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Rectifying Note concerning the BELL gravity meter

In our Bulletin d'Information N° 35, p.I-49, we reported a wrong information on this gravity meter.

We publish, hereafter, the letter sent by the Bell Aerospace Company about the production of this instrument.

Gentlemen:

We have read the report of the Seventh Annual Meeting of the International Gravity Commission (Bureau Gravimetrique International No. 35 November 1974) which states that the Bell gravity meter is no longer on the market.

We wish to state that the Bell gravity meter is definitely on the market.

Bell Aerospace has been and is a leader in the development and production of precision inertial instruments and systems for over twenty years. We have been producing gravity meters for ten years. In the judgement of the U. S. Naval Oceanographic Office, the contributions made by Bell Aerospace have significantly advanced the state-of-the-art of gravity measurement instrumentation.

The Bell gravity meters are being used by the U. S. Navy, Oil and Survey companies and have a proven reputation of high accuracy combined with minimum loss of operational time and data. To maintain this reputation it has been necessary, on occasion, to defer purchase requests when in our judgement we were not in a position to provide systems that would meet these high standards. This policy will be maintained, however, we have not had any difficulty in responding to new requests during the past year, nor do we foresee any difficulties responding to requests in the future.

During the recent years Bell has been continuing to upgrade the performance of the gravity meter through improvements in the gravity accelerometer, the system reliability and the processing and recording of the data.

Bell's current efforts in related areas include the development of an extremely precise gravity gradient meter capable of being used on aircraft, surface ships and submarines. Special techniques are incorporated that allow use of components that are within the current state-of-the-art. We are also expanding the gravity meter capability by the addition of real time Eötvos correction.

It is our hope that this letter will clarify and emphasize Bell's continuing desire to be of service to the gravity meter community.

Yours very truly,

18 April 1975

R. N. Burnfield

R. N. Burnfield
Technical Director
Gravity Meters
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Bell Aerospace Company

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T A B L E des M A T I E R E S

1ère Partie

2ème Partie

S. CORON
Acting Director I.G.B.

* Published in : J. Spacecraft and Rockets, v.11, n°9, p.637-644, Sept. 1974.

A

VARIOUS TOPICS

1°) International Gravity Net

In Bureau of Mineral Resources Bulletin 161 "Australian and Soviet gravity surveys along the Australian Calibration Line" by WELLMAN, BOULANGER, BARLOW, SHCHEGLOV & COUTTS an error was made in that it was assumed that station 6491.0160 was Hobart K (49027 K). It is now suggested that station 649.0160 be given the letter T (Hobart I, 49027 T).

N.G. CHAMBERLAIN
Letter of 20.2.1975

2°) Gravity Surveys at Sea - Projects

(Complement to Bull. Inf. N° 34, p.I-14).

- U.S.A. - SCRIPPS INSTITUTION of OCEANOGRAPHY, UNIV. of CALIFORNIA

The Institution recently acquired a Graf-Askania sea gravimeter and has begun a continuing program of observation and analysis.

In March and April, the gravimeter was used aboard the R/V THOMAS G. THOMPSON of the University of Washington; in support of a seismic investigation of the east flank of the East Pacific Rise and the continental margin of Mexico between the Clipperton and Orozco Fracture Zones.

In June and July, the meter was installed aboard the R/V THOMAS WASHINGTON and an investigation was made of the Siqueiros Fracture Zone, with emphasis on the gravity edge effect and the structural changes across the fracture zone and transform fault as revealed by seismic refraction.

From August, 1974 to July, 1975, on Expedition EURYDICE, gravity measurements will be made in the western Pacific and eastern Indian Oceans as part of a multidisciplinary cruise.

LeRoy M. DORMAN
Letter of 29.7.1974

- UNITED KINGDOM - UNIVERSITY of CAMBRIDGE, Dept. of Geodesy & Geophysics.

We have a cruise, on which Dr. R.B. WHITMARSH is to be senior scientist in a ship sailing from Djibouti (French Somaliland) via Dubai (Trucial Oman) to Bombay.

D.H. MATTHEWS
Letter of 6.3.1975

B

COMPTE-RENDU of the VIIth MEETING of the INTERNATIONAL GRAVITY COMMISSION

Paris, September 2 - 6, 1974 (continued)

- IV -

INTERNATIONAL GRAVITY STANDARDIZATION NETWORK

Special Study Group n°3.05

One meeting was held on Friday morning 6th September, under the leadership of Prof. C. MORELLI, Chairman of the Special Study Group : "World-wide Gravity Net".

Prof. W. TORGE (Hannover) presents a paper* summarized hereafter :

Error analysis of gravity measurements carried out in 1972 with LaCoste-Romberg gravity meters along the northern part of the European Calibration Line.

In 1972 the northern part of the European Calibration Line between Irschenberg South of Munich (g = 980 618 mGal) and Bodö (g = 982 373 mGal) has been observed with 8 resp. 9 LaCoste-Romberg gravity meters. Main reason for the project was the determination of the calibration factors and possibly of non-linear terms of the calibration functions. Altogether 64 stations have been occupied, 19 of which are clearly identified IGSN-71 stations. The average gravity distance between adjacent points is 100 mGal. In the south and in the north, a densification over 370 resp. 220 mGal has been carried out, reducing the average gravity difference to 20 resp. 10 mGal.

The main results of the investigations are :

1. Different LCR gravity meters may give significant differences in accuracy, ranging from ± 0.02 to ± 0.1 mGal for one observation.
2. A physical correlation due to common transport could not be detected from this survey.
3. Significant linear long-time drift of different sign and order (0.1 ... 1.0 mGal/1000 h) may occur at field measurements.
4. Significant quadratic calibration factors may occur. If taken into account, the results improve significantly. The question whether the instruments or the IGSN 71 stations cause this effect, remains open. The calibration factors have been determined with ± 1... 3.10^{-5} accuracy.
5. Higher order drift and calibration terms at the order of 0.01... 0.02 mGal are to be supposed, their evaluation being hardly possible.

* It will be published in the Deutsche Geodätische Kommission, Reihe B, München, in 1975.

6. Using a few instruments of good quality, carefully calibrated at some IGSN 71 stations, accuracy of about ± 0.01 mGal, referring to the level and scale of the IGSN 71 stations, may be obtained in the calibration range.
7. The 0.01 mGal accuracy level seems to be sufficient for the field work procedure commonly employed, as some other sources generally neglected may produce errors of the same order.

We mention the identification errors in position and height if the stations are not monumented, uncontrolled mass shifts and height variations at and near the station, variations of ground water level and of air pressure, variable effects of ocean tides at coastal stations, and time variations of the calibration functions.

Prof. C. GERSTENECKER (Darmstadt) reports on : <u>Calibrational problems</u> - <u>Investigation of calibration functions.</u> (See p. I-7). He mentions particularly that the linear scale factors can be determined with an accuracy of $\pm 1.10^{-4}$ and the power spectra of the calibration functions show peaks, which indicate periodical errors.

Dr. B.S. SCHULZ says : "It is sure that the gravity measurements with different types of gravity meters along a gravity calibration line in the IGSN are independent but show the same apparent non-linearity . Cannot we then conclude from this that this apparent gravimeter scale non-linearity would be due to the non-linearity of the IGSN rather than to common non-linearity characteristics of many types of gravity meters ?

Mr. R.K. McCONNEL mentions that : "Apparent non-linearities in the scale of the IGSN 71 were noted at the time the Working Group was carrying out the IGSN adjustment. These occurred at the extremes of gravity where we have few absolute measurements. UOTILA found that the inclusion of second order scale unknows for the gravimeters seemed to give better results ; but without the necessary absolute measurements to control error propagation at the extremes of gravity we will not be able to define a second order scale term with any degree of certainty.

Then Prof. W. TORGE makes some remarks :

a) Might the results of the adjustments be influenced by changes in the airport stations, partly established already in 1958/59 by Dr. BETTAC
b) Is the accuracy obtainable in scale factor, which you give with $\pm 10^{-}$ for the 1800 mGal range, not too low ? From our investigations an average accuracy of the order $\pm 10^{-5}$ might be obtained

Dr. P. WELLMAN (Australia) presents a paper (see p. I-16) : "Comparison of Western Pacific and Australian Calibration Line, gravity scales and an evaluation of secular variation".
(P. WELLMAN, B.C. BARLOW & D.A. COUTTS).

He points out particularly that : "LaCoste and Romberg gravity meter measurements suggest that the IGSN 71 scale on the Western Pacific Calibration Line is about 3 ± 1 parts in 10^5 smaller than the GAG-2 gravity meter scale along the Australian Calibration Line.

Mr. R.K. McCONNEL wonders why a scale based on the GAG gravimeters would be adopted in Australia simply because a discrepancy between GAG meters and the IGSN 71 have been observed since the IGSN 71 is an internationally standard.

Prof. G.P. WOOLLARD asks : "What is the history of stability of the Russian pendulums. Other pendulums (Gulf Quartz pendulums and Cambridge invar pendulums), both have a history over more than 30 years of going through periods of instability (creep and susceptibility to tares) and then recovering stability for several years.

It is therefore no guarantee that using the Russian pendulums in Australia will provide a better standard and datum than has been derived from the IGSN 71 solution.

Prof. Yu.D. BOULANGER mentions that Sydney is strongly tied to Moscow and Potsdam by recent Soviet OVM pendulum work (Gusev, 1973) and gravity meter ties, and that Soviet result at Sydney A, agrees at 0,02 mGal with the IGSN 71 value : 979671.86 mGal (adopted as the new datum for Australia).

He adds that the Soviet work suggests a correction to Potsdam datum of - 13,95 ± 0.05 mGal.

Dr. Cl. ELSTNER & G. HARNISCH sent too late for distribution at the I.G.C. a paper on : Gravity connections between Potsdam, Moscow and several stations of IGSN 71. *

... The investigations show the need for an exact determination of the localizations at the single stations and the structure of the gravity field in the nearest surrounding, to get comparable results within 10 µGal or better. Also the determination of the gravity differences to the excentres should be done as accurate as possible. The used data confirm the IGSN 71 gravity value at Potsdam with an error of about ± 0.02 mGal. With nearly the same accuracy a gravity value for Moscow (Ledovo) was determine

* The complete text will be published in the next Bulletin d'Information.

Calibrational problems
- Investigation of calibration functions -

by C. Gerstenecker, Darmstadt

A b s t r a c t

The calibration functions of the LaCoste-Romberg-Gravimeter LRC-G-195 and LCR-G-258 are tested according to scale factors, time depending changes and periodical errrors.

As results were found:

Linear scale factors can be determined with a accuracy of $\pm 1 \cdot 10^{-4}$. The use of quadratic scale factors is not advisable. The calibration functions are not changed within a period of three years. The power spectra of the calibration functions show peaks, which indicate periodical errors.

1) Introduction

The calibration functions for LaCoste-Romberg-Gravimeters were determined by the manufacturer

1. in the laboratory while placing various weights on the gravimeter-beams
2. in the field while measuring well-known gravity differences.

These calibration functions generally differ from the scale of the International Gravity Standardization Net 1971 (I.G.S.N. 71), include periodical errors, (Honkasalo, 1971; Eberhard, 1967) and may change depending on time.

2) Observations

The calibration functions of the LaCoste-Romberg-Gravimeters G-195 and G-258 will be tested according to these mentioned features as follows.

The tests were based on gravity measurements, carried out on a part of the I.G.S.N.71 (see fig. 1).

The net comprises all together 38 measurements for the LCR-G-258 and 20 measurements for the LCR-G-195. The instruments were transported by air, except the trips between Frankfurt-Darmstadt, Darmstadt-Zürich-Stuttgart-Darmstadt and Darmstadt-Stuttgart-München, which were carried out by car.

The maximum gravity difference on this net amounts to about 1900 mgal.

2) Linear and quadratic scale factors

For the adaption of the calibration function to the scale of the I.G.S.N.71 linear and quadratic scale factors are calculated on the basis of the above measurements according to the equations (1) and (2) by adjustments.

$\Delta g = \Delta \bar{g}\ (1 + m)$ (1)

$\Delta g = \Delta \bar{g}\ (1 + m_1 + m_2)$ (2)

Δg = gravity difference in the scale of the I.G.S.N.71

$\Delta \bar{g}$ = gravity difference in the scale of the manufacturer

m = linear scale factor

m_1, m_2 = terms of a quadratic scale factor

The observations are adjusted with the aid of choice of various weights, according to which

$p = 1/\Delta t$ (3)

respectively

$p = 1/\Delta s$ (4)

is given.

p = weight

Δt = time for the measurement of the gravity difference between two points P_i and P_{i+1}

Δs = distance between P_i and P_{i+1}.

For the results see table 1 and 2.

The scale factors m agree for both calibration functions during adjustment according to (1).

The choice of weights according to (3) and (4) do not alter the results signicicantly.

The relativ errors r of the gravity differences Δg are calculated from the standard errors of the I.G.S.N.71 according to

$$s_{\Delta g} = \sqrt{s^2 g_i + s^2 g_{i+1}} \qquad (5)$$

$$r_{\Delta g} = s/\Delta g \qquad (6)$$

and amount $1.8 \cdot 10^{-4}$ on the average. If this errors are considered simultaneously, it becomes obvious, that an accuracy above $\pm\ 1 \cdot 10^{-4}$ for the scale factors m cannot be obtained on this part of the I.G.S.N.71 due to net-tensions.

Changes of m within a range of $\pm\ 1 \cdot 10^{-4}$ may therefore be caused too by net-tensions.

The calibration functions are not improved considerably by a quadratic scale factor. The terms of 1.st.o. m_1 do not significantly differ from m for both instruments. m_2 is small for the LCR-G-258. If neglected, it produces a deviation of 30 μgal with a gravity difference Δg of 1000 mgal. This deviation is generally below the standard error $s_{\Delta g}$ of Δg.

m_2 for the LCR-G-195 is larger than the term of 2.nd.o. for the LCR-G-258. However, this term is not significant because of its standard error (Marzahn, 1957). It is therefore not advisable to use non linear scale factor.

4) Time depending changes of the calibration functions

In order to test the time dependence of the calibration functions the above measurements for the LCR-G-195 were subdivided into two groups, connected within a certain space of time, these for the LCR-G-258 into three groups.

For the results see table 3.

The results indicate that the time-depending changes of the linear factors m do not exceed $1.2 \cdot 10^{-4}$ for both instruments. Changes of these orders may be interpreted according to chapter 3 also as net tensions of the I.G.S.N.71 or as non-linearities of the calibration functions, since the measurements of the different groups were carried out on different parts of the net (see also Gantar, McConell in I.G.S.N.71).

Significant time depending changes of the calibration functions regarding gravimeters LCR-G-195 and LCR-G-258 cannot be proven within a period of three years.

5) Periodical errors of the calibration functions

Periodical errors of the calibration functions could not be shown. Scale factors, calculated from measurements of the northern part of the European gravimeter calibration line (EGCL) regarding the LCR-G-195 and the LCR-G-258, indicate a strongly alternative correlation, that may be interpreted more as net tensions in the EGCL (fig. 2) than as periodical errors of the calibration functions.

Periodical errors can probably be determined only on special extra-precise calibration lines.

But the analysis of power spectra of both calibration functions demonstrates, that the calibration functions themselves contain frequencies, which may produce periodical errors.

Distinct peaks appear at 143, 100, 71, 61, 50 and 47 revolutions of the counter dial above the noise-level. The period of 71 revolutions may correspond to that of 70.88 revolutions given by Kukkasalo, 1971 (see fig. 3).

Substitution of the calibration functions - uncontinous in the samples - by a continous spline - function (Sauer, Szabo, 1968), had no smoothingeffect on the power spectrum.

The peaks are not caused by the uncontinous calibration functions.

6) Conclusion

The adaptation of the calibration functions of the LCR-G-195 and LCR-G-258 to the scale of the European Part of the I.G.S.N. 71 is sufficiently accurate with a linear scale factor m.

The standard error of m cannot be considerably below $\pm 1 \cdot 10^{-4}$ due to net-tensions.

The calibration functions of both instruments can be considered sufficiently stable ($\pm 1 \cdot 10^{-4}$) within a period of three years. The power spectra of the calibration functions show peaks, which indicate periodical errors.

A spline function substituting the calibration function has no smoothing effect.

7) Acknowledgement

We are grateful to the German Research Society, that sponsored this paper.

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Table 1
Results for a linear scale factor m

Instrument	$m[1\cdot10^{-4}]$	$m[1\cdot10^{-4}]$	$m[1\cdot10^{-4}]$
	p = const	p = 1/Δs	p = 1/Δt
LCR-G-195	4.0 ± 0.7	4.6 ± 0.7	4.8 ± 0.7
LCR-G-258	4.2 ± 0.6	4.1 ± 0.6	4.3 ± 0.5

Table 2
Quadratic scale factors m_1 and m_2

	p = const		p = Δ/s		p = Δ/t	
	$m_1[10^{-4}]$	$m_2[10^{-8}]$	$m_1[10^{-4}]$	$m_2[10^{-8}]$	$m_1[10^{-4}]$	$m_2[10^{-8}]$
LCR-G-195	+3.9±.7	-2.1±1.5	+4.8±0.8	-1.3±2.1	4.9±.7	-1.6±1.8
LCR-G-258	+4.2±.6	- .3± .5	+4.1±0.6	-0.3± .8	+4.2±.5	- .3± .5

Table 3
Changes of linear scale factors m depending on time

	m_{1969}	m_{1971}	m_{1972}	m_{1973}
LCR-G-195	+ 3.8 ± .9	- - -	+ 5.2 ± 1.1	- - -
LCR-G-258	- - -	4.1 ± .7	4.4 ± .8	3.5 ± 2.3

FLUGGRAVIMETRIERUNGEN

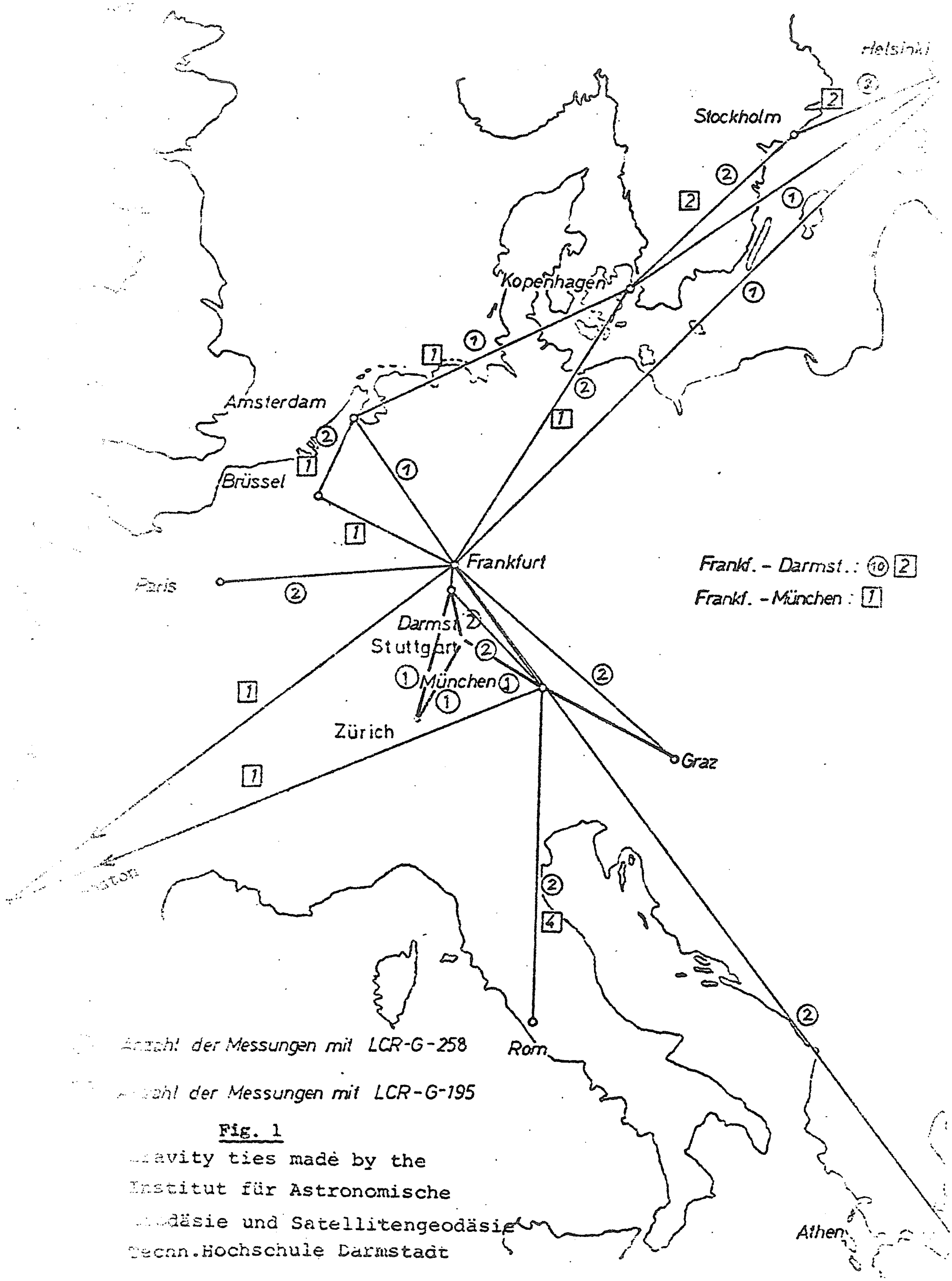

Fig. 1
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Institut für Astronomische
..däsie und Satellitengeodäsie
Techn.Hochschule Darmstadt

