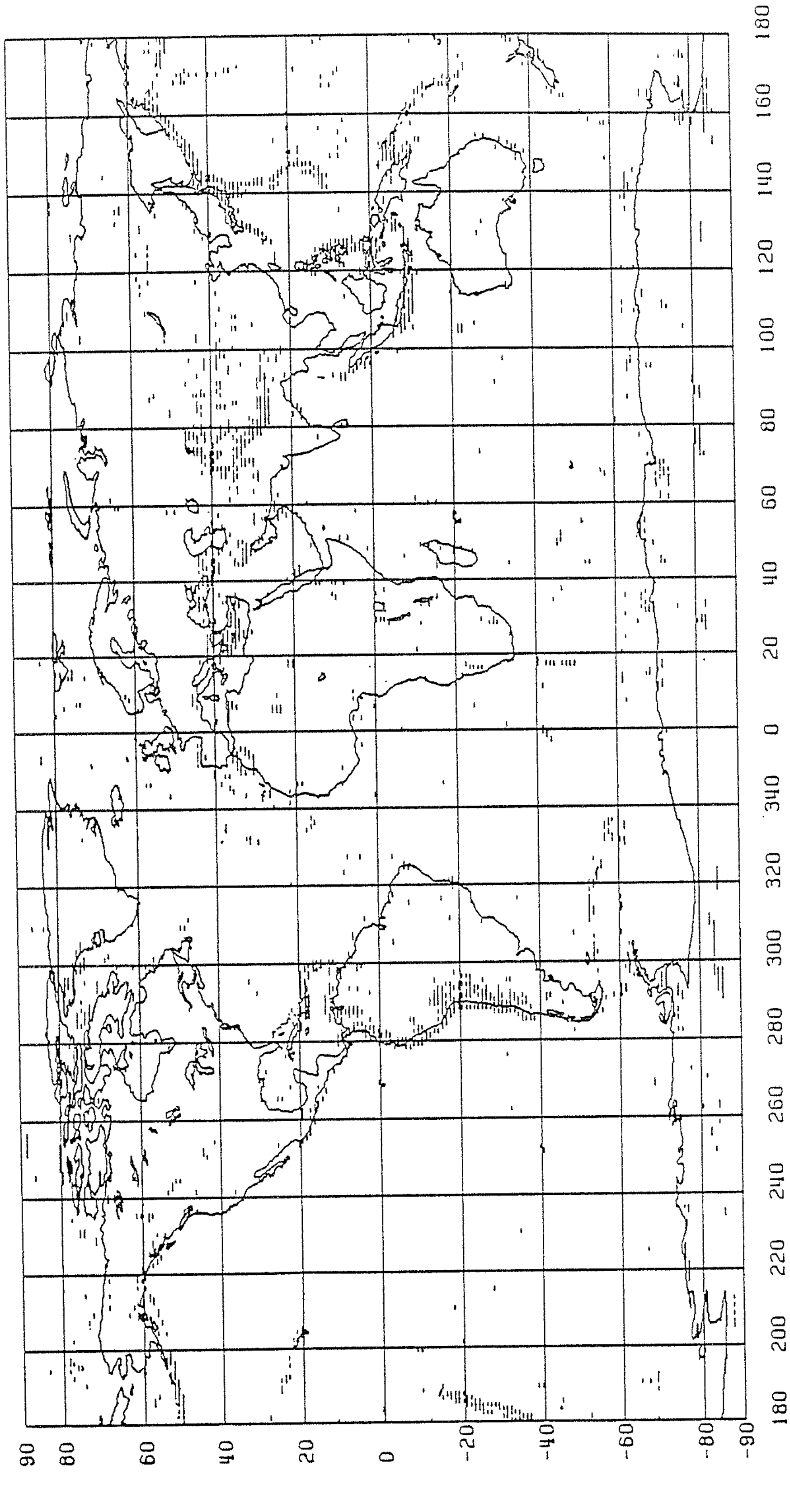
Figure Legends

Figure 1 Location of Blocks Where $|(\Delta g_s - \Delta g_T)|$ Exceeds 50 mgals

Figure 2 Location of Blocks Where $|(\Delta g_s - \Delta g_T')|$ Exceeds 20 mgals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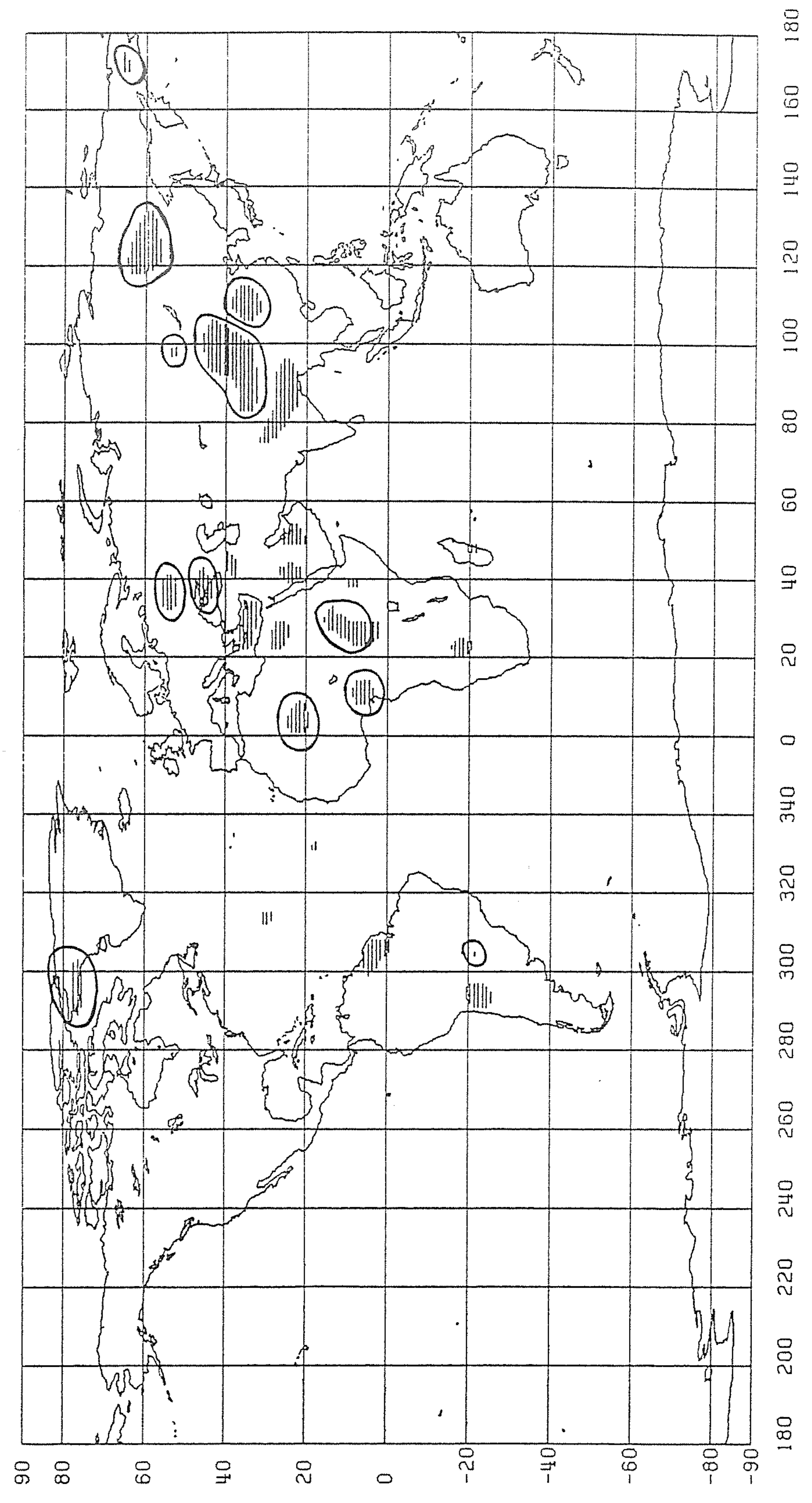
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90 80 60 40 20 0 -20 -40 -60 -80 -90