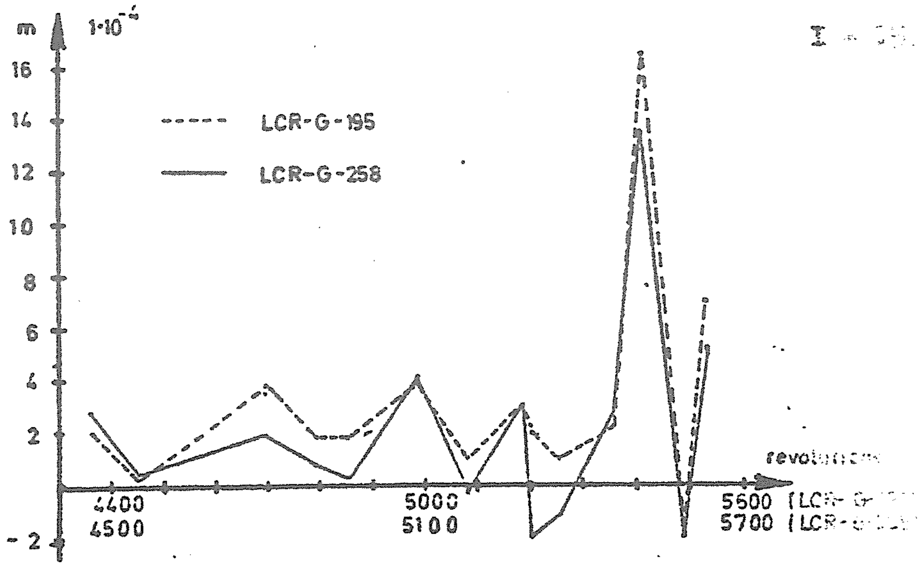
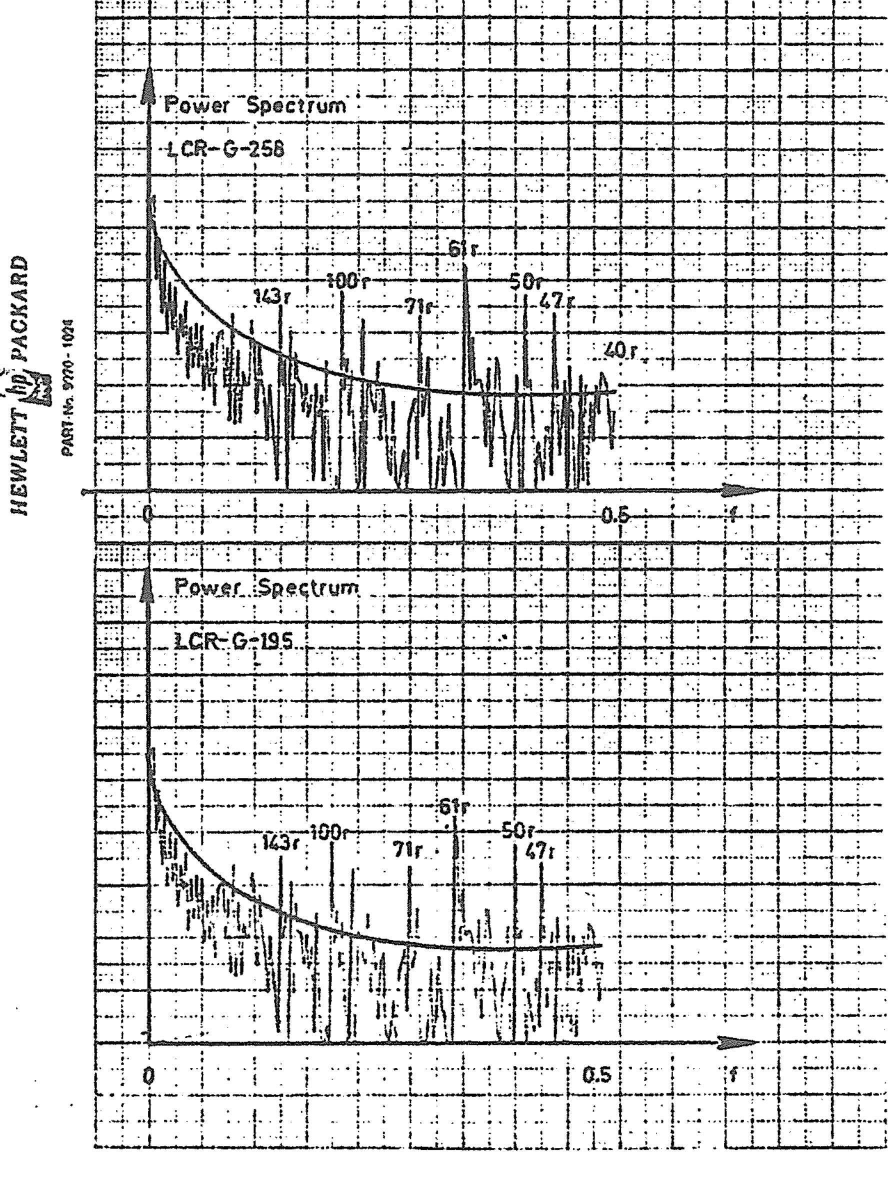


Fig. 2 : Changes of the calibration factors m, depending on counter dial revolutions

Fig. 3 : Power spectra of the calibration functions regarding to LCR-G-258 and LCR-G-195



COMPARISON of WESTERN PACIFIC and AUSTRALIAN CALIBRATION LINE GRAVITY SCALES and an EVALUATION of SECULAR VARIATION

by

P. WELLMAN, B.C. BARLOW & D.A. COUTTS

An accurate gravity scale has been established for the Western Pacific Calibration Line (WPCL) in the IGSN71 adjustment (Morelli et al., 1974), and an independent scale accurate to 2.5 parts in 10^5 has been established for the Australian Calibration Line (ACL) by co-operative Soviet-Australian measurements using GAG-2 gravity meters (Boulanger et al., 1973; Wellman et al., 1974). It is possible to accurately compare these scales using the results of those LaCoste & Romberg gravity meter surveys that included both the WPCL and at least part of the ACL. If secular variation of gravity at base stations on a calibration line is a function of distance along the line, then effects of different types will result, depending on the wavelength of this function. Short-wavelength effects should only decrease the accuracy of scale comparisons, whereas long-wavelength effects will cause an apparent change in scale. The transition wavelength if about half the length of the observed part of the line. Gravity measurements on the ACL and WPCL have been made over a period of many years, so secular variation effects may be significant.

LaCoste meters were used for gravity measurements along the WPCL, and along the central part of the ACL by the U.S. Air Force in 1965 (Whalen, 1966), by the Dominion Observatory of Canada in 1966 (Dept. Mines, Energy and Resources, pers. comm.), and by the Australian Bureau of Mineral Resources, Geology and Geophysics (BMR) in 1969-1970. Measurements restricted to the ACL were made by BMR in 1971, 1972, and 1973 (Wellman et al., 1974). Results from these measurements have been reduced to a common scale and datum as follows. Observations were reduced to equivalent readings in milligals using manufacturer's tables, and then corrected for earth tides. Gravity intervals were calculated, intervals with obvious tares were rejected, observations with full drift control were corrected for drift, and then intervals were meaned and summed along the calibration line. Observations along the WPCL (between Alaska and Darwin) were fitted by least squares to IGSN71 values (Morelli et al., 1974). Observations along the ACL were fitted by least squares to ISOGAL74 values which are on GAG-2 ACL scale (Wellman et al., 1974) and have the IGSN71 value at Sydney as datum. Results of meter G7 in 1966, and of G101 in 1969, 1970, and 1971, could not be used because they contained too many tares.

The ratio IGSN71 WPCL scale/ISOGAL74 scale was calculated for each of the remaining gravity meters (Table 1). G132, G20, and G104 give a wide spread in ratio values, probably because of changes in meter calibration factors between WPCL and ACL surveys which were separated by 7 months to three years. Calibration factor changes of the required magnitude and rate have been detected in repeat surveys along the ACL (Wellman et al., 1974, table 5). Results from these three meters are therefore unsuitable for accurate scale comparison. The 1965 and 1966 measurements on the WPCL and ACL were each completed within a few months, and over this time calibration factors are unlikely to have changed. If secular variation effects on the WPCL and ACL scales are insignificant, the 1965 and 1966 results show that the IGSN71 scale on the WPCL is only slightly smaller than the ISOGAL74 scale on the ACL, the best estimate of the difference being 3 ± 1 parts in 10^5 (Table 1) Boulanger et al. (1973) have shown that the IGSN71 scale on the ACL is considerably smaller than the GAG-2 scale on the ACL, the best estimate of the difference being 15 parts in 10^5. The poorly defined IGSN71 scale on the ACL must therefore differ by about 12 parts in 10^5 from the IGSN71 scale on the WPCL.

On the ACL, secular variation effects of short wavelength (i.e. much less than the length of the line) have been evaluated as follows. The differences have been determined between the ISOGAL74 values and the values calculated from LaCoste results on the same scale and datum. From these differences, mean differences have been calculated for the 1965 survey, the 1970 and 1971 surveys combined, and the 1973 survey (Table 2). Apparent gravity changes are shown in Figure 1. The changes based on the 1965 and 1973 mean differences range from +51 ± 15 (standard deviation) μGal at Townsville, to -49 ± 24 μGal at Brisbane; the corresponding rates of secular variation range from +6±2 μGal/year to -6 ± 3 μGal/year. It is to be expected that, at most places, secular variation of gravity will be in one direction and approximately constant over a period of eight years. Figure 2 shows that the amounts of apparent gravity change for the two periods (1970.9-1965.2 and 1973.4-1970.9) have the expected ratio of +2.3 to within experimental error, with the possible exception of one station. Short-wavelength secular variation effects are not proven from these results, but secular variation seems to be the best explanation for the apparent gravity changes between 1965 and 1973.

A scale change of 3 parts in 10^5 would result from a change of 40 μGal in the 1.5 Gal interval of the central part of the ACL observed in 1965-1966. Secular variation effects of long wavelength (i.e. greater than half the length of the observed part of the line) could cause such a change. The secular variations suggested above have large enough magnitude, but could not cause a significant scale change because the maximum wavelength (Fig.2) is too small by a factor of two. Longer-wavelength secular variation effects may actually exist and may have been removed as an apparent change in the calibration factors of the gravity meters. Accurate absolute determinations of gravity repeated after an interval of several years are required to measure such effects.

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TABLE 1 COMPARISON OF IGSN71 WPCL SCALE AND GAO-2 ACL SCALE

Meter number	Year	$\frac{\text{LaCoste scale}}{\text{IGSN71 WPCL scale}} - 1$ x10^4 *	ERMS µGal	$\frac{\text{LaCoste scale}}{\text{ISOGAL74 scale}} - 1$ x10^4 *	ERMS µGal	$\frac{\text{IGSN71 WPCL scale}}{\text{ISOGAL74 scale}} - 1$ x10^4 *	Weight used ($1/\text{s.d.}^2$)
G43	1965	−3.517 ± .220	96	−2.508 ± .284	45	−1.009 ± .359	7.7
G44	1965	−1.280 ± .060	27	−1.182 ± .254	40	−0.098 ± .261	14.4
G47	1965	+0.465 ± .099	43	+0.473 ± .218	34	−0.008 ± .239	17.5
G48	1965	−0.164 ± .047	21	+0.164 ± .113	18	−0.328 ± .122	67.2
G9	1966	−1.521 ± .131	53	−1.049 ± .555	81	−0.472 ± .570	3.1
G132	1969/1970	−3.725 ± .026	13	−4.202 ± .008	27	+0.477 ± .029	100.0
G20	1969/1970	−5.477 ± .138	60	−3.849 ± .150	44	−1.629 ± .204	24.0
G104	1969/1972	−2.549 ± .066	34	−3.141 ± .105	30	+0.592 ± .124	65.0
				1965–1966 results weighted mean		−0.298 ± .116 **	
				unweighted mean		−0.385 ± .177	
				1965–1972 results weighted mean		+0.047 ± .273	
				unweighted mean		−0.309 ± .261	

* = standard deviation (s.d.); ** = standard devistion of mean; ERMS = root mean square error

Table 2 Values of g Observed (ISOGAL74 Scale) - g ISOGAL74 in microgals

Gravity meter	G43	G44	G47	G48	G9*	G20	G132	G20	G132	G252	G104*	G20A	G101	G132	G252	Mean ± sdm	Mean ± sdm	Mean ± sd
Year	1965	1965	1965	1965	1966	1970	1970	1971	1971	1971	1972	1973	1973	1973	1973	1965	1970-71	1973
Place																		
Laiagam						-78	-77	-	-	-	-	+19	-11	-32	-16		(-77 1)	-10 11
Mount Hagen						-33	+41	-96	+28	-	-41	+25	- 3	- 5	+ 2		-15 31	+ 5 7
Lae						+96	+21	+43	-26	-	-18	-12	-33	-21	+ 3		+33 25	-16 8
Port Moresby						+64	+18	+71	-19	-	-36	-13	+ 7	-10	-17		+33 21	- 8 5
Iron Range						- 5	-11	-	-	-	-	+ 2	+ 8	+25	+ 6		(- 8 3)	+10 5
Cooktown						+41	- 4	-	-	-	-	-14	- 6	+39	-17		(+18 22)	+ 0 13
Cairns	-30	-25	+55	+ 3	-12	-18	-15	-26	-23	-	+27	-	-	-	-	+ 1 20	-20 2	-
Townsville	-40	-37	-57	-15	- 2	-18	+35	+19	+ 8	-54	+16	- 9	+ 4	+47	+15	-37 9	- 2 15	+14 12
Mackay	- 6	+ 7	-36	-11	+75	+ 9	- 4	+10	- 1	+ 5	+45	-12	+39	+ 3	+ 7	-11 9	+ 4 3	+ 9 11
Rockhampton	+40	+54	+23	+13	-142	-34	+ 7	-17	+26	+ 2	+22	- 5	+40	+ 8	+10	+32 9	- 3 10	+13 10
Brisbane	+70	+47	+18	+36	+79	-32	+28	-14	+27	+47	+33	0	- 6	-19	+ 2	+43 11	+11 15	- 6 5
Kempsey	-11	-50	- 8	-21	-	+26	+12	-	-	-	-	- 5	-24	- 7	+20	-22 10	(+19 7)	- 4 10
Sydney	-42	-32	+25	-14	-12	-21	-16	+19	+25	+42	+ 3	+ 3	-13	- 6	- 2	-16 15	0 13	- 4 3
Canberra	+51	+32	+ 2	- 0	+66	+24	+ 5	+ 3	+ 9	-13	+ 3	+ 3	+ 6	-23	+20	+21 12	+ 6 6	+ 1 9
Albury	+16	+27	-19	0	-	+ 5	-27	+15	- 5	+18	+ 2	-	-	-	-	+ 6 10	+ 1 8	-
Melbourne	-49	-24	- 5	+ 8	-52	-25	-15	+39	- 1	-11	- 9	+ 6	- 5	-	+ 9	-17 12	- 3 11	+ 3 4
Flinders Island						-	- 9	-	-	-	-	- 6	+13	-	- 8		- 9 -	0 7
Hobart							+10	-66	+ 2	-35	-47	+18	-16	-	-34		-22 17	-11 15

sdm = standard deviation of mean

* Data not used in assessment of secular variation

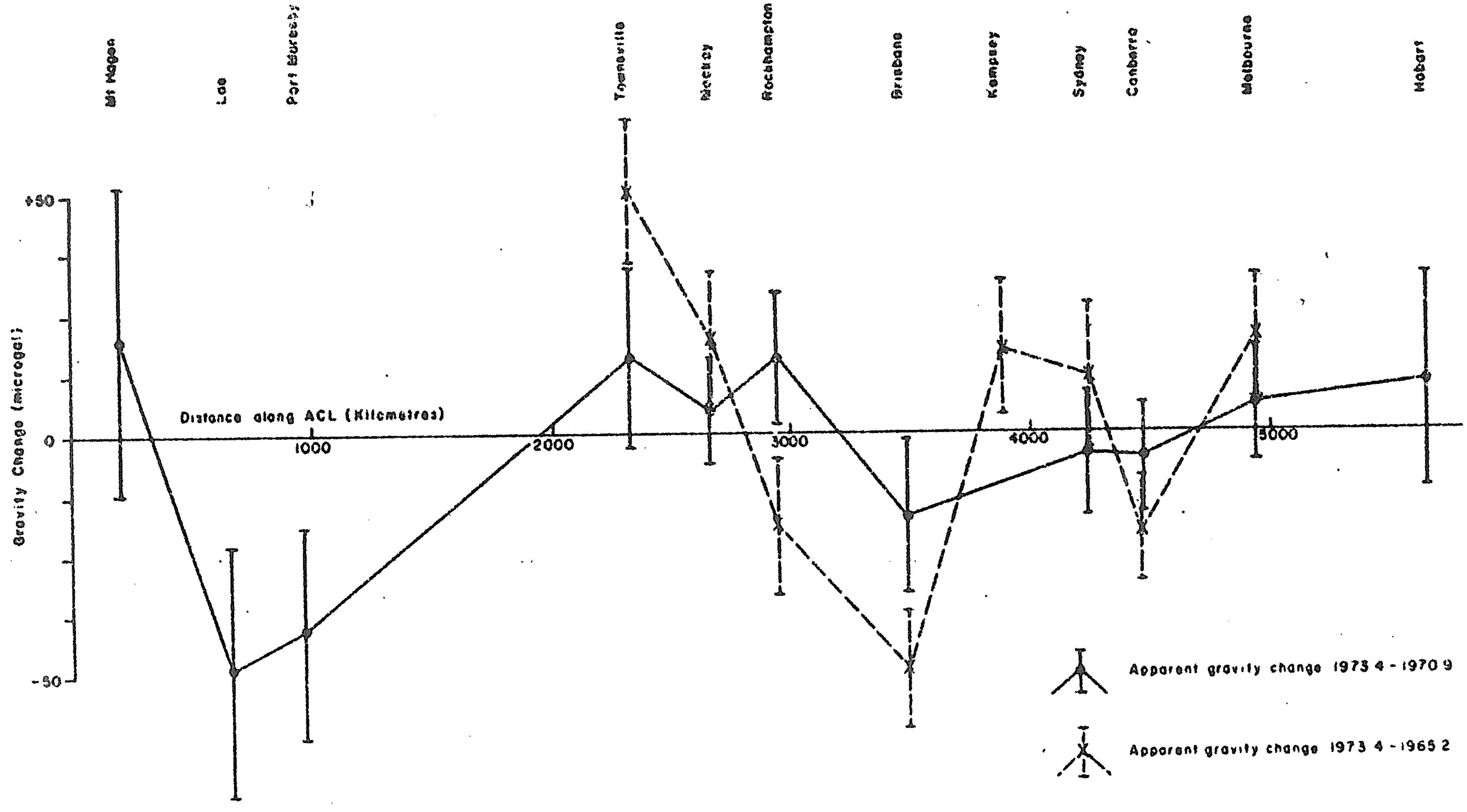


FIG.I APPARENT GRAVITY CHANGES

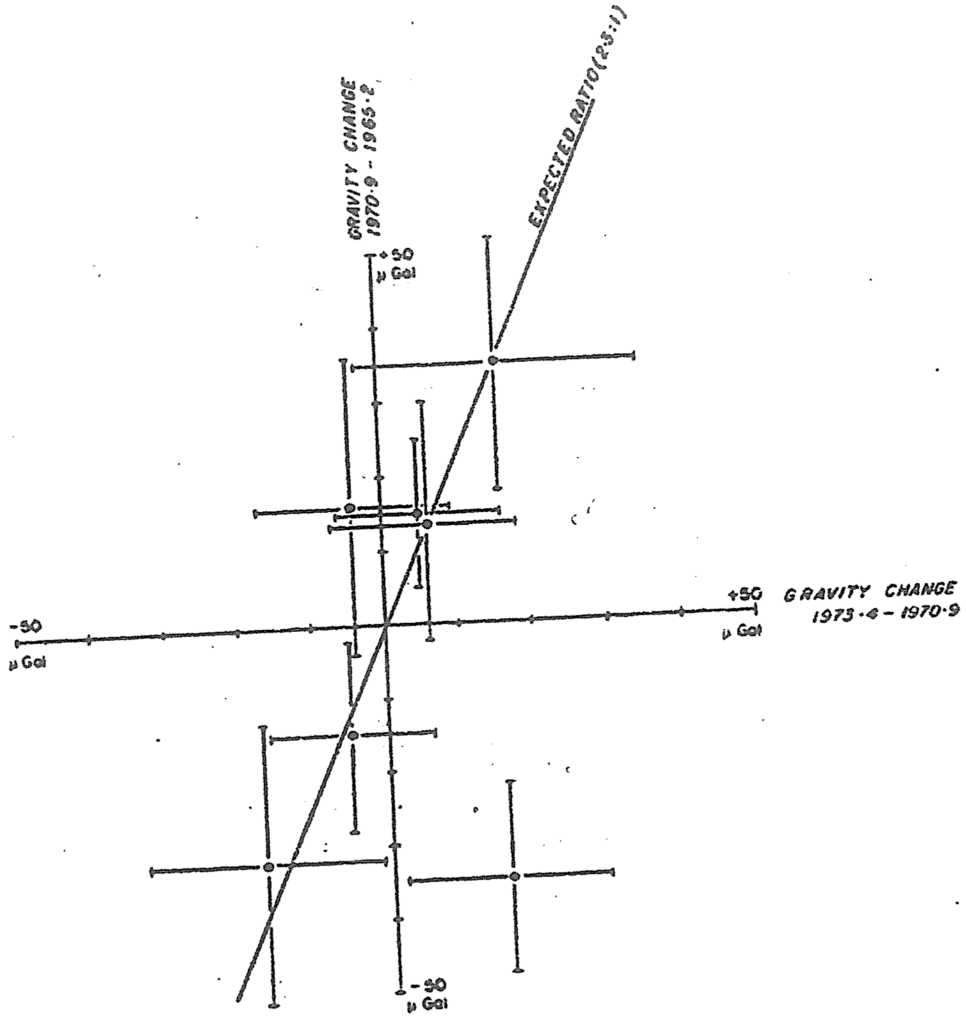


FIG.2 COMPARISON FOR SEVEN TOWNS OF THE OBSERVED AND EXPECTED RATIO OF THE GRAVITY CHANGES 1970·9 - 1965·2 / 1973·4 - 1970·9

- VI -

AIRBORNE GRAVITY MEASUREMENTS

On Tuesday afternoon 3rd September, Mr. O. WILLIAMS presents a report on :

Airborne Gravity Instruments

INTRODUCTION

As I have for more than a decade, I have been asked again to present a short summary report on Airborne Gravity Instrumentation. Gravity gradiometry will not be included here as it is a subject in itself and will be discussed in another paper. I will limit my comments to aircraft and helicopter gravity measurement activities since our last meeting in 1970. This report will be brief, since I must inform you that very little has been done since our meeting in 1970. Possibly others in attendance will want to add comments about their recent activities outside of the United States at the end of my presentation.

HISTORY

Historically, the first flight tests of an aircraft gravimeter took place in 1958, sixteen years ago. In the 1960's, airborne gravimetry tests were conducted as joint ventures by industrial, educational and governmental agencies. By 1962, the United States Air Force Cambridge Research Laboratories test results indicated that ± 10 mgals were obtainable by airborne gravimeters and, by 1968, navigation was identified as a major error contributor to obtaining accurate airborne gravity measurements.

During that decade, several types of gravimeters were evaluated and flight tested. These included:

1. Model S, LaCoste and Romberg air-sea gravimeter.

2. GSS-2, Type 2, Askania-Graf sea gravimeter.

3. Model 128, Texas Instruments Airborne Gravity Sensor (referred to as Worden System).

4. Massachusetts Institute of Technology PIGA-25 accelerometer system.

These gravimeters were flight tested over a large range of aircraft types—from low performance helicopters to high performance jets. An excellent summary of activities during this period is given in Anthony & Perry (1971).

RECENT ACTIVITIES

Moving into this decade (the 1970's), Massachusetts Institute of Technology (MIT) and Honeywell performed studies on the design configuration and error analysis of an airborne gravity measurement system for the U. S. Air Force. [Rusler, Tidwell & Brown, 1970 and Frey & Harlen, 1971].

These studies identified major components, including those which might need minor modification, which could acquire accurate airborne gravity data. The MIT study did not investigate navigation and navigation equipment, but concluded:

1. The Bell BGM-2 and LaCoste and Romberg Model S gravimeters have adequate performance and reliability for aerial gravimetry.

2. The stabilized platform for these meters is suitable with minor modifications.

3. The Terrain Profile Recorder, TPR-6, is satisfactory for radar altimetry, and the Kollsman Precision Pressure Monitor and Rosemont Pressure Port Calibrator are satisfactory in performance as pressure sensors.

4. Improved airborne computer programming for gravity, earth rate and in-flight navigation computations will be needed.

5. Kalman smoothing process should be implemented in the data processing.

The Honeywell study corroborated the MIT study and ascertained additionally that (1) the PIGA accelerometer would require a much more sophisticated platform; (2) accuracies of ± 0.1 knot ground speed and 1 minute arc in azimuth would be required from the navigation system. [Rusler, Tidwell & Browne, 1970].

Let us turn, now, to activities in airborne gravity measurements using a helicopter as a platform. The successful results of the airborne gravity measuring tests led, in 1967, to the conclusion that a Helicopter Gravity Measuring System could be assembled with off-the-shelf components to perform with a RMS of ± 3 mgals.

The U. S. Government tested a system consisting of a LaCoste and Romberg gravimeter on fast response stabilized platform, a high precision circular ranging system for horizontal position, a Rosemont pressure port calibrator, a laser altimeter and a digital tape recorder. The autotape was also tested as a possible substitute for the circular positioning system. Approximately 100 flights at speeds between 85 and 115 knots were conducted over the test areas which included mountainous and flat terrain. The rest results were not as good as expected, as the average RMS error for all lines was ± 7.2 mgals with biases in the range of -16 to +30 mgals. The origin for the biases could not be identified. The U. S. helicopter tests were terminated, with a recommendation for additional testing under carefully pre- and post-flight calibration, necessary to isolate certain systematic errors. [LeRoy, Marchant, Varum & Vitek, 1971]. Iverson and Gumert of EN-TECH, Associates, investigated a similar helicopter gravity measuring system and reported test results of better than ± 5 mgals at speeds of 60 knots. [LeRoy, et al, 1971].

A recent gravity study for the U. S. Navy by the Applied Physics Laboratories, investigated the feasibility of modifying the Geophysical Airborne Survey System (GASS) aircraft for airborne gravity collection. [Levy & Ford, 1973]. The major new thrust of this effort is based on the improved inertial navigation system of the GASS aircraft. The new U. S. Air Force-developed AN/ASN-101 Gimbaled Electrostatic Gyro Aircraft Navigation System (GEANS) will provide navigation to ± 1 nautical mile and provide valuable assistance in measuring the vertical and horizontal accelerations necessary for isolating the gravitational forces. It was determined through the study that by adding a Bell BGM-2 or LaCoste and Romberg ASGM gravimeter with a Honeywell HG-7140 radar altimeter and Rosemont 843C barometric pressure sensor, the system could achieve gravity with RMS error of ± 10 mgals for 30-nautical mile areas. The gravity processing scheme features post-flight Kalman filtering and smoothing of the horizontal navigation aids, inertial system, gravimeter and altitude outputs to accurately estimate profile means of the Eotvos, gravity and vertical acceleration. Currently, the design and implementation of a post-flight optimum filter is being accomplished for the navigation program. The filter will be tested to determine the expected accuracies of Eotvos and horizontal aircraft motion corrections.

Next year, it is proposed to install and interface the gravimeter, altimeter and pressure sensor into the aircraft and flight test the system for gravity data collection.

Most recently, new tests of the Helicopter Gravity Measuring System have been undertaken by Carson Helicopters, Incorporated, in cooperation with geophysical exploration companies, the U. S. Navy and Defense Mapping Agency. The test/demonstration was to be conducted in mid-August using a three axis LaCoste and Romberg gravimeter. The test purpose is to show data collection at the ± 2 mgal level over all combinations of lines.

- VII -

HIGH PRECISION GRAVIMETRY

Special Study Group n°3.37

Two sessions were held under the Chairmanship of
Prof. T. HONKASALO : Tuesday 3rd September, 5.40 to 6.15 p.m.
Wednesday 4th " , 3.30 to 4.30 p.m.

Firstly, Prof. T. HONKASALO, Chairman of the Sp. St. Gr. 3.37 on : Special Techniques of Gravity Measurements, makes a general report on this subject (see p. I-26).

Secondly, Prof. E. GROTEN presents a paper : Microgravimetry - High precision observations of small differences *. This paper concerns different topics : gradiometry, vertical gradient, secular variation of g. Particularly, it deals with the establishment of a high precision gravity net in the Northern area of the Rhine graben in agreement with the first order levelling net for studying secular variations. (See abstract p.I-47).

Mr. R.K. McCONNEL reports on : An evaluation of the LaCoste-Romberg model D microgravimeter. (see p.I-35).

Some remarks are made by the Delegates, in particular on the stability of the gravimeters.

Prof. P. MELCHIOR says : We have compared at Bruxelles some 21 gravimeters from different makers (LaCoste-Romberg, Geodynamics, Askania of the last models). We reached the conclusion that a correct comparison cannot be made within only a few days. The best to do is to record the tidal effects during 3 months and analyze the data by tidal harmonic analysis. Then one observes that the instrumental phase lag is a function of the tidal frequency. It is different for diurnal and semi-diurnal waves and can be important as it depends from the degree of astatisation and of the damping. Details will be soon published by Dr. DUCARME.

Another point has been observed with the Model G of LaCoste-Romberg gravimeter which basically is a field instrument of very small size. Due to its small size, the screws are very near and its stability in levelling is rather poor on long intervals. We took out the screws and firm attached the instrument upon a more heavy and larger base plate having good screws at right angles and large levels. An additional thermic protection was added on that plate. In these conditions the instrument sensitivity was very stable as its levelling remained itself extremely stable.

* Published in Bulletin Géodésique n° 115, March 1975.

Report of IAG Special Study Group No 3.37 on Special Techniques of Gravity Measurements

by

Tauno Honkasalo

1. INTRODUCTION

This Special Study Group was established at the General Assembly of the IAG in Lucerne 1967. It gave its working report to the General Assembly in Moscow 1971, where it was decided to continue the work of this Group.

The Study Group organized an international measurement of the Fennoscandian gravity line for studying the secular gravity difference variation due to the land uplift in 1971 and 1972. The main experiences and provisional results are reported here.

In March 28 I sent a circular asking the members of the SSG about works in other countries in the field of this SSG. This report is based on the answers to this circular and publications.

2. THE FENNOSCANDIAN LINE OF SECULAR GRAVITY VARIATION

This line was proposed in the Symposium of Recent Crustal Movements in Aulanko 1965. The first measurements were carried out in Finland in 1966 and the line was extended over the Gulf of Bothnia, Sweden and Norway to the Atlantic Coast in 1967. The line is 1200 km long and consists of 8 stations, viz.

Finland:	Joensuu, Äänekoski and Vaasa
Sweden:	Kramfors, Stugun
Norway:	Kopperå, Meldal, Vågstranda

For high precision measurement of gravity differences experience has confirmed the following principles.

1. Differences must be small, <1 mGal, still better if $\Delta g < 0.1$ mGal.
2. Symmetric measurement for eliminating the drift.
3. Car transport is better than air transport due to smaller air pressure changes and vibration.

4. In planning the observation times the tidal effect shall be taken into consideration because of the local variation of the gravimetric factor.
5. The gravimeters must be investigated, especially
   a) Effect of air pressure
   b) Effect of earth's magnetism
   c) Effect of air temperature on the reading of the gravimeter, on the drift and on the calibration
   d) Calibration and especially the periodic errors of cogwheels in the gearbox or dials.

The most important of these are the periodic errors, especially those of the smallest periods, the effects of air temperature, the tidal corrections and in some cases the irregular drift. The Fennoscandian line has been measured with LaCoste Romberg gravimeters. In most cases the drift was so regular that a linear drift for the whole measuring period of 5-12 days was applied. In some cases a second order term was considered. Great differences in the precision between different LaCoste-Romberg gravimeters were stated. In the measurements of the Fennoscandian line gravimetrists from Finland, Federal Republic of Germany, Norway, Sweden and USA have been participated and used all together nine gravimeters.

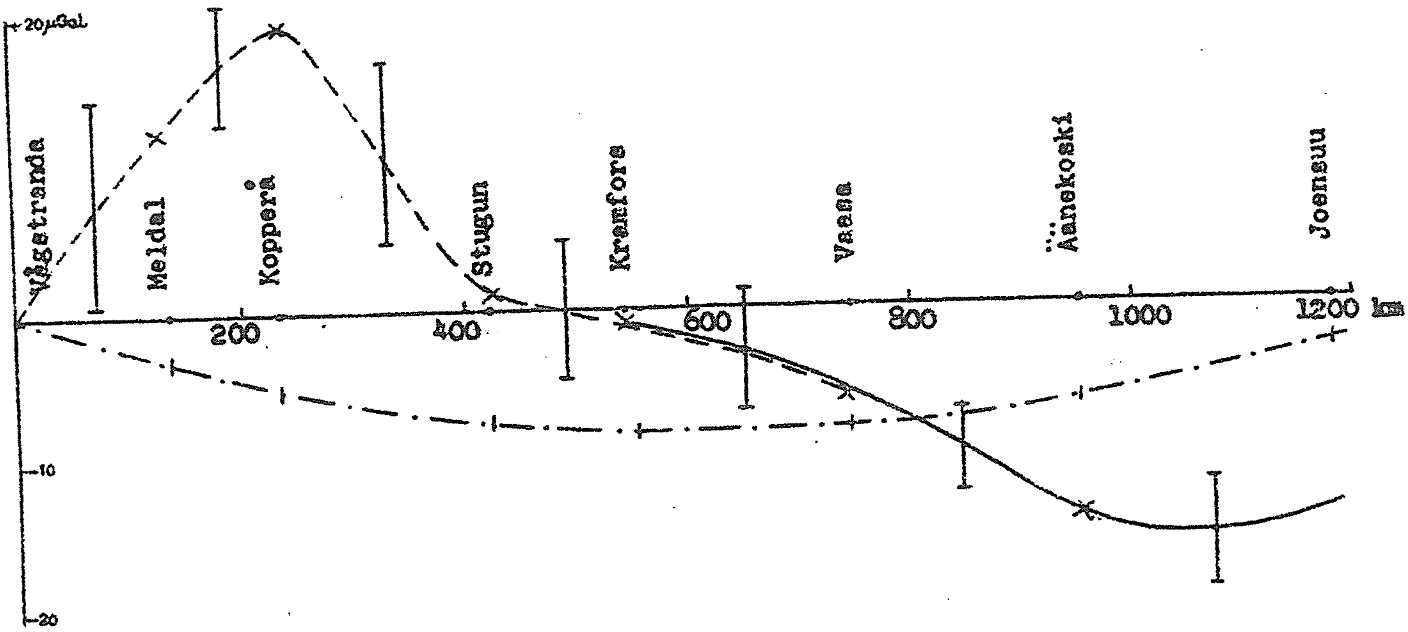
The following measurements have been carried out

Year	Vågstranda		Meldal		Kopperå		Stugun		Kramfors		Vaasa		Äänekoski		Joensuu	Participants
1966												-		-		F,U
1967		-		-		-		-		-		-		-		F,S
1971										-		-		-		F,G
1972		-		-		-		-		-		-				F,G,N,S
1973												-				F

The results of different years have shown that in using 3-4 gravimeters and measuring the gravity difference four times back and forth, a real accuracy of ±2 -3 μGal was obtained.

The results of the measurements on the Fennoscandian line give a constant gravity difference between Vågstranda on the Atlantic coast in Norway and Kramfors on the coast of the Gulf of Bothnia in Sweden but between these stations in Kopperå an increase of g-value

OBSERVED CHANGES OF GRAVITY



Observed changes of gravity and their standard errors (PETTERSSON)

Observed changes of gravity and their standard errors (KIVINIEMI)

Estimated gravity changes computed on the basis of Fennoscandian land uplif by 20 ±8 μGal in 5 years and a decrease of g-value at Äänekoski in Finland by 14 ±6 μGal ([13] , [15]). The maximum change in this line is thus between Kopperå and Äänekoski, 34 ±8 μGal. Such great changes were not expected on the basis of known land uplift values.

3. EXPERIENCES IN DIFFERENT COUNTRIES

The following has been reported about the studies on the field of this study group in different countries.

3.1 Canada

For evaluation of LaCoste-Romberg model D gravimeter has been tested in laboratory and in actual field survey conditions by the Earth Physics Branch. According to the first phase of the tests a precision of 1 microgal over gravity intervals 10 mGal or less using relatively straightforward field procedures can be obtained.

3.2 Czechoslovakia

Two secular gravimetric lines have been established for investigating the secular variations of the Earth's field of gravity [18]. The measurements have been carried out with two Askania GS 12 and a Canadian gravimeter. An accuracy of ±19 μGal for one gravity difference was achieved. Special studies on the charasteristics of the gravimeters have been made ([19] , [20] , [21]).

3.3 Finland

Instrumental investigations for the measurements reported in chapter 2 have been continued. The 1 mGal calibration line of six stations has been observed 13 times with gravimeters LCR G-55 and G-62. An observation set of this type takes about one hour if the gravimeter is observed three times back and forth the line, in all 36 setting-ups and readings. The quadratic mean of all standard deviations is ±4 μGal for one gravimeter observation, including short transport, clamping effects, levelling accuracy, reading precision of the mean of three readings and deviations from the linear drift.

The field measurements with the same gravimeters on the Fennoscandian line gave a standard deviation of ±13 μGal for one gravimeter observation when the drift was expressed by a first or second order polynomial for the whole measuring period of one or two weeks [13] .

3.4 France

In cooperation with Istituto di Metrologia G.Colonnetti Torino, Italy the BIPM hasconstructed a transportable absolute gravimeter of 2.10^{-7} m/s^2 accuracy. The apparatus is built by a French firm ([5] , [17]).

3.5 German Democratic Republic

Observations on the GDR gravimetrical test line have been continued using sharp-prospecter gravimeters. The line consists of 6 stations where the greatest gravity difference is 5.1 mGal ([8], [12]) the observed variations in µGal are:

Year / Distance	1970		1971		1972		1973
1		-13.4		+3.4		+3.5	
2		+ 5.2		+0.6		-0.1	
3		- 2.9		+4.8		-6.1	
4		+ 4.3		-1.3		-1.2	
5		- 1.0		-12.9		+1.3	
		- 7.8		-5.4		-2.7	

The internal accuracy of yearly measurement of one gravity difference has been ±2.0 µGal and the effects of temperature, air pressure and drift rate have been evaluated [22] . Estimations of density variations caused by variations of soil moisture and ground water table indicated that in the vicinity of the observation points, up to more than 100 m distance, these data must be known, because effect of several µGal can occur [12] .

3.6 German Federal Republic

The gravimeters used in the measurements reported in chapter 2. were accurately investigated partly in the laboratory, partly on the European gravity calibration line and partly on the Finnish 1 mGal calibration line ([9] , [11]).

A study of LCR gravimeters No 79 and 85 used for measurements in Europe and Africa shows significant calibration changes between the observation periods 1964/65, 1967 and 1970. The maximum variation being $15 \cdot 10^{-5}$ [23] .

An increase of the reading accuracy has been achieved by using a recording gravimeter similar to that in the studies of the earth's tides. A 15 min. recording gives an inner accuracy of ±1 μGal. In field measurement by car transport with specially damped spring suspension of the gravimeter, good drift linearity was obtained. However, 15 % of the observations have been cancelled because of 3-17 μGal discrepancies [1] . A new construction of transport suspension and an additional thermostat has further improved the results.

3.7 Hungary

For studying the secular gravity variations two special lines have been established. The E-W line consists of 10 stations at 30 km intervals. On the N-S line the gravity intervals are about 40 mGal. International measurement with 7 Canadian CG-2 gravimeters and 3 Askania GS-12 gravimeter was carried out. Special investigation on dependence of instrumental constants on temperature, on geographical latitude, on height above sea level, on time, on vibration and personal errors were made ([6] , [7] , [14]).

USA

The National Geodetic Survey (formerly the Coast and Geodetic Survey) measured gravity stations at the 842 levelling bench mark in the southern part of the San Joaquin Valley in California in 1962 using two Worden gravimeters. The net consist of 11 lines forming 6 loops. The adjustment of this net gave standard errors of ±33 and ±29 μGal for a single gravity determination.

Eight years later 633 of the stations were remeasured with two LaCoste-Romberg gravimeters. The standard error of a single measurement was ±24 and ±6 μGal for these gravimeters, a very significant difference.

In the greatest part of the net no free air anomaly changes could be stated, though elevations had changed up to 3 feet. In a small area in the southern part of the net gravity anomaly changes ranging between 0.1 and 0.2 mGal over the eight-year period were found. In this area the elevation changes were small (< 0.5 feet) and no faults running through this area are known [4] .

USSR

The repeated observations in relation to Potsdam at the points Warsaw, Prague, Budapest, Bucharest, Sofia and at the Soviet stations in Moscow, Kazan, Sverdlovsk, Perm and Petrozavodsk show the stability of the gravity field in these points for the last 5-6 years with an accuracy of ±10 µGal/year.

A special method for measuring great gravity intervals by using 8-10 Soviet GAG-2 gravimeters simultaneously has developed [3]. An accuracy of ±12 -20 µGal was attained.

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APPENDIX

Members of Special Study Group 3.37

Name	Institute
Prof. Tauno Honkasalo (President)	Geodeettinen laitos Pasilankatu 43, SF-00240 Helsinki, Finland
Prof. György Barta	Hungarian State Geophysical Institute
Prof. Yu.Boulanger	Academy of Sciences of the USSR Soviet Geophysical Committee
Dr. Rudolf Brein	Institut für Angewandte Geodäsie, Frankfurt a.M.
Dr. T. Danbara	Geographical Survey Institute,Japan
Dr. Claus Elstner	Zentralinstitut Physik der Erde, Potsdam
Prof.Dr.-Ing. Carl Gerstenecker	Geodätisches Institut der Technischen Hochschule Darmstadt
Mr. Aimo Kiviniemi	Geodeettinen laitos, Finland
Dr. Lucien LaCoste	LaCoste and Romberg Inc. USA
Mr. Å. Midtsundstad	Norges Geografiske Oppmåling
Dr. I. Nakagawa	Geophysical Institute, Kyoto University, Japan
Dr. Lennart Pettersson	Statens Lantmäteriverk, Sweden
Dr. A. Sakuma	Bureau International des Poids et Mesures
Prof. Dr.-Ing. R.Sigl	Technische Hochschule München
Mr. William E.Strange	National Geodetic Survey, USA
Dr. H. Suzuki	Geographical Survey Institute,Japan
Dr. Bela Szabó	AFCRL, Terrestrial Sciences Laboratory, USA
Dr. J.G. Tanner	Earth Physics Branch, Canada

AN EVALUATION OF THE LACOSTE-ROMBERG MODEL D MICROGRAVIMETER

BY

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Earth Physics Branch
Dept. of Energy, Mines and Resources
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1. Introduction:

The recently introduced LaCoste and Romberg model D Microgravimeter will permit the determination of relative gravity values to a precision of 1 to 2 ugals using standard field procedures. Although most of the tests carried out to date at the Earth Physics Branch have been limited to gravity ranges of 10 mgals or less there are indications that this precision may be achieved over ranges of up to 200 milligals. The possibility of achieving such a precision opens up a wide range of new applications of gravimetry both in the field of engineeering and in the study of gravity variations with time. The purpose of this report is to present the results of an evaluation of one model D microgravimeter under laboratory and field conditions.

2. Description of the Instrument

The model D microgravimeter is virtually identical in external configuration to the La Coste and Romberg geodetic gravimeter. While the principle of operation of the sensor unit is similar to the geodetic meter, the geometry of the system has been modified somewhat so that the measuring screw, lever system and zero length spring combination covers a range of 200 rather than 7000 mgals. Reset is accomplished through an external screwdriver adjustment. Both optical and galvanomter readouts are provided. In practice the optical readout is used to obtain an approximate reading and the higher sensitivity galvanometer unit is used during final nulling. One dial division corresponds to approximately one microgal. The instrument used in the tests described here (serial number D-6) has not been modified in any way except for the replacement of the standard levels (sensitivity: 1 div = 60 arc secs.) with levels having a sensitivity of 30 arc secs. per division.

Unlike the geodetic gravimeter, the D-meter is claimed to have a linear dial response. Therefore, the customary table of dial factors is replaced with a single scale factor for use throughout the range of the instrument.

3. Laboratory Tests

3.1 Level Sensitivity

During the initial checks and adjustments of the instrument there was some indication that the transverse level bubble was not sufficiently sensitive. A series of readings carried out in rapid succession, off-levelling in the transverse direction and relevelling between each reading, showed a scatter of several microgals. Replacement of the standard levels with levels having twice the sensitivity (30 arc seconds per division) supplied by the manufacturer seemed to cure this problem. Although the sensitivity of the transverse level was more critical both levels were replaced as a matter of course. The use of 30" levels increases slightly the time required to level and read the instrument.

3.2 Reading Sensitivity

The instrument was set up on a pier in a temperature controlled room (±1°C). Readings were taken at about hourly intervals, converted to milligal values and compared with the earth tide as recorded by a LaCoste and Romberg earth tide gravimeter in an adjacent room. The first day of observations were made leaving the meter unclamped throughout the test. On the second day the meter was clamped after each reading and unclamped before the next. Over the next two weeks the observer practised reading

the instrument under a variety of conditions. The pier reading tests were than repeated to evaluate the improvement, if any, due to the accumulated experience of the observer.

Fig. 1 shows the gravity differences for the microgravimeter compared with those from the earth tide meter for the first two days of tests. The rms deviation of the microgravimeter values from a smooth curve drawn through those values is 1.7 μgals with clamping between readings and 1.4 μgals without clamping.

If the separation between the observed earth tide and microgravimeter curves is interpreted simply as drift in the microgravimeter then it is obviously non-linear over the course of the day. The explanation is probably somewhat more complicated, however, since detailed comparisons of observed and predicted earth tides at Ottawa by Dr. Bower of the Earth Physics Branch show apparent scale fluctuations of a few percent in the earth tide meter over periods of weeks. How these apparent fluctuations vary over periods of hours is not known but it is likely that the deviation between the microgravimeter values and the observed earth tide is a combination of factors relating to amplitude variations in the earth tide measuring equipment and the drift of the microgravimeter.

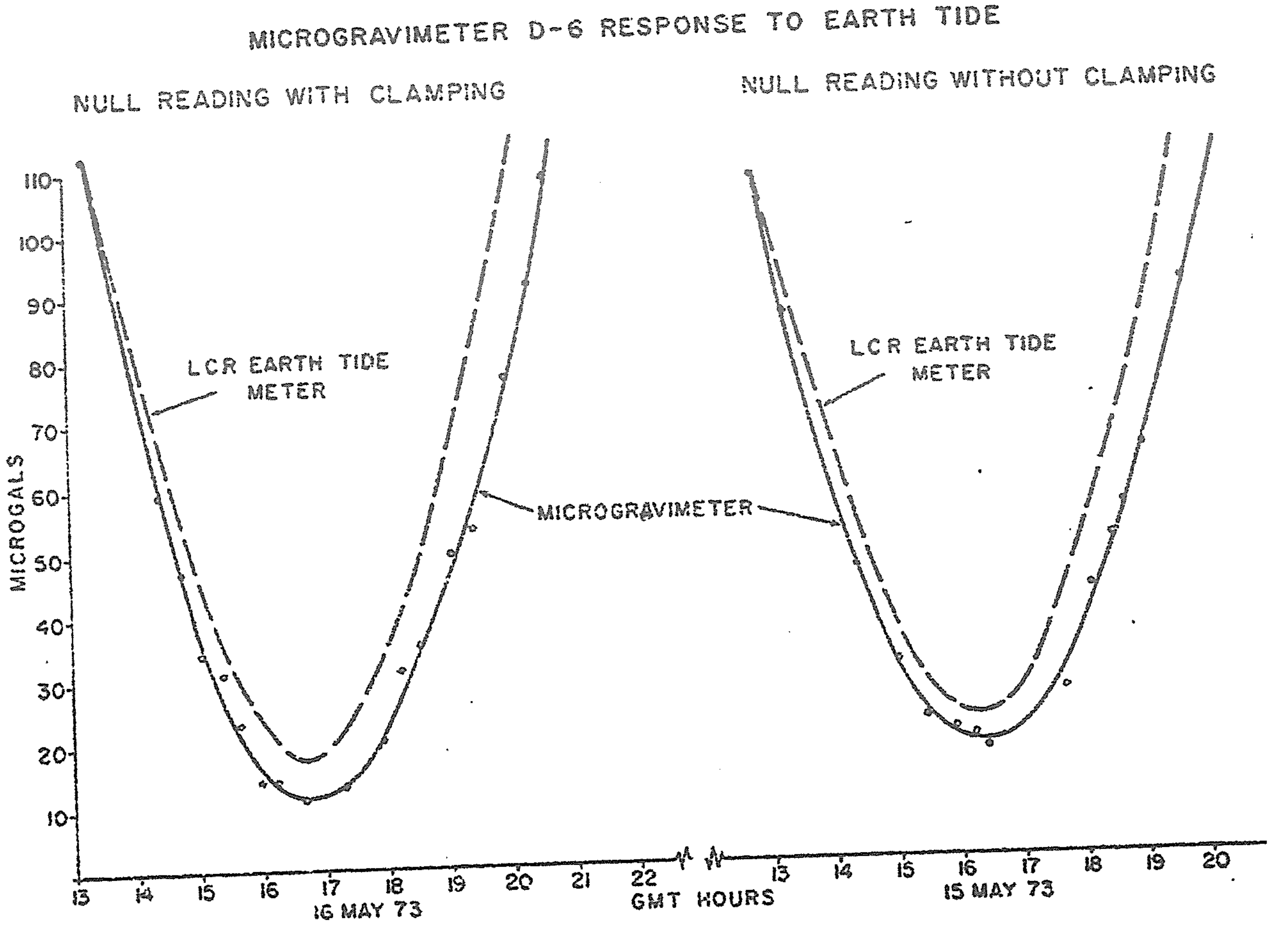


Fig. 1

Fig. 2 shows the repeat test carried out two weeks later. The experience gained by the observer in taking many readings during the previous two weeks is reflected in the smaller scatter of the microgravimeter readings. The rms deviations about the mean curve are 0.7 μgals without clamping and 0.2 μgals with clamping. No explanation is offered for the apparent increase in accuracy when the instrument is clamped between readings. However, it is safe to say that the operation of the clamping mechanism does not degrade the observations in any way.

Fig. 3 shows a comparison of the continuously recorded output of the microgravimeter capacitor readout system (corrected for gravimeter scale factor) with the earth tide meter output and the predicted earth tide over a 24-hr period. The drift rate of the microgravimeter is approximately 2 μgal/hr. The large amplitude difference is apparently due to non-linearity of the capacitor readout unit. Thus, the microgravimeter cannot be used as a recording earth tide meter without calibration of the electronic readout unit. The non-linear response of the readout unit is shown in Fig. 4.

3.3 Vibration Tests

A series of vibration tests similar to those described by Hamilton and Brulé (1964) were carried out on the microgravimeter. Tests were done at an acceleration of 0.5 g for several frequency ranges.

MICROGRAVIMETER D-6 RESPONSE TO EARTH TIDE

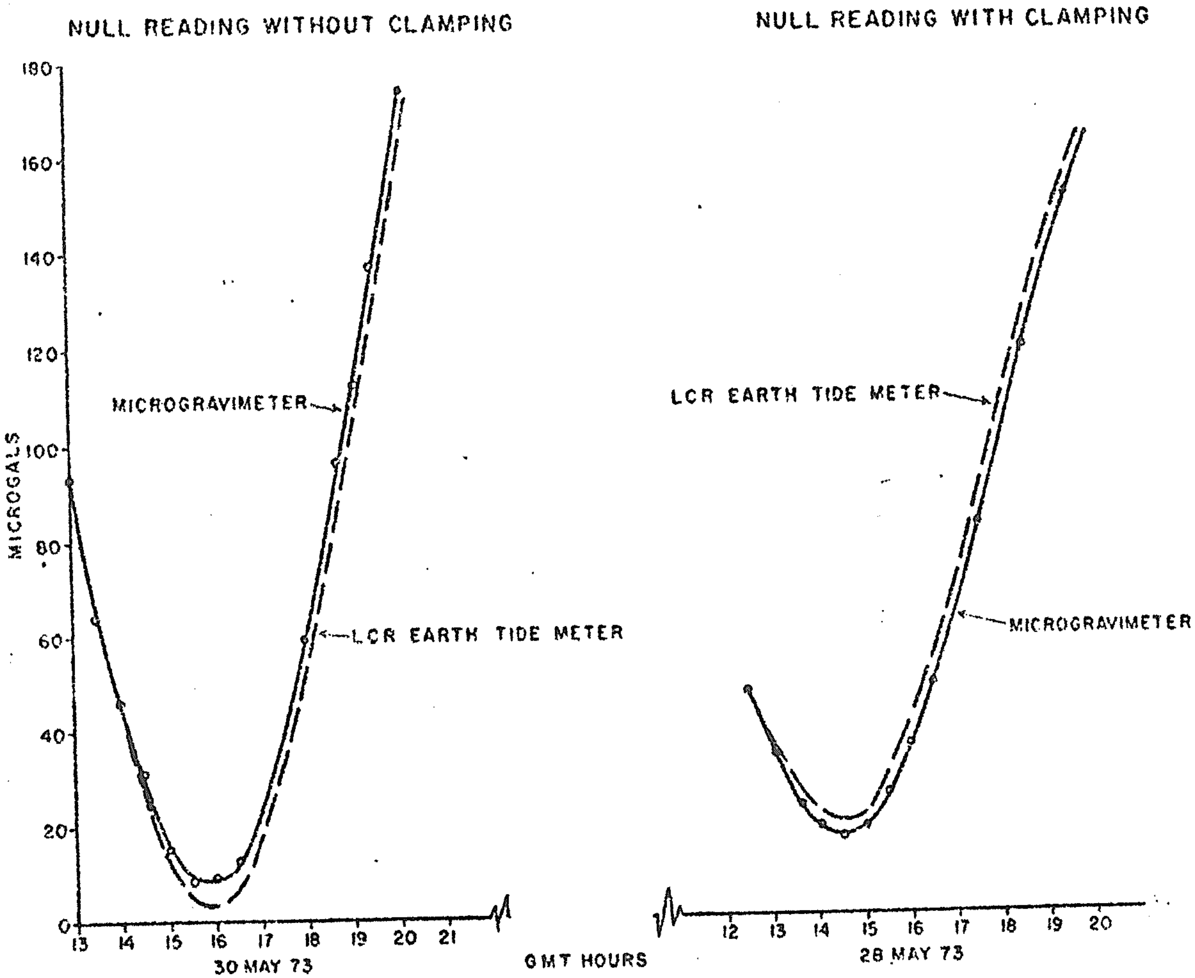


Fig. 2

MICROGRAVIMETER D-6 RESPONSE TO EARTH TIDE
DIRECT RECORDING METHOD

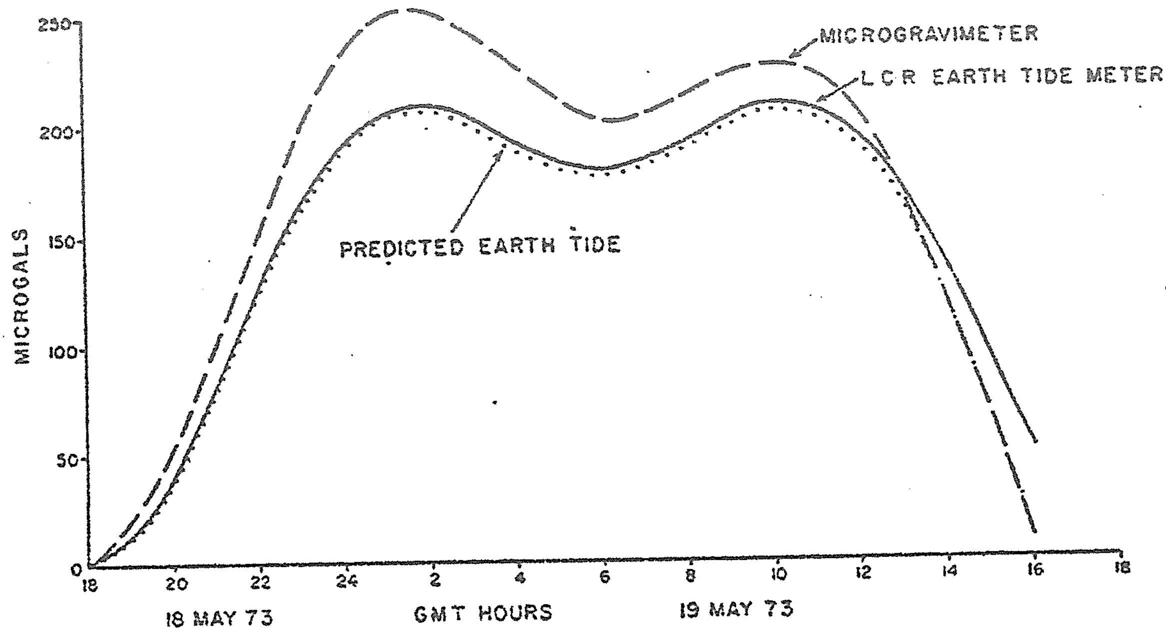


Fig. 3

MICROGRAVIMETER D-6 MINUS EARTH TIDE METER

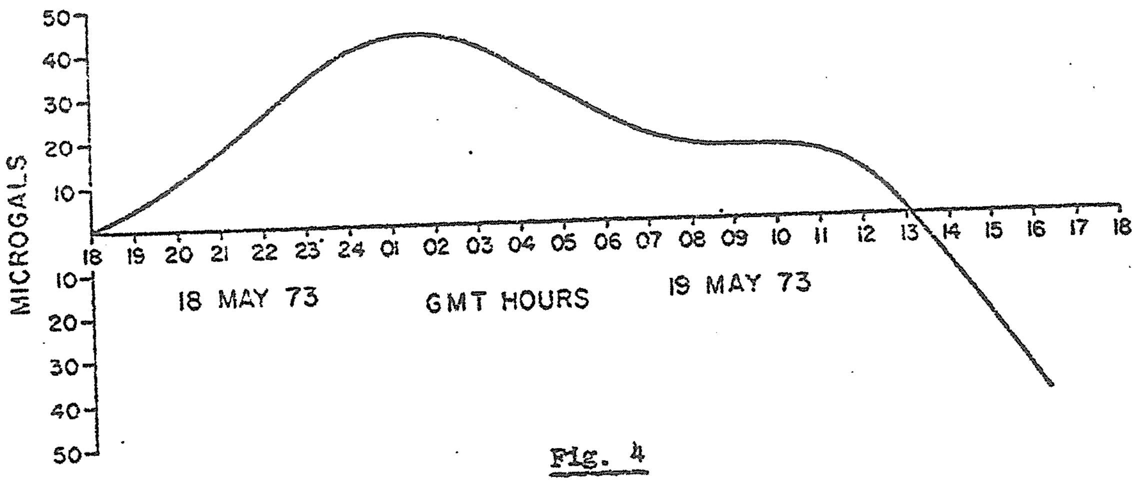


Fig. 4

Vibration induced reading changes were a maximum of (+2.5 mgal) in the 40-50 cycle range as expected. Vibration insulators effective in the 30-70 cycle range were installed in the microgravimeter carrying case and used for all subsequent tests.

3.4 Magnetic Tests

Tests for variation in reading with orientation of the instrument in the earth's magnetic field were carried out immediately after the vibration tests and showed variations of up to 100 μgals at a given station. Since the manufacturer had obtained negligible magnetic effect in similar tests performed at the factory and we had not observed spurious errors of this magnitude previously, it was presumed that we had magnetized the meter by subjecting it to strong AC fields during the vibration tests. The meter was therefore returned to the factory for degaussing. Upon return to us the meter showed negligible magnetic effect but as a safely precaution a standard procedure of observing the meter in the same orientation with respect to the earth's field was adopted for all subsequent work.

3.5 Transportation Tests

A variety of field conditions were simulated to test the response of the microgravimeter to various forms of transportation.

3.5.1 Hand Transport

Two stations differing in gravity by 2.5 mgals and located about 200 metres apart were each observed 40 times in alternating sequence. The standard deviation of the 40 tide corrected gravity differences was 7 μgals. Subsequent tests carried out in varying weather conditions showed standard deviations of from 3 to 13 μgals for sample sizes of 5 to 31 measurements with the higher standard deviations correlating with gusty wind conditions.

3.5.2 Car Transport

The response of the microgravimeter to car transport was tested by reading the instrument on a laboratory pier followed by a ½ hr. drive over a gravel road and then a repeat reading on the pier. A 1" thick horsehair pad was placed under the gravimeter carrying case on the floor of the car. [illegible] six sets of observations the standard deviation of the tide corrected readings was 3 μgals indicating that the instrument is not significantly affected by the shocks encountered in this form of transportation. It should be noted that this small standard deviation can only be obtained with measurements over a zero gravity difference. A field survey

(Sec 4.0) carried out by car showed a significantly higher standard deviation (6 μgals) presumably due to the additional noise introduced by observing at differ- end positions on the measuring screw.

3.5.3 Helicopter Transport

A series of readings were taken before and after each 20 minute flight. The instrument was placed on a 1" thick piece of horsehair padding resting on the floor of the helicopter cabin. A sample of 4 measurements using a Bell 47G4A helicopter showed a standard deviat- ion of 8.6 μgals after correction for earth tides. Only 2 readings were taken with a Bell Jet Ranger (206A) helicopter. These differed by 26 μgals indicating that further testing and vibration insulation will be required if this type of helicopter were to be used in an actual survey operation.

3.6 Circular Error Tests

An attempt was made to verify the manufacturer's claim that the microgravimeter is essentially free from period- ic dial screw error. Since one measuring screw revolu- tion corresponds to 5 mgals the maximum effect of period- ic screw error would occur at 2.5 mgal intervals on the dial. In an attempt to detect this type of error we measured a 2.5 mgal gravity difference 4 times, then reset the meter about 0.2 mgals and repeated the interval 4 times. This sequence was repeated for 10 resets. The mean gravity difference for each set varied by as much as 10 μgals from the mean of all 40 difference measure- ments but there was little evidence to suggest that the means were periodically distributed with respect to the dial reading. It seems more likely that we are looking at small errors introduced by random irregularities in the measuring screw system, the effect of environmental factors (ground vibration, wind, etc.) and the effect of resetting the meter. In any case, the nature and magni- tude of screw irregularities should be investigaged further. We are presently devising a series of tests which we propose to ask the manufacturer to carry out using his weight calibration apparatus.

3.7 Pressure Tests

No tests of the response of the microgravimeter to atmospheric pressure variations were made since a vibr- ation free pressure chamber was not available. Based on experience with LaCoste and Romberg geodetic meters this effect is likely to be negligible since the sensor unit is sealed. In the event of leakage provision has been made for barometric compensation in the sensor unit itself.

4.1 Field Evaluation of the Microgravimeter

The initial phase of an experiment to evaluate the potential of the microgravimeter in detecting changes in level of groundwater commenced in July, 1974. The survey consisted of repeated observations at a set of five wells in the vicinity of Charlottetown, Prince Edward Island. Based on past measurements of fluctuations in water level in these wells a seasonal change of 1.5 to 3 meters can be expected. Assuming 10% porosity of the sandstone in this area the total mass transfer would be roughly equivalent to an infinite slab of water 15 to 30 cm in thickness. Thus we expect to detect gravity variations of 6 to 12 microgals over the season. The second phase of the survey will not be carried out until October, 1974. The results of the first phase are presented here simply to illustrate the performance of the microgravimeter on an actual field survey.

The structure of the network set up to interconnect the five wells is shown in Fig. 5. A total of 112 measurements were made between all possible pairs of stations. Survey procedures were similar to those employed when using a LaCoste-Romberg geodetic meter except that the instrument was protected from solar radiation and wind by a small tent. Gravimeter readings were corrected for earth tide (Longman, 1959). For each interval observation equations were set up as follows:

$$g_i - g_j - \Delta g_{ij} - d\Delta T_{ij} = \bar{\epsilon}_{ij}.$$

where g_i is the unknown gravity value of the i^{th} station

g_j is the unknown gravity value of the j^{th} station

Δg_{ij} is the observed gravity difference between the i^{th} and the j^{th} station

d is the unknown drift rate

ΔT_{ij} is the time difference between observations at the i^{th} and the j^{th} station.

ϵ_{ij} is the observational error.

The system was solved by least squares holding the value of station 0 fixed. No rejection of data was made in the first solution. The solution was then iterated several times using a rejection limit of 3 σ (σ = standard error of unit weight from previous solution) and the gravity values from the previous solution. After the third iteration no further rejections occurred. A summary of the adjustment is given in Fig. 5. Gravity values are given with respect to an arbitrary value of 0 at station 0. Standard error of the drift term (1.5 μgal/hr) indicates that the assumption of linear drift over the course of the survey is not a particularly good one. Later analyses will include a drift unknown for each of the seven days of observations to see if any improvement in the results occurs.

Fig. 6 shows the histogram of residuals from the least squares adjustment. The χ^2 test indicates that there is no reason to believe that the sample is not drawn from a normal population. The fact that the distribution is slightly skewed may be due to a small systematic error introduced into some legs of the network by neglecting ocean tide effects.

5. Calibration of the Microgravimeter

The manufacturer claims that the dial response of the microgravimeter is linear over the 200 mgal range of the zero length spring. Whether or not the dial calibration factor changes as the instrument is reset is unclear. For the present we have taken the skeptical view that it is not. Therefore, repeat surveys in a given area will be carried out in the same dial reading range.

Before this type of instrument can be employed to measure long term variations in gravity a precise absolute calibration will be required in order to distinguish real changes in gravity from apparent changes due to long term variations in the characteristics of the instrument itself. Conventional calibration lines will not be of much help unless we can establish that the gravity values of the stations are stable to a few μgals over periods of many years. Until a portable absolute apparatus with microgal precision becomes available the calibration problem of the microgravimeter will not likely be resolved.

6. Conclusion

The main conclusions which are drawn from this evaluation of the LaCoste-Romberg Model D microgravimeter are:

(a) The instrument has a reading sensitivity of about 1 μgal.

(b) Under field conditions (car transport) it is reasonable to expect a standard deviation of 3 μgals over small gravity intervals (less than 100 μgals) and a standard deviation of 6 μgals for larger gravity differences.

(c) Relative gravity values with standard errors of 1 to 2 µgals can be obtained from an adjusted network of observations having about 10 repeat observations on each leg of the network.

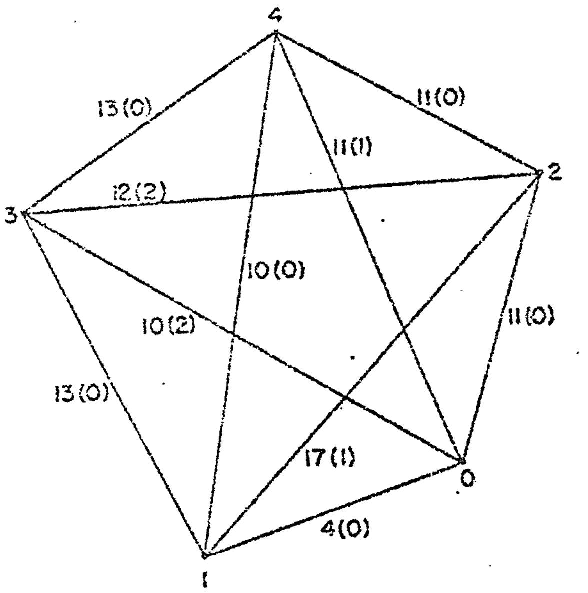
12. References

A.C. Hamilton, B.G. Brule, 1967: Vibration induced drift in LaCoste and Romberg geodetic gravimeters. J.G.R., 72, 8, pp 2187-2197.

I.M. Longman, 1959: Formulas for computing the tidal acceleration due to the moon and the sun. J. Geoph. Res., 64, pp 2351-2355.

CHARLOTTETOWN SURVEY

NET STRUCTURE



12(2) = NO. OF INTERVALS (NO. REJECTED)

SUMMARY OF LEAST SQUARES ADJUSTME

GRAVITY VALUE UNKNOWNS	4
DRIFT UNKNOWNS	1
NUMBER OF INTERVAL MEASUREMENTS	112
INTERVALS REJECTED	6
REJECTION LIMIT	18 µ gal
S.E. OF UNIT WEIGHT	6 µ gal

UNKNOWN	SOLUTION VALUE	S.E.
g_1	-832 µ gal	1.4 µ gal
g_2	605 µ gal	1.2 µ gal
g_3	2289 µ gal	1.3 µ gal
g_4	2957 µ gal	1.3 µ gal
d	1.6 µ gal/hr	1.5 µ gal/

Fig. 5

CHARLOTTETOWN SURVEY
DISTRIBUTION OF RESIDUALS
FROM LEAST SQUARES ADJUSTMENT

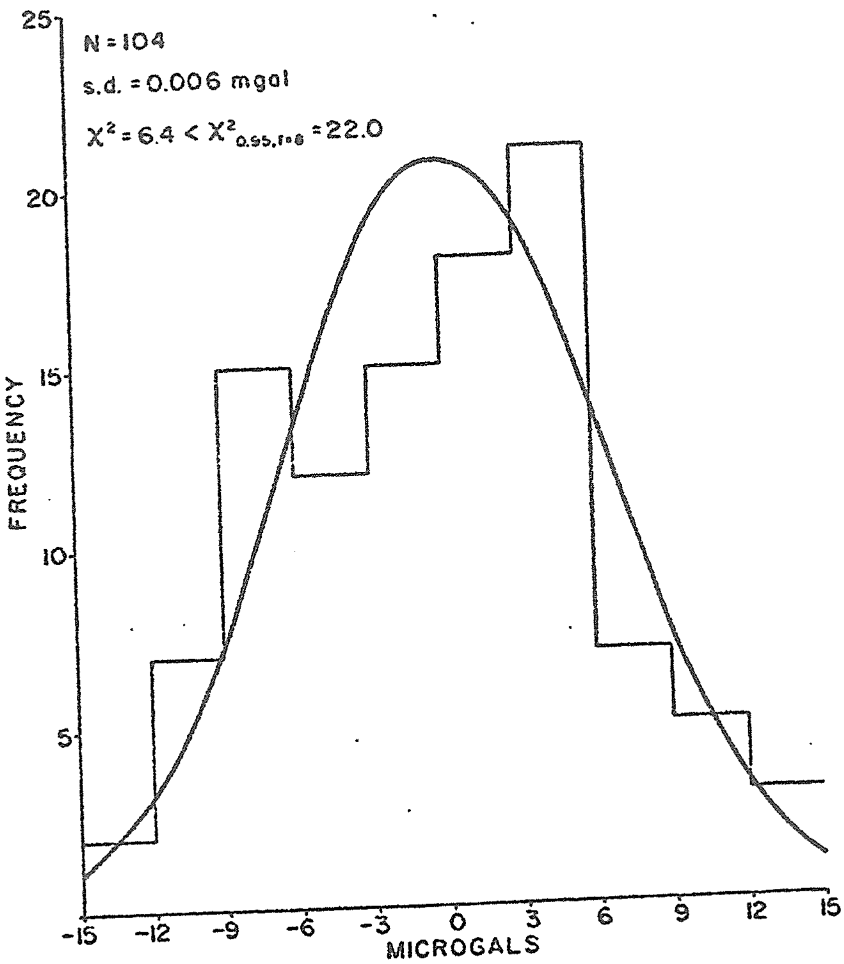


Fig. 6

- VIII -

NEW GRAVIMETRIC INSTRUMENTATION

Gravity Gradiometry

One session was held on Wednesday 4th September, in the afternoon, under the Chairmanship of Mr. O. WILLIAMS.

During the following session "High precision gradiometry" presided over by Prof. T. HONKASALO, Prof. E. GROTEN presents a paper dealing with different topics : gradiometry, high precision observations and secular gravity changes.

The complete abstract is included in this topic (see p. I-47).

Mr. O. WILLIAMS presents a general report : Gradiometry an assessment of the state-of-the art (see p. I-48), in which instrument prototypes which are felt to have potential as moving base gradiometers are described. The application of gradiometers to mass anomaly detection, inertial navigation assistance and global gravity modeling are discussed.

Prof. D.B. DeBRA gives information concerning the mass anomaly detection, the Earth gravity modeling, pointing out that the real impact of gradiometry in gravity modeling will occur in world-wide modeling using satellite gradient data. He speaks about the different techniques used to compute spherical harmonic coefficients and shows the regions of best sensitivity for altimeter, Doppler and gradiometer by harmonic degree and altitude.

Mr. B. CHOVITZ asks : "For determination of the Earth's gravity field by satellite gradiometry, 0.01 Eötvös Unit is needed for significant improvement at the 50 to 60 harmonic degree level, what is the practical possibility of attaining this sensitivity with the instruments under development to day ?".

Mr. O. WILLIAMS thinks that an accuracy of 0.01 E.U. is not impossible, and gives concluding remarks (see p. I-57).

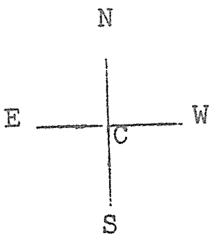
Ing. J.J. LEVALLOIS souligne l'importance de la mesure du gradient qui peut être utilisé pour déterminer le géoïde à l'intérieur d'un cadre connu en altitude. (Problème d'interpolation).

Une discussion du Laplacien du potentiel perturbateur T permet de présenter le problème sous la forme :

$$\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + f\ (x,\ y) = 0$$

où f est un terme numérique, différence entre le gradient observé et le gradient théorique.

Cette équation différentielle partielle
devient en termes potentiel :



$$T_N + T_W + T_S + T_E - 4\,T_C + f = 0$$

condition - ou relation d'observation -
on peut ajouter d'autres observations sur le contour et à l'intérieur pour déterminer entièrement le problème y compris la détermination du cadre.

Au point de vue numérique, je présente un exemple de 300km x 150 km (maille de 10 km) du géoïde français ...

Dr. E. GROTEN demande si le gradient a été corrigé ou réduit ?
Réponse : Ce gradient a été fourni par le B.R.G.M. et ne correspond pas exactement à la définition ci-contre, mais le calcul formel est possible et donne de bons résultats.

Prof. E. GROTEN reports on : Microgravimetry – High precision observations of small gravity differences

Abstract :

The application of a Sartorius 4104 microbalance after Gast in vertical gradiometry was tested. A small mass of about 20 grams is suspended on thin fibers of different lengths $\Delta l \leqslant 80$ cm. From the weight difference of the small mass obtained at different levels along the plumb line the corresponding differences of gravity along the plumb line are inferred. The microbalance is mounted on a steal rack ; measurements at constant low pressure (moderate vacuum) show the applicability of the balance as gravity difference sensor for field work. When environmental effects are further reduced (i.e. temperature is kept constant within $\pm$ 0.1°C) pressure is controlled within 0.1 Torr etc.) the resolution of the balance can be fully exploited so a relative accuracy of $\pm 10^{-9}$ should be feasible and for laboratory experiments should be of the order of a few parts in $\pm 10^{-10}$.

Vertical gravity gradients as observed on an improved moving platform with a LaCoste model G gravimeter are discussed. New possibilities of microgravimetry are pointed out.

High precision observations and the establishment of a system in an area of tectonic interest for detecting secular gravity changes are described.

DEFENSE MAPPING AGENCY

WASHINGTON, D. C.

GRADIOMETRY
AN ASSESSMENT OF THE STATE-OF-THE-ART

Owen W. Williams

September 1974

INTRODUCTION

Gradiometry, or the measurement of the gradients (spatial derivatives) of the earth's gravity vector at a point on the surface of the earth or in space, is currently enjoying a rebirth. The concept of gradiometry is by no means new. As early as 1880 Baron Roland von Eotvos developed the torsion balance for the purpose of measuring the distortion of the gravity field, Figure 1. As early as 1915, the instrument was used for geophysical exploration, and was first introduced into the United States for oil prospecting in 1922. The torsion balance provided gravity gradients; gravity gradients aid in the location of geological structures. Because the Eotvos Torsion Balance is so cumbersome and requires such a long time to accomplish a single observation, the more portable gravimeter soon replaced it as a prospecting instrument.

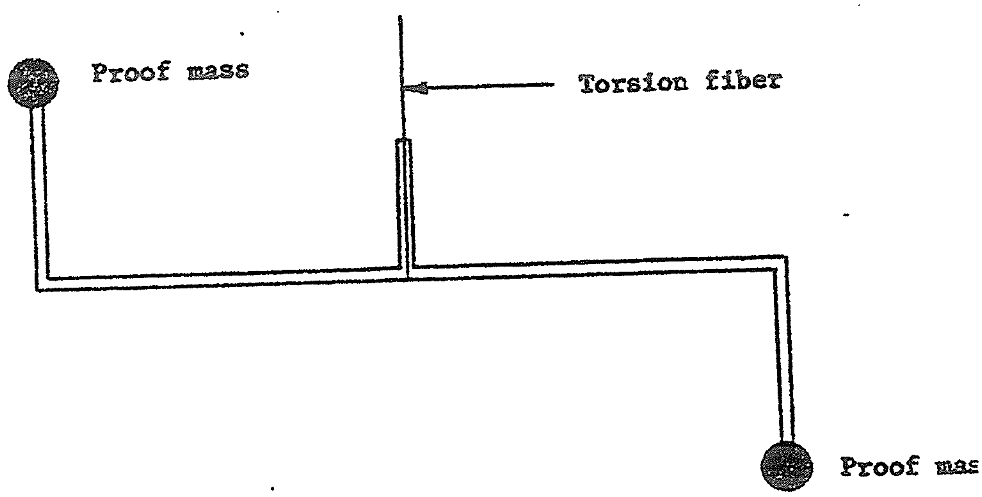


Figure 1. The Eotvos Torsion Balance

It is significant that in the current energy shortage, when new deposits of fossil fuels are urgently needed, that several new gravity gradient sensors are being developed. Many schemes have been tried; many provide usable data. The instruments described in this paper are instruments which we feel have potential as moving base gradiometers, i.e., capable of being readily transportable and capable of providing gravity gradient measurements while in motion.

In addition to the direct application in geophysical exploration mentioned above, gradiometry has a wide range of applications in the mapping, charting and geodesy field. A few of these applications are discussed in this paper.

INSTRUMENTATION

Fundamental Principles:

The gravity gradient is defined as the derivative of the gravity vector with respect to distance. Thus, the gravity gradient at a point is the tensor quantity

$$G = \begin{bmatrix} \frac{\partial g_x}{\partial x} & \frac{\partial g_x}{\partial y} & \frac{\partial g_x}{\partial z} \\ \frac{\partial g_y}{\partial x} & \frac{\partial g_y}{\partial y} & \frac{\partial g_y}{\partial z} \\ \frac{\partial g_z}{\partial x} & \frac{\partial g_z}{\partial y} & \frac{\partial g_z}{\partial z} \end{bmatrix}$$

where the gravity vector is given by

$$\vec{g} = \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix}$$

Although this tensor contains nine elements, only five are independent, the matrix is symmetric, i.e., $\partial g_x/\partial y = \partial g_y/\partial x$, etc. and Laplace's equation holds for the diagonal terms, i.e.,

$$\frac{\partial g_x}{\partial x} + \frac{\partial g_y}{\partial y} + \frac{\partial g_z}{\partial z} = 0$$

These properties can be invoked in designing instrument packages.

The cartesian coordinates in which the gradients are defined can be either global (earth-centered, earth-fixed) or local (centered at the observation site). Figure 2.

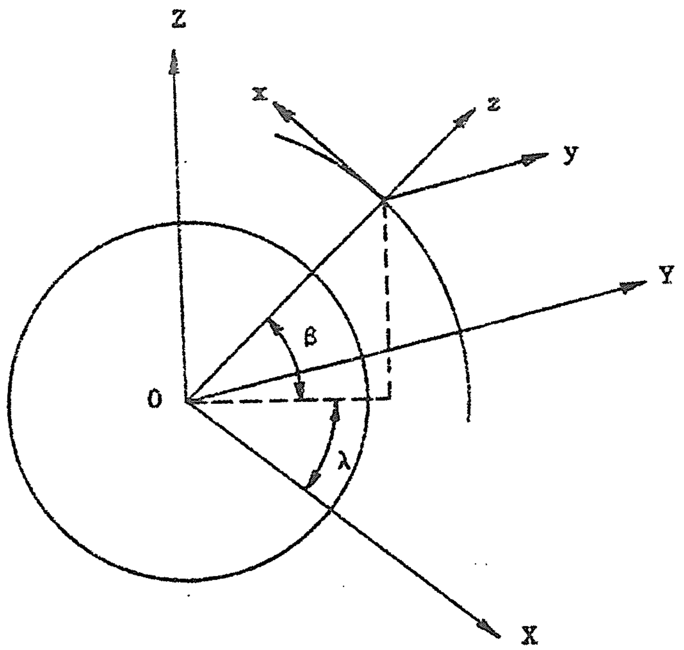


Figure 2. Global and Local Coordinate Systems.

Generally, we define the global cartesian coordinate system such that the Z axis coincides with earth's polar axis, the XY plane coincides with the equatorial plane, and the X axis extends through the Greenwich meridian. The Y axis forms the third axis of a right handed orthogonal triad. The local cartesian coordinate system is defined such that the z axis coincides with the local vertical, the xy plane coincides with the horizon plane, and the x axis is directed northwards. The eastward directed y axis completes the triad.

The transformation between gradients in the local and global systems is [Moritz, 1971]

$$\begin{bmatrix} G_{XX} & G_{XY} & G_{XZ} \\ G_{YX} & G_{YY} & G_{YZ} \\ G_{ZX} & G_{ZY} & G_{ZZ} \end{bmatrix} = A \begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix} A^T \qquad (1)$$

$$\begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix} = A^T \begin{bmatrix} G_{XX} & G_{XY} & G_{XZ} \\ G_{YX} & G_{YY} & G_{YZ} \\ G_{ZX} & G_{ZY} & G_{ZZ} \end{bmatrix} A \qquad (2)$$

where

$$A = \begin{bmatrix} -\sin\beta\cos\lambda & -\sin\lambda & \cos\beta\cos\lambda \\ -\sin\beta\sin\lambda & \cos\lambda & \cos\beta\sin\lambda \\ \cos\beta & 0 & \sin\beta \end{bmatrix} \quad (3)$$

and

β = geocentric latitude

λ = geocentric longitude

$G_{XX} = \partial g_x/\partial x$, etc.

The gradiometer platform can thus be stabilized to maintain either an orientation to the local vertical and north or to an orientation to an inertial frame of reference.

The definition of a gravity gradient leads directly to the basic design concept. Since the gradient is defined as the spatial derivative of the gravity vector, the instrument must provide a means of determining the slight difference in the acceleration of gravity at two points, separated by as little as a few centimeters. The design problem is further complicated by the fact that this is the only quantity to be measured - the instrument cannot be sensitive to temperature gradients, platform jitter or linear accelerations, and electromagnetic or electrostatic influence. In addition to all this, the instrument must have a moving-base capability. The three instruments described, in alphabetical order, in the remainder of this section show promise of meeting these criteria.

The Bell Aerospace Instrument

The Bell Aerospace Company, a division of Textron, Inc., has a well established reputation in the field of high precision inertial instruments and inertial measuring systems. It was logical, then, for Bell to propose that on-the-shelf accelerometers be used to develop a gravity gradient sensor.

The Bell concept [Bell Aerospace, 1971] employs four accelerometers mounted on a rotating table, which is stabilized in the orientation of its spin axis as shown in Figure 3.

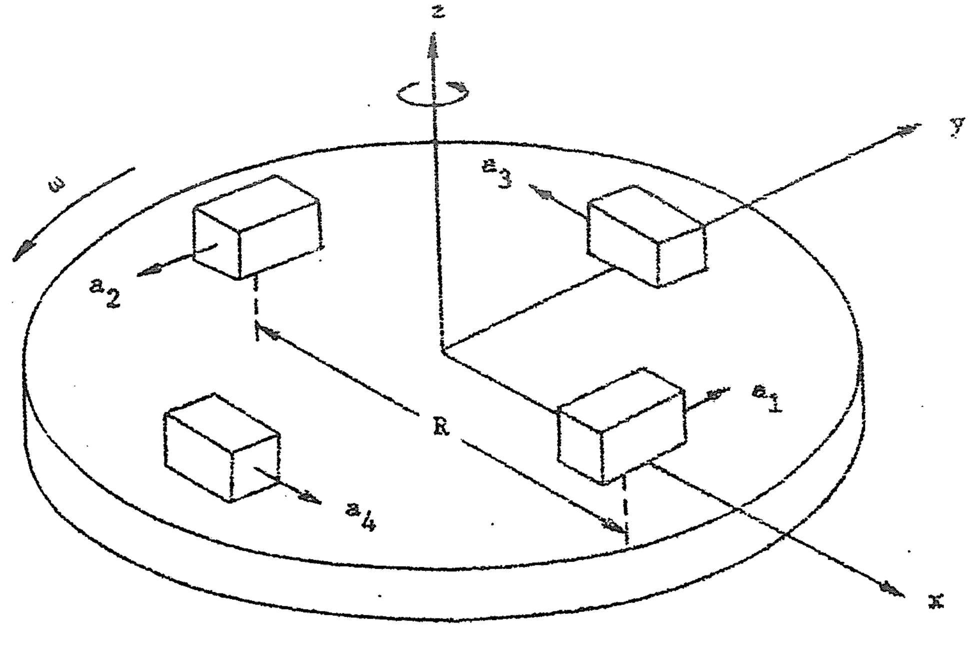


Figure 3. The Bell Gradiometer Concept.

In this figure, the table rotates about the z axis at a constant rate, ω. As the instrument passes a mass anomaly, that component of the gravitational attraction of the mass anomaly that lies in the xy plane causes differential accelerations in the pairs of accelerometers due to the differences in distance from the mass anomaly to the individual accelerometers of the pair. The measured accelerations are related to the elements of the gradient tensor by

$$(a_1 + a_2) - (a_3 + a_4) = -2R(G_{xx} - G_{yy}) \sin 2\omega t + 4R(G_{xy}) \cos 2\omega t \quad (4)$$

where a_1, a_2, a_3, a_4 = accelerometer outputs

R = separation of accelerometer pairs

ωt = phase angle of system.

Now, equation (4) reveals that a single sensor yields one element of the gradient tensor and the difference of two others. Thus, a triad of orthogonally mounted instruments will yield the entire tensor.

The advantage gained by rotating the instrument is that the gradient signals are modulated at twice the rotation frequency (i.e., 2ω), while most error sources are modulated at the rotation frequency (ω). Thus, a simple frequency filtering technique can be used to separate the signal from the noise. Use of pairs of accelerometers further serves to reduce these effects by cancellation.

The expected grand total error for the gradient sensors and the stabilized platform is 0.77 EU [Bell Aerospace, 1971]. (Note: 1 EU = 10^{-9}cm/sec^2/cm.)

Although the appropriate accelerometers are available, a working model of the Bell gradiometer is yet to be assembled. It is contemplated that this will be accomplished by November 1974.

The Hughes Instrument

The Hughes Research Laboratories of Malibu, California, a division of the Hughes Aircraft Company, has several years experience in the design of gravitational sensors for exploration. The problem of detecting and measuring gravity gradients was approached by the development of an instrument as illustrated in Figure 4.

The gradient sensor of the Hughes instrument consists of two pairs of proof masses mounted on pairs of cross arms. Relative torques between the cross arms can be measured by torsion sensitive sensors at the flexture point. The instrument is caused to rotate at a constant rate ω.

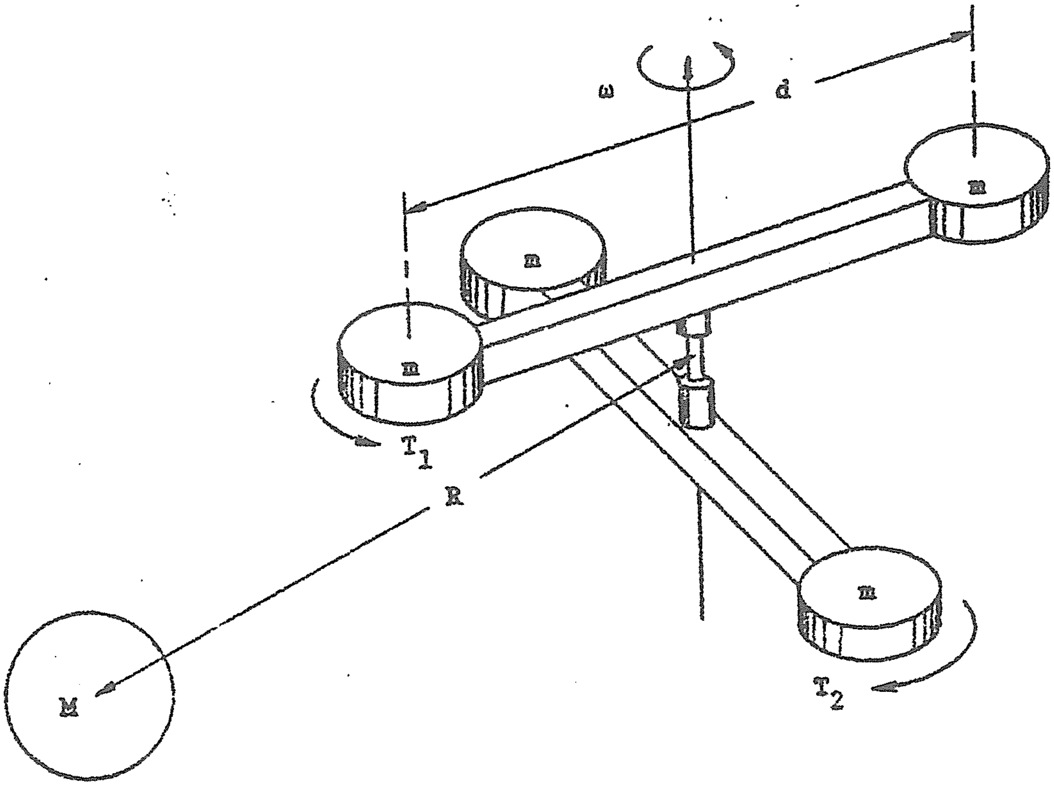


Figure 4. The Hughes Concept.

As the instrument passes over a mass anomaly, the slight differences in the gravitational attraction of the mass anomaly upon the proof masses cause slight differences in torque between the two cross arms. The differential torque is given by [Forward, 1971]

$$\Delta T = \frac{md^2}{4} \, [(G_{xx} - G_{yy}) \cos 2\omega t + 2G_{xy} \sin 2\omega t] \qquad (5)$$

where

m = mass of proof mass

The rotation rate is selected so that it is precisely one half the undamped natural frequency of the torsion sensitive sensor. The rationale for rotating the instrument has been discussed for the Bell Aerospace instrument. Again, a triad of orthogonally mounted instruments will be required to sense all elements of the gradient tensor.

An extensive error analysis [Ames, et al, 1973] of the prototype sensor and proposed platform system indicates an accuracy of about 0.6 EU in any component of the gradient tensor. A prototype instrument has been laboratory tested and performed as expected. Current plans are to build a rugged instrument for field testing.

The MIT Instrument

The Charles Stark Draper Laboratory, Inc., formerly a division of the Massachusetts Institute of Technology, is recognized as a leader in the development of gyros and accelerometers for inertial navigation systems. The technology employed in the successful gyros was extended into the development of the MIT gradiometer.

The gradient sensor of the MIT instrument is a cylindrical float composed of a light shell supporting diametrically opposed proof masses of some dense material illustrated in Figure 5 [Trageser, 1972].

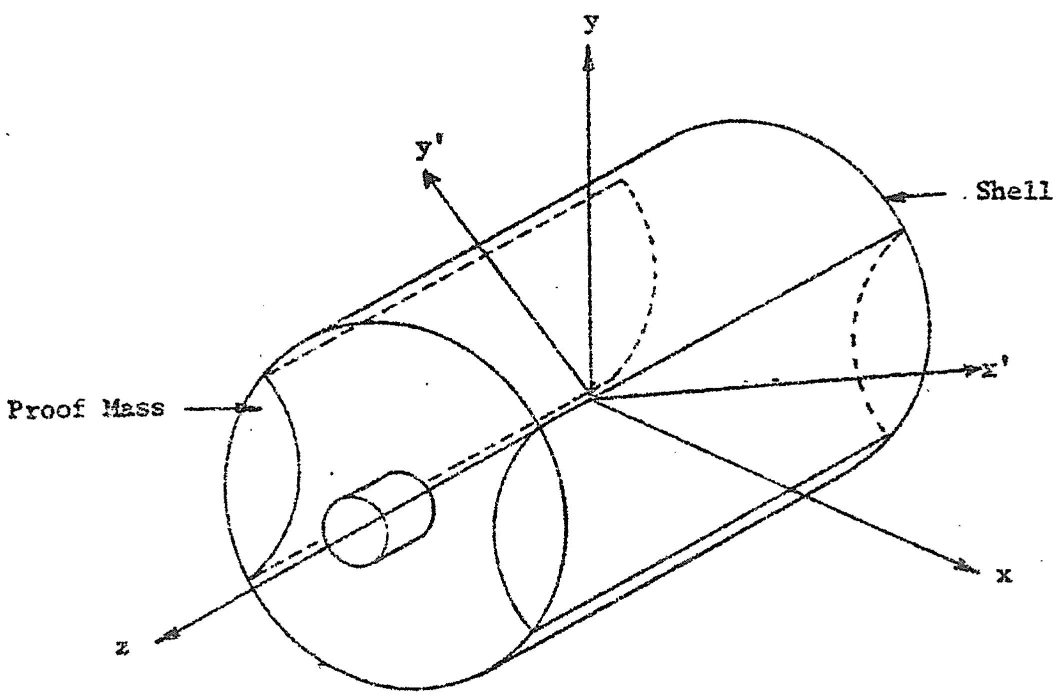


Figure 5. The MIT Instrument Concept.

The gyro technology carried over into the gradiometer design is the principle of buoyancy support [Trageser, 1970]. The mass of the float structure is supported against gravity and other accelerations by placing it in near-neutral buoyancy in a thin layer of liquid. Small capacitave structures can compensate for any residual buoyancy imbalance. To rotate the float about its support axis requires but a small shearing of fluid, but a translation requires the displacement of a significant amount of fluid through a small gap. The fluid nearly perfectly supports the float by neutral buoyancy.

The slight differences in the components in the xy plane of the gravitational attraction caused by a mass anomaly upon the two proof masses cause the cylinder to rotate about the z axis due to the moment M given by

$$M = -1/2(G_{y'y'} - G_{x'x'})\ (I_{yy} - I_{xx}) \tag{6}$$

where M = moment

$I_{yy} - I_{xx}$ = moments of inertia.

A minute torque is applied to restore the float to its original position; this torque is an indication of the gravity gradients. The rotation angle is precisely sensed by a capacitative pickoff on the cylinder and its housing. It is obvious that a triad of three instruments will measure the diagonal of the gradient tensor. A skewed arrangement of the proof masses would yield sensors sensitive to the products of inertia and hence the cross terms of the tensor.

Since the sensor element is not rotating, the MIT design cannot use frequency filtering to remove spurious gradients. It is essential that the gradiometer floats be superbly stabilized. The MIT instrument is very sensitive to thermal gradients. The gradients must be limited to 5×10^{-7}° C across the instrument.

The laboratory performance of the sensor is in the order of 0.14 EU [Trageser, 1973]. A reasonable expectation for this instrument in conjunction with a good platform is about 0.1 EU at 12 minute correlation times in any of the measured gradients.

APPLICATIONS

Gradiometer observations may be incorporated into the mapping, charting, and geodesy fields in an impressive number of ways. One might group these applications into mass anomaly detection, inertial navigation assist, and earth gravity modeling.

Mass Anomaly Detection

The gravity gradients detected by the instruments described arise from mass anomalies which the instrument is sensing. Depending upon the sensitivity of the instrument and the manner in which it is used, these mass anomalies may be highly localized.

Trageser has described in detail many such applications of gravity gradient sensing [Trageser, 1971]. An appropriately sensitive instrument can detect the mass excess or deficit caused by small subterranean features. As an aid to submarine navigation, a suitable gradiometer system might be used to detect the passage of the vessel over an ocean bottom ridge, peak, or valley, thus aiding in fixing the vessel's position.

By accomplishing a systematic gradiometer survey over an area, the gradient data obtained may be used to prepare maps of vertical deflections, gravity anomalies, and geoid heights in the area. By removing the ellipsoid contribution and the rotation terms, the anomalous gradients are obtained. The vertical deflections are the first integral of the horizontal gravity gradients, as are the gravity anomalies. The second integral, then, is the geoid height. In each of these applications, it is necessary to have independently known initial conditions at only a few points in the area.

Inertial Navigation Assist

The state-of-the-art in gyroscopes and accelerometers used on inertial navigation systems has progressed to the point where the principal source of error in such systems is the unmodeled vertical deflections. A stochastic gravity model has been incorporated into many inertial navigation systems through the Kalman filtering process, but this involves only the general characteristics of the field. Ideally, the inertial navigation system should have a continuous input of vertical deflection data. The gradiometer can provide this data.

The incorporation of gravity gradient sensors into the inertial navigation system was suggested by the Bell Aerospace Company [Jircitano and Metzger, 1972 and Trageser, 1970]. In a similar manner, the gradiometer might be included in a land survey system [Hopkins and Dimitrijevich, 1974]. In these systems, a triad of gradiometers provides all elements of the gravity gradient tensor. The gradient data is used in the inertial navigation system to provide vertical deflection data for the maintenance of position and velocity. As a bonus, the system provides accurate position and refined gradient data for geophysical applications.

Larger areas may be surveyed by this technique by use of high speed aircraft. The problems associated with vertical accelerations of the aircraft and uncertainties in the application of the Eotvos correction in airborne gravimetry do not occur in gradiometry. A sufficiently stable platform for the gradient sensor package is within the state-of-the-art [Ames, et al, 1973].

Earth Gravity Modeling

Although the gravity gradient data obtained by the moving base applications described just above might be used in defining regional gravity models in terms of gravity anomalies, etc., the real impact of gradiometry in gravity modeling will occur in worldwide modeling using satellite gradient data.

The quantities measured by a gradiometer carried by a spin stabilized satellite are $G_{zz} - G_{xx}$ and G_{xz} (Figure 2). The sensor can be as large as the diameter of the spacecraft itself; thus, an accuracy of .01 EU is not unreasonable. With an integration time of some 35 seconds, five days of data will provide enough data for improvement of the gravitational model of the earth. Since the gradiometer is insensitive to accelerations, the satellite need not be drag free, and can thus be at a low enough altitude to sense the shorter wave length in terms of the gravity field.

Spherical harmonic coefficients can be computed from the gradient data using least squares techniques [Glaser and Sherry, 1971] or by integration [Glaser, 1972], using a technique analogous to the computation of harmonic coefficient from gravity anomaly data by integration. Least squares collocation [Moritz, 1971] provides still another technique.

Alternatives to the spherical harmonic model include point mass models, density layer models, and Taylor Series models [Hopkins, 1973]. For each of these models, expressions can be written for the measured gradients. A least squares technique can then be used to compute the parameters of the model.

CONCLUDING REMARKS

The advent of truly moving base gravity gradient sensors holds the promise of significant advances in the field of mapping, charting, and geodesy. The enhancement of the accuracy of inertial navigation systems by the inclusion of gravity gradient sensors could have substantial impact in both surveying and navigation applications. Valuable spinoffs are envisioned in geophysical exploration and related areas of endeavor.

In the earth modeling aspect of gradiometry, controversy exists between the advocates of Doppler observation, satellite to satellite tracking, radar altimetry, and gradiometry. It is pretty well agreed that the Doppler techniques are preferred for lower degree terms, while the altimeter and gradiometry are preferable for the higher degree terms.

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- IX -

SECULAR VARIATION OF GRAVITY

One session was held on 3rd September, Tuesday morning, under the Chairmanship of Prof. Yu.D. BOULANGER; who made a General Report on this subject.(See p. I-63).

Prof. W. TORGE raises the question, whether the second proposal of Prof. BOULANGER (systematic repeated gravity determinations by relative methods) with which he fully agrees, might be influenced by systematic calibration errors. There are, e.g. at LaCoste-Romberg gravity-meters, different calibration functions, long periodic terms producing differences of 0.05 ... 0.06 mGal, and short periodic terms of 0.02 mGal, which we cannot detect completely up to now. Furthermore, calibration functions of gravity-meters may change with time at the order of the supposed gravity variations with time.

Prof. R. LECOLAZET attire l'attention sur la carte du géoïde établie par le B.G.I. à partir de valeurs moyennes des anomalies (5° x 5°) et il montre les grandes zones de signe différent (ondulations du géoïde positives ou négatives).

Il pense que si l'hypothèse d'un excentrement de la graine (inner core, Prof. BARTA) est exacte (explication des anomalies exceptionnelles de la gravité, négatives au sud des Indes, positives au voisinage de l'Australie) et s'il existe un déplacement séculaire de la graine, c'est au voisinage de ces anomalies et particulièrement entre les deux zones que se produiraient les plus fortes variations séculaires de la gravité.

Ing. J.J. LEVALLOIS fait remarquer que la localisation des stations de contrôle de g le long ou au voisinage de l'Equateur lui paraît être insuffisante et il pense personnellement que le réseau de contrôle des variations séculaires de g devrait couvrir le monde entier (30 ou 40 stations) indépendamment de la latitude.

Ensuite, il s'informe auprès du Prof. BOULANGER pour savoir si des mesures ont été faites dans les régions où l'on connaît de forts et rapides déplacements verticaux.

Le Prof. BOULANGER répond que des mesures n'ont pas encore été faites, mais sont prévues.

Dr. J.E. FALLER thinks we should keep in mind that we have two new geophysical tools at the centimeter accuracy : lunar laser ranging and high precision gravimetry. If as appears probable a mobile lunar laser ranging station is developed which would be capable of going to interesting geophysical sites, this would give geometrical height information which, if taken in combination with gravimetric data(which gives a combination of geometry and integrated masses in flow) will provide a highly sensitive tool which in combination is much more powerful than either individually.

Prof. G.P. WOOLLARD highly recommends specific progress of study to determine secular changes related to the :

1) Chandler wobble and changes in astronomical position ;
2) subduction effects at crustal plate convergence boundaries as the Peru - Chile Trench-Andes mountains and ;
3) tectonic effects related to mountain fronts in continental interiors (Rocky mountains, Alps) and ;
4) isostatic rebound from Pleistocene glacial loading (Scandinavia - Eastern Canada) and ;
5) skewing of continental base gravity nets as a result of the above.

Mr. B. CHOVITZ says that at the meeting of IAU Colloquium N° 26 August 26-31 at Torun, Poland, it was discussed and advocated that gravity and geophysical surveys be made at the astronomical stations of the ILS and IPMS.

Dr. P. WELLMAN reminds that on the Australian Calibration Line, differences have been observed between measurements in 1965, 1970-71 and 1973 ; these changes suggest that secular variation may be occuring at rates of up to 6 μGal per year (see p. I-17, 20).

SECULAR VARIATIONS of GRAVITY

Yu.D. BOULANGER

(Institute of Physics of the Earth, Acad. of Sci. of the USSR)

The problem of secular variations of gravity is one of the most acute problems of gravimetry and has fundamental interest for such sciences as metrology, physics, astronomy, geodesy, geophysics, geology. The complex set of data on recent crustal movements, gravity variations, irregularity of the Earth's rotation and oscillations of the world ocean level allows to establish the displacement of masses within the Earth, thus obtaining new data about the dynamics and, consequently, about the history of development of our planet.

This is a complex task which shall demand longstanding efforts of an extensive group of specialists. Its integral part is the study of gravity changes in time in a wide spectrum of frequencies caused both by endogenous and exogenous processes. In this study the determination of the fact and regularities in the gravity changes in time is decisive.

In the Soviet Union the researches in this field were started as far back as the twenties when such great discrepancies in the g values were obtained at repeated gravity determinations, that it was difficult to explain them only by the errors of measurements. This gave ground to some of the authors (1, 2) to suggest an opinion about the possibility of considerable gravity variations in time, associating them with tectonic processes occurring in the Earth's crust.

Further works proved these conceptions to be erroneous. Thus Pariysky (3), analysing the processes which can cause the irregularity of the Earth's rotation, has shown for the first time that such processes can be either the vertical movements of large regions of the Earth's crust or the transformation of the matter within the Earth with a noticeable change of density. Both these reasons can cause the change of gravity value on the surface, but they must be small and cannot exceed tenths of mGal per year.

As the result of researches of the vertical crustal movements carried out by Kalashnikova (4), it was established that a large part of depressions and uplifts develops independently of the basic gravitational fields. This provides ground to suppose, that the vertical movements are generated by compression or extension of the deep material without change of the general mass. In this case the transportation of the matter within the Earth does not cause gravity changes. Proceeding from that, even in the regions with intensive tectonic activity, apparently, we can hardly expect considerable gravity changes of the secular character.

In his works on the study of the irregularity of the Earth's rotation,Pariysky has shown, that the observed changes in the rotation rate of the Earth cannot cause changes of gravity of more than several microgals per year.

Somewhat later Barta (5, 6, 7, 8, 9) and then Vogel (10) have suggested a hypothesis about the possible gravity changes in time, caused by the displacement of the Earth's core in respect of its mantle. According to their calculations the gravity variations can reach tenths of mGal per year and can have quasi-periodic character with the period of about 500 - 1000 years.

Comparison of these two concepts indicates that there are two points of view on the possible gravity changes with time. According to one of these opinions, these changes can be small of the order of several microgals per year ; the second opinion states that they may reach tenths of mGal. At the same time modern requirements of practical gravimetry need the answer to a concrete question : does gravity change with time, or not ? If it does, then what is the order of these changes and what is the law, according to which they occur ?

To use gravity data for applied purposes, it is necessary to establish basic networks. Modern requirements to their organisation are rather high. The accuracy of determinations at initial points in countries should be not less than ± 0.05 mGal, while the accuracy of points on the controlling standard polygons should be still higher, of the order of ± 0.01 mGal.

Therefore, if gravity changes at the rate of the order of the first microgals per year, then the control of the world basic networks is sufficient once in 20-25 years. If the second conception about rapid gravity changes is probable, then before the law is established, according to which these changes take place, it is necessary to conduct measurements, apparently, not less than once a year. The volume of work in this case is easily imagined and, consequently, the costs.

The first repeated gravity determinations in the Soviet Union were conducted in 1935 in the Caucasus. The measurements were made with pendulum instruments. It has been established that gravity changes, if they exist, lie within measurement errors and cannot exceed several tenths of mGal per year.

The next set of measurements was carried out only after the War in 1954-55. The measurements were accomplished along the line Potsdam Petropavlovsk-on-Kamchatka, and in several points in the Caucasus and in the Middle Asia. The points were chosen in such a way as to cover with measurements regions tectonically quiet and seismically active.

Repeated observations were carried out 10 years later in 1964. Notable changes of gravity were not detected. All the changes were much less than the errors of their determination. As the result of their careful processing, a conclusion was made that if at the indicated points the gravity changes occurred, they did not exceed 10-15 microgals per year (11).

Similar observations were conducted at a number of points in Eastern Europe in 1958 and 1968. The same result was obtained here. The changes of gravity were less than the errors in their determination and their annual rates could not be more than 10 microgals per year (12).

In order to control reliability of determinations of the International Gravimetrical Point in Moscow (Ledovo) and the stability in time of the gravity value at that point relative to Potsdam the Δg value Potsdam-Ledovo was repeatedly measured. During the last 16 years, 5 measurements were made. As seen in Table I, all the observed changes are less than their mean square errors. Assuming the gravity field is unchanging, its stability in the point of Ledovo relative to Potsdam in this case is characterised by the error ± 11 microgals per year.

In 1970 the differences were measured Moscow-Murmansk and Moscow-Tbilisi. The measurements were made by 5 gravity meters GAG-1 and by 3 gravity meters GAG-2. In 1973 these measurements were repeated by 8 gravity meters GAG-2. No changes in the measured values of Δg were detected. The change of difference Tbilisi-Murmansk, the value of which is of the order of 2.5 gl, was found equal to 0.00 ± 0.070 mgl.

In recent years in the scientific publications of the Soviet Union a number of works (13, 14, 15, 16, 17, 18, 19) were published, which present data on gravity variations in time, obtained as the result of comparison of gravimetric maps, compiled in different years. Comparisons were made of the maps of the Ukraine, the Volga region, the Volgasidi, the Northern Caucasus. According to the opinion of the authors of these works, they have discovered gravity variations which have good correlation with the tectonics of these regions. Moreover, the variations reached several tenths of mgl/year.

The experience of highly accurate repeated relative determinations of gravity testifies to considerable difficulties of comparison of data of different epochs. It is done with reliability only for separate points with their precise identification and the presence of complete information on the metrology of the carried out measurements. At the slightest inaccuracy in this information, as a rule, the measurements show systematic errors which considerably distort the conclusions. It is therefore, rather difficult to agree with the reality of the conclusions, obtained on the basis of comparison of repeated area surveys.

Thus, as the result of repeated determinations of gravity on the territory of Eastern Europe, and also along the chain of points Potsdam-Kamchatka and in some points of the Middle Asia the changes of gravity exceeding the measurement errors were as yet not detected. This allows for a statement that in the indicated points, even if gravity changed its changes can be not more than 10-15 microgals per year.

At the same time there is a number of theoretical aspects, which suggest that gravity should change with time and, perhaps, in some regions at a considerably greater rate. It is, therefore, considered necessary to conduct further study of changes of the gravity field of the Earth in the programs of international works, using in these studies as much as possible the entire facilities.

In the first place, it is extremely important to establish a network of gravimetric observatories with highly accurate stationary instruments for absolute determinations. It is desirable to place these observatories closer to the equator, since gravity changes in the equatorial zone have the greatest influence on the change of the rotation velocity of the Earth.

Of considerable interest is the organisation of systematic repeated gravity determinations by relative methods along long-distance traverses (of the order of thousands of km) with different orientation and location on different continents.

Finally, it is necessary to continue repeated measurements with the purpose of detection of local gravity changes, apparently caused by local tectonic processes.

The Soviet Geophysical Committee is prepared to take part both in the elaboration of projects of global works on the study of gravity changes with time and in their accomplishment.

Starting from 1975 in the Soviet Union it is planned to make repeated gravity determinations along the traverses: Moscow--Ashkhabad-Tashkent-Dushanbe and Moscow-Novosibirsk-Dushanbe. Besides, studies of local gravity changes shall be continued in Middle Asia, Baikal region, Crimea, Ukraine and Caucasus.

Table 4

Results of gravity determinations at the International Gravimetric Point in Ledov.

g_{s2} = 981 274.71 ± 0.00

1958	981 565.34	± 160
1968	.26	57
1970	.31	55
1971	.31	24
1974 (January)	.32	07
1974 (July)	.34	19

Mean 981 565.313 ± 12

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- X -

GRAVITY MEASUREMENTS ON THE MOON

On Wednesday morning 4th September, Dr. C. BOWIN presents a report on : "Mascons : a Two Body Solution.

Almost all of the mass distributions that have been proposed to account for the large positive gravity anomalies associated with lunar mascons have assumed single body sources of a mass excess. In the case of mare fill with a reasonable density contrast (+ 0.5 gm/cm^3) with crustal material, this requires a fill thickness of about 16 km for Mare Serenitatis to account for the observed gravity values at 100 km height. Such a great thickness would require a 16 km deep hole prior to filling and such a topographic depression is inconsistent with gravity anomalies away from the mare basins where near isostatic conditions appear to prevail. It also is inconsistent with the depths of the topography of Mare Nectaris and Mare Oriental basins which have but little fill, and with estimates of mare thicknesses based on buried crater dimensions. A two body mascon solution, however, requires only a 2 km thickness of fill and a 12 km rise of a lunar Moho beneath Mare Serenitatis to account for the observed gravity anomalies. The top of the mantle dome or plug is placed at 60 km depth to match observed seismic velocity structure. This mascon structure has an anomalous gravity field that is in good agreement with anomalies observed at several heights above Mare Serenitatis. The surface loading for this structure is only 680 kg/cm^3, less than that for previously proposed single body solutions, thus lowering the strength of the lunar crust required to support the super-isostatic mare fill.

Dr. J.E. FALLER asks what fundamental difference is between the Earth and the Moon such that no mascons exist (are left) on Earth.

It is answered that the lithosphere on the Earth is much thinner (70 - 150 km thick) than that on the Moon (about 1000 km thick). The Earth cannot support (because of the thin lithosphere) a static load of 600 kg/cm^3 which is approximately the load represented by the mascons.

- XI -

INTERPOLATION OF GRAVITY VALUES
and
THE BOUNDARY VALUE PROBLEM OF GEODESY

During the session presided over by Prof. U.A. UOTILA on Wednesday morning 4th September, 3 papers were presented.

Mr. C.C. TSCHERNING reports on : Application of Collocation for the Planning of Gravity Surveys. *

Least squares collocation can be used to determine the density of a gravity survey, when the object of the survey is :

1. To produce a (free-air) gravity map, so that point gravity values can be interpolated with a standard error of $\pm X_1$ mGal,
2. To interpolate deflections of the vertical with a standard error of $\pm X_2$ arc sec. between astronomical stations Z km apart,
3. To compute an upward continuation of a point gravity anomaly to a height of Z meters with a standard error of $\pm X_3$ mGal,
4. To compute mean gravity anomalies of block size Z degrees with a standard error of $\pm X_4$ mGal,
5. To obtain a (local) gravimetric geoid with a standard error of $\pm X_5$ m.
6. To compute density anomalies at a depth of Z km with a standard error of $\pm X_6$ g/cm^3.

Dr. V. VYSKOCIL makes the following remark :

The gravity field is a time-space field existing during the long geological history of the Earth. We know only our realisation of it in the present time.

The random field may be defined as a set of realisations corresponding to the points of the geological time scale.

Then, Dr. V. VYSKOCIL presents a paper : Comments on the Statistical Analysis of Gravity Anomalies.

In statistical analyses of gravity anomalies the mathematical apparatus of homogeneous and ergodic random processes is usually applied. The assumptions of homogeneity and ergodicity are introduced as working hypotheses ; their validity in the case of the anomalous gravity field has not been verified. Moreover, the gravity data are mostly available only in limited areas. Under these conditions the computed mean values and covariance functions cannot be considered to be statistical characteristics in the meaning of the exact probabilistic theory of the homogeneous random fields.

* The definitive text will be published later in a Bulletin Géodésique.

The obtained results indicate, that the values of the statistical characteristics of the anomalous gravity field depend on the dimensions and geological nature of the given areas. The correlation analysis carried out in Czechoslovakia has proved the different properties of gravity anomalies and the different relations between them and the deep structure of the Earth's crust in the Bohemian Massif and in the Carpathians.

In geophysical interpretations the assumption of global homogeneity of the anomalous gravity field seems to be useless. On the contrary, it is expedient to mark out the variety of geophysical and geological properties of crustal blocks. Some possibilities of using the moving average and other moving statistical characteristics and a general procedure of correlation analysis of a system of geophysical fields, in which one can take into account both the real initial conditions and the purpose of the solved problem in every actual case, are outlined in the paper.

At the end, Prof. G.P. WOOLLARD speaks on : Gravity Data and Crustal Parameters. (See topic XIII, p.I-106).

On Wednesday afternoon Prof. E.TENGSTROM reports on : The Boundary Value Problem of Geodesy. (See next page).

Prof. W. TORGE mentions the transportable photographic zenith tube developed in Hannover, as another possibility to determine astronomic latitude and longitude. The prototype now being in field test, gives an accuracy of about $\pm$ 0".5, depending on road and wheather conditions ; some stations can be observed in one night.

Note : On this subject, we can mention the following publication :

Mascons and Lunar Gravity, J.R. BOOKER, R.L. KOVACH & L. LU, J. Geophys. Res., v.75, n°32, p.6558-6564, Nov. 1970.

The mascon in a lunar ringed mare is approximately proportional to the area of the mare material in the basin. This relationship is consistent with the hypothesis that the lunar mascons are produced by dense plugs in the maria, and it means that the maximum thickness of the uncompensated rock is the same for all maria. The relationship also predicts the presence of mascons in other ringed lunar structures, such as Maria Orientale and Smythii, which are consistent with satellite Doppler data. The relative masses of the known and predicted mascons accurately predict the moon's dynamical asymmetry without any large mascons on the lunar farside. However, reconciliation of the absolute differences between the lunar moments of inertia with satellite accelerationsdirectly above the maria requires mascons buried deeper than 250 km. Such deeply buried mascons seem unlikely. It therefore also seems unlikely that the differences in the lunar moments of inertia are completely due to the mascons. However, a converse relationship cannot be ruled out. Examination of the degree variances of harmonic analyses of lunar gravity reveals a gentle peak near degree 10. This peak is predicted by the spacing of the two largest mascons, Imbrium and Serenitiatis.

The Eötvös tensor, and its importance for the detailed mapping of the gravity field near the Earth's surface, and for defining a suitable level surface for solving the external BV-problem of Geodesy as a unique Neumann-problem.

Eric VERMAAT & Eric TENGSTRÖM

As well known, the symmetrical tensor of Eötvös is:

$$\omega = \begin{Bmatrix} W_{\xi\xi} & W_{\xi\eta} & W_{\xi\zeta} \\ W_{\xi\eta} & W_{\eta\eta} & W_{\eta\zeta} \\ W_{\xi\zeta} & W_{\eta\zeta} & W_{\zeta\zeta} \end{Bmatrix} \qquad (1)$$

It has three invariants with respect to coordinatetranslations and rotations, namely I_1 (trace = $W_{\xi\xi} + W_{\eta\eta} + W_{\zeta\zeta}$), I_2 (determinant of ω), and I_3 (sum of the sub-determinants of the elements in the main diagonal). It describes the change of the gravity vector $\underline{G}$ ($d\underline{G}$) in the direction $d\underline{r}$, according to

$$\omega d\underline{r} = d\underline{G} \qquad (2)$$

In (1) ξ , η , ζ denote rectangular coordinates in the local astronomical system (ξ North, η East, ζ Nadir) of an observation-station P.

The value of the vector $\underline{G}$ is denoted G. So, $\frac{1}{G} W_{\xi\eta}$ is the change of plumb-line direction component in ξ- axis along η or, which is the same, the change of the plumb-line direction component in η- axis along ξ.

$\frac{1}{G} W_{\xi\xi}$ is the change of plumb-line direction component in ξ- axis along ξ.

$\frac{1}{G} W_{\eta\eta}$ is the change of plumb-line direction component in η- axis along η.

These components of Eötvös' tensor, which need torsion-balance - and gradiometer-observations to be determined are of importance, if we like to study $d\underline{G}$ in an arbitrary direction $d\underline{r}$.

The purpose of this paper is, however, to show, that - when knowing the astronomical latitude and longitude from measurements at each observation station P, or interpolated by some differential method (e.g. the Russian way of differential polarisation information), the detailed gravity (and gravitational) field beneath an equipotential surface of gravity, not touching the Earth's surface, it will be possible to use only threedimensional gradiometers, measuring at different heights of the straight line, equal to the tangent of the plumb-line at P. In this case, the only information at P and at the measuring points above P is the O-information from ω.

We know, that gradiometers exist, measuring grad G on the ground and in the air. Their accuracy should correspond to measuring the components of grad G to within some tenths of an Eötvös (0,01 mgal/km).

The O-information at the P:s and along aforementioned straight lines makes it possible to map the gravity vector $\underline{G}$ near the Earth's surface in detail, say up to a level surface of gravity (S°), not touching this surface anywhere. This level surface, the coordinates of which can be determined in a geocentric coordinate system (see below), is a boundary along which $\frac{\partial V}{\partial n}$ (normal derivative of gravitational potential v) will be known. To determine the external gravitational field, we have only to solve the Neumann integral equation for the density of a single layer. The solution is unique and has all correct properties in infinity.

When Stokes' chose the Geoid as reference surface for determining the external gravitational field, he did not know, that instrumental techniques in the future would be able to transfer measurements of gravity upwards. So he had to trust an approximation (accepted density of topography and accepted values of the vertical gradient of gravity) to reach the Geoid.

Now we have tools for making the upward transfer before we start to solve the geodetic Boundary Value Problem, <u>at the same time</u> securing a detailed mapping of the gravity (gravitational) field near the surface of the Earth.

Professor Marussi has told us, that - for last-mentioned studies - the equation

$$\omega\, \underline{dr} = \underline{dG}$$

is essential, which presupposes the knowledge of all the components of the Eötvös tensor ω.

The general theory of this treatment of the problem of studying the Earth's gravity field is beautifully outlined in his treatise "Fondamenti di Geodesia Intrinseca", 1951, which represents an important step in Geodetic Research history toward a better understanding of the intimate relation between geometrical and physical geodesy.

Therefore in general cases both $\square$ - and $\bigcirc$ -informations from ω are needed.

With three-dimensional gradiometers and torsionbalancies, this might be achieved. Because the gradiometers give the components of

$$\text{grad } G = \frac{\partial G}{\partial \xi} i + \frac{\partial G}{\partial \eta} j + \frac{\partial G}{\partial \zeta} k \quad ,$$

and the information $\square$ is given by gradiometers and torsionbalancies in the following way:

$W_{\xi\eta}$ and W_Δ are measured by the conventional torsionbalance.

We also have: $W_{\eta\eta} + W_{\xi\xi} = 2\omega^2 - \frac{\partial G}{\partial \zeta}$ (acc. to the I_1-properties and the gradiometer-result),

and $W_{\eta\eta} - W_{\xi\xi} = W_\Delta$ (torsion-balance by definition) ,

which equations determine $W_{\xi\xi}$ and $W_{\eta\eta}$.

The mapping of the field in the space between a chosen level-surface of W (S^* with potential $W_{S^*} = W_o + \Delta W^*$, where W_o is the potential of the Geoid, ΔW^* a constant, proceeds in the following way.

The following equations (supposing convergent Taylor-expansions)

$$\Delta W^* - \Delta W_P = -G_p H_{pp^*} + \frac{1}{2} \frac{\partial G_p}{\partial \zeta} H^2_{pp^*} + \ldots \qquad (3a)$$

$$\underline{G}_{p^*} - \underline{G}_p \equiv \Delta \underline{G}_{pp^*} = -(\text{grad } G_p) H_{pp^*} + \frac{1}{2} (\text{grad } \frac{\partial G_p}{\partial \zeta}) H^2_{pp^*} \ldots$$

(3b)

give H_{pp^*} (from (3a)), as G_p, $\frac{\partial G_p}{\partial \zeta}$ etc. and $\Delta W_p = W_p - W_o$ are measured, ΔW^* conveniently chosen, and $\underline{G}_{p^*}$ (from (3b)), as the components of grad G_p and grad $\frac{\partial G_p}{\partial \zeta}$ etc., are also measured together with the astronomical latitude ϕ and longitude λ (E.Gr.) at P. See figure 1).

With $P^*(\phi_{p^*}, \lambda_{p^*}, H_{pp^*})$ given for all suitable chosen P:s on the Earth's surface, S^* is known in the same rectangular Cartesian system (x, y, z), which has been used for fixing the P:s. Also $\underline{G}_{p^*}$ can be mapped along the smooth S^* in the same coordinate system. We have namely

$$\begin{Bmatrix} x_{p^*} \\ y_{p^*} \\ z_{p^*} \end{Bmatrix} = H_{pp^*} \begin{Bmatrix} \cos\lambda & \cos\phi \\ \sin\lambda & \cos\phi \\ & \sin\phi \end{Bmatrix}_p + \begin{Bmatrix} x_p \\ y_p \\ z_p \end{Bmatrix} , \qquad (4a)$$

and for G_{p^*} through the rotation

$$(\xi, \eta, \zeta) \rightarrow (x, y, z)$$

$$\begin{pmatrix} G_{p'}^{(x)} \\ G_{p'}^{(y)} \\ G_{p'}^{(z)} \end{pmatrix} = \begin{pmatrix} -\cos\lambda\ \sin\phi & -\sin\lambda & -\cos\lambda\ \cos\phi \\ -\sin\lambda\ \sin\phi & \cos\lambda & -\sin\lambda\ \cos\phi \\ \cos\phi & 0 & -\sin\phi \end{pmatrix}_p \begin{pmatrix} G_{p'}^{(\xi)} \\ G_{p'}^{(\eta)} \\ G_{p'}^{(\zeta)} \end{pmatrix} \quad (4b)$$

If we write $H_{pp'} - n\cdot\Delta\zeta$ with $n=0$ at S', and $\Delta\zeta$ constant, instead of $H_{pp'}$, (3) and (4) will map threedimensionally W and $\underline{G}$ beneath S' down to the surface F of the Earth, taking e.g. P:s with constant $\Delta(\lambda\cos\phi)$, $\Delta\phi$. The threedimensional grid of W, $\underline{G}$ with the coordinates λ_p, ϕ_p $H_{pp'} - n\cdot\Delta\zeta$ or corresponding x,y,z. Observe, that we do not use intrinsic coordinates for the grid, but express the scalar field $W(x,y,z)$, and the vector field $\underline{G}(x,y,z)$ as space-functions in the accepted global coordinate-system x,y,z, the axis of which are parallel to those of the geocentric one. And this is done by utilizing the results of gravity measurements G_p, grad G_p etc. and astronomical measurements λ_p, ϕ_p at P.

The components of grad G_p are the Eötvös' tensorelements $W_{\xi\zeta}$, $W_{\eta\zeta}$ and $W_{\zeta\zeta}$, which now-a-days can be measured by threedimensional gradiometers on the ground at P or along $H_{pp'}$ in air-crafts. The curvature elements $W_{\xi\xi}$, $W_{\eta\eta}$, $W_{\xi\eta}$ are not needed in this type of mapping.

The Taylor expansions in (3) might for maximal height, of say 10 km, be divergent. Flying at so small $\Delta\zeta$-intervals, that we are certain of linear changes of the gradient-components in the ξ, η, ζ system, such a failure should be excluded.

The three-dimensional mapping of the space close to the Earth's surface, performed by measurements on the ground, and in this space should be of greater importance for attacking the problem of obtaining possible solutions for the subsurface density mapping than surface-measurements of G and doubtful computations of its derivatives, which is the procedure in Geophysics.

Determination of the massconstant of the Earth and the coordinates x_0, y_0, z_0 of its masscenter.

We have $W = V + \Phi$, where V is the gravitational potential, Φ the potential of the centrifugal force, corresponding to

$$\underline{G} = \underline{g} + \underline{\omega} \quad ,$$

where $\underline{g}$ is the gravitational force vector, $\underline{\omega}$ the centrifugal force vector.

From Gauss' theorem of the relation between the volume-integral inside S' of div $\underline{g}$ and the surface integral of $\underline{g}_{p'} \cdot \hat{\underline{n}}_{p'}$ along S', we obtain

$$-4\pi k^2 M' = \iint_{S'} (\underline{g}_{p'} \cdot \hat{\underline{n}}_{p'})\, dS' \quad , \tag{5}$$

where M' is the total mass inside S', ignoring the mass outside S', $\hat{\underline{n}}_{p'}$ the outward unit normal vector. k^2 is the universal gravitational constant.

By extension of Gauss' theorem we also obtain

$$-4\pi k^2 M' x_0 = \iint_{S'} x_{p'} (\underline{g}_{p'} \cdot \hat{\underline{n}}_{p'})\, dS'$$

$$-4\pi k^2 M' y_0 = \iint_{S'} y_{p'} (\underline{g}_{p'} \cdot \hat{\underline{n}}_{p'})\, dS' \tag{6}$$

$$-4\pi k^2 M' z_0 = \iint_{S'} z_{p'} (\underline{g}_{p'} \cdot \hat{\underline{n}}_{p'})\, dS'$$

Since $\iint_{S'} (\underline{g}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' = \iint_{S'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - \iint_{S'} (\underline{\omega}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS'$,

and
$$\iint_{S'} x_{p'} (\underline{g}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' = \iint_{S'} x_{p'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' -$$
$$- \iint_{S'} x_{p'} (\underline{\omega}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS'$$

we get for the rotating Earth with

$$\Phi = \frac{1}{2}\omega^2 \left[(x - x_o)^2 + (y - y_o)^2\right] \text{ from (5) and (6)}$$

$$-4\pi k^2 M' = \iint_{S'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - 2\omega^2 V' \qquad (5a)$$

and

$$x_o \left[\iint_{S'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - 3\omega^2 V'\right] = \iint_{S'} x_{p'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - 3\omega^2 \iiint_{V'} x_i\, dv_i$$

$$y_o \left[\iint_{S'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - 3\omega^2 V'\right] = \iint_{S'} y_{p'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - 3\omega^2 \iiint_{V'} y_i\, dv_i \qquad (6a)$$

$$z_o \left[\iint_{S'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - 2\omega^2 V'\right] = \iint_{S'} z_{p'} (\underline{G}_{p'} \cdot \underline{\hat{n}}_{p'})\, dS' - 2\omega^2 \iiint_{V'} z_i\, dv_i$$

Here V' is the total volume inside S'. Introducing the coordinates $\tilde{x}_o, \tilde{y}_o, \tilde{z}_o$ for a point, which would be the masscenter of S', if S' was filled with matter of constant density, the volume integrals in (6b) can be written $\tilde{x}_o V'$, $\tilde{y}_o V'$, $\tilde{z}_o V'$.

x_o', y_o, z_o from (6a) give the geocentric coordinates (x_c', y_c', z_c') of all points on S', and the boundary of the Neumann-problem is known with its $\underline{G}$ and $\underline{g}$-distribution along it in a geocentric coordinate system.

Solution of the Neumann BV-problem.

Define, as usual a single layer gravitational potential

$$V_y = \iint_{S'} \mu \cdot \frac{1}{\Delta_{P_{yQ'}}} \, dS_{Q'}' \quad \text{(see fig. 2)} , \tag{7}$$

which is valid everywhere outside S'. μ is then determined by the solution of the integral equation

$$-(\underline{g}_{P'} \cdot \hat{\underline{n}}_{P'}) = 2\pi\mu(P') - \iint_{S'} \frac{\cos(\Delta_{P'Q'}, \hat{\underline{n}}_{P'})}{\Delta^2_{P'Q'}} \mu(Q') dS_{Q'} \tag{8}$$

To be able to work with small quantities,[x)] we introduce a "disturbing" potential

$$T = W - W_M = V - V_M \quad ,$$

W_M and V_M being values for an accepted model, which is not too different in potential and gravitational properties from the real Earth, and also a disturbance vector $\underline{\Delta} = \underline{G} - \underline{\Gamma} = \underline{g} - \underline{\gamma}$.

With
$$T_y = \iint_{S'} \Delta\mu(Q') \cdot \frac{1}{\Delta_{P_{yQ'}}} \, dS_{Q'} \tag{7a}$$

x) and only for this reason.

we get the integral equation for $\Delta\mu = \mu - \mu_M$ at S'

$$- (\underline{\Delta}_{P'} \quad \hat{\underline{n}}_{P'}) = 2\pi\Delta\mu(P') - \iint_{S'} \frac{\cos(\underline{\Delta}_{P'Q'} \, \hat{\underline{n}}_{P'})}{\Delta^2_{P'Q'}} \times \Delta\mu(Q')dS_{Q'}$$

$$= - \lim \left(\frac{\partial T}{\partial n}\right)_{P_y} \to P' \qquad (8a)$$

Mr Eric Vermaat, Delft, working at my institute in Uppsala several years ago, has investigated Somiglianamodels of suitable ellipsoids and derived formulas for $\underline{\Delta}$, to be used with (8a). He is also responsible for the short and elegant derivations of most of the formulas above. My own suggestions to him were not presented in a very elegant form. I owe Eric a great gratitude for his interest in my idea and for his energetic and devoted work, in carrying it out in details. I am also very grateful to Professor Koch, who inspired me to free myself from new and useless divings into refinements of the free boundary value solution.

Much more has, however, to be done to make Koch's original ideas and Eric's and my own developments usable for practical geodesy.

We have certainly another starting point than the geodesists of last century, and we have to face and take advantage of the enormous developments of geodetic techniques of our own century, also when treating theoretical problems and in trying to find practical solutions to them.

Uppsala 28.8 1974

Erik Tengström

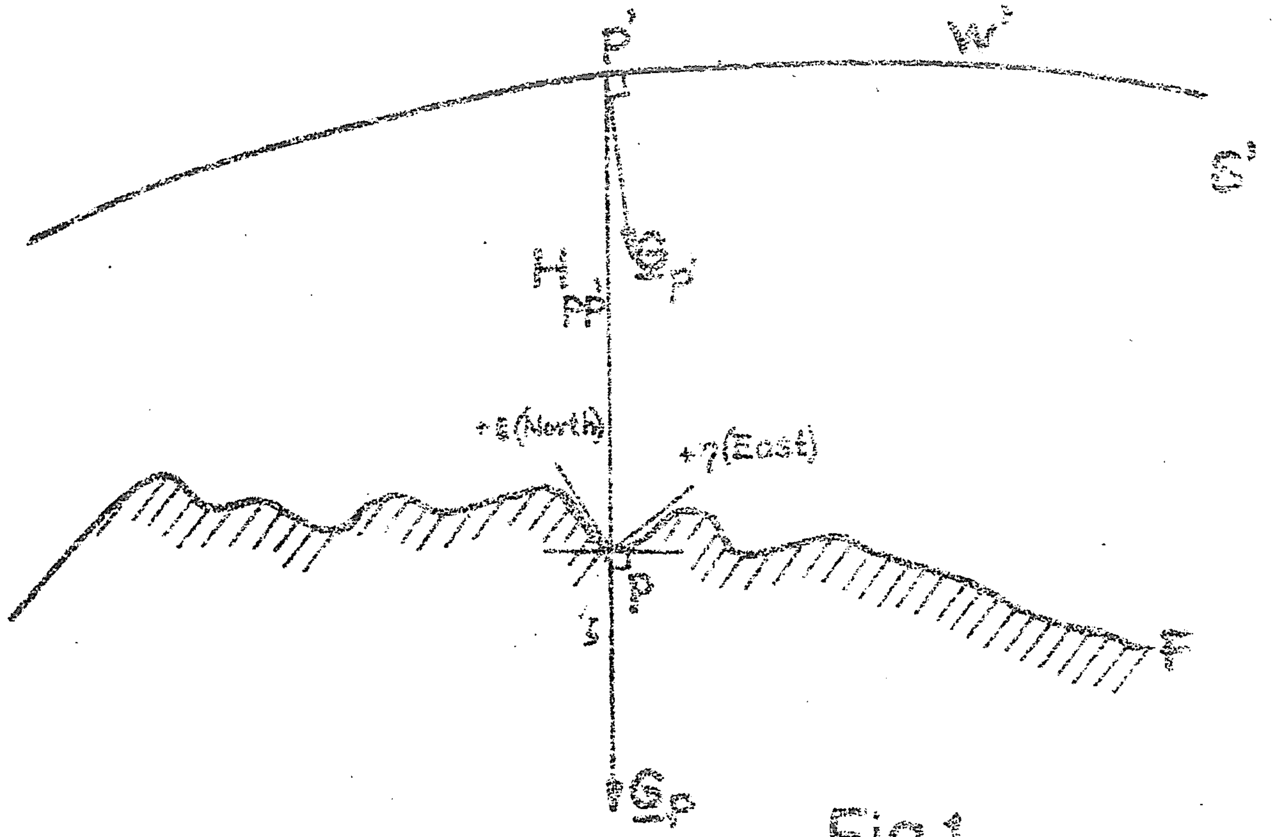

Fig.1

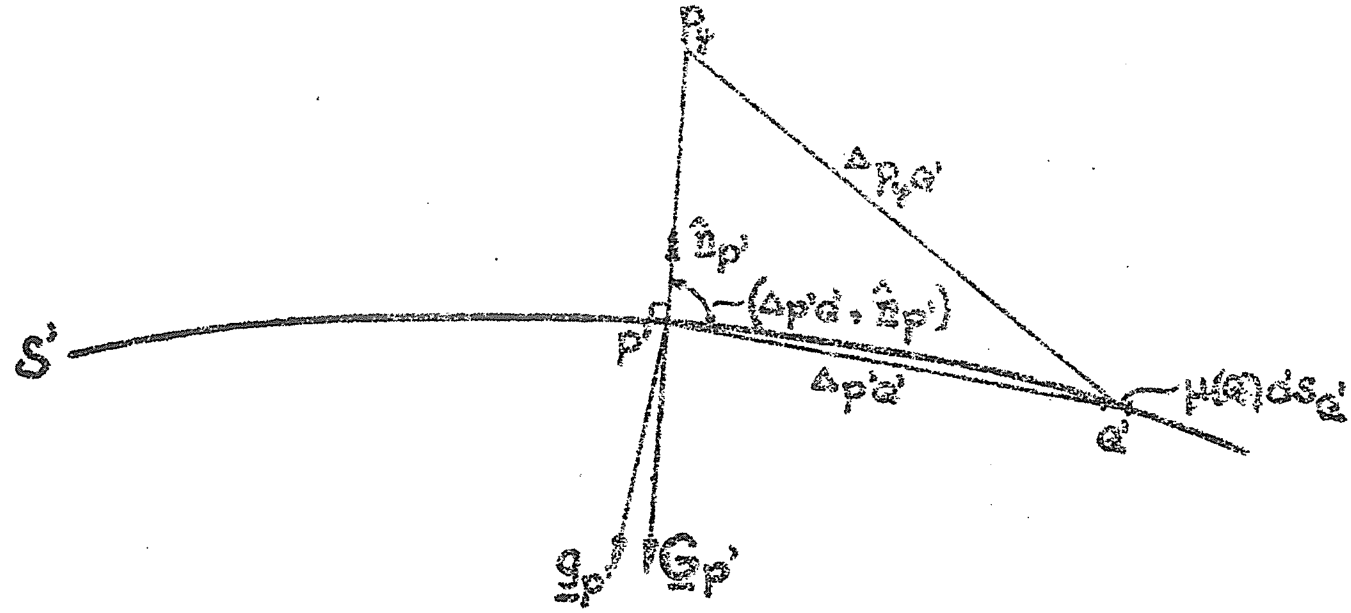

Fig.2

Summary of and appendix to Vermaat-Tengström's paper "The Eötvös' tensor etc", (B.V. part).

Each measured $\underline{G}_p$ on the Earth's surface with coordinates x_p, y_p, z_p, give a $\underline{G}_p$ on S' with coordinates $x_{p'}, y_{p'}, z_{p'}$ acc. to (4) by means of known or measured quantities at P (and above). The volume inside S' is then

$$V' = \frac{1}{3}\iint_\sigma r_{p'}^3 d\sigma \quad , \text{ where } r_{p'}^2 = x_{p'}^2 + y_{p'}^2 + z_{p'}^2 \; ,$$

$d\sigma$ being the space angle differential. With V' known from the transferred coordinates, k^2M' and x_o, y_o, z_o of the masscenter are determined by (5a) and (6a) as follows:

$$4\pi k^2 M' = \iint_{S'} G_{p'} ds' + 2\omega^2 V' \tag{5a}$$

$$x_o \left[\iint_{S'} G_{p'} ds' + 3\omega^2 V' \right] = \iint_{S'} x_{p'} \cdot G_{p'} ds'$$

$$+ 3\omega^2 \iiint x_i dv_i \quad , \quad \text{etc.} \tag{6a}$$

where $$\iiint x_i dv_i = \frac{1}{4}\iint_\sigma x_{p'} V_p^3 \, d\sigma = \tilde{x}_o V'$$

After translating the coordinatesystem to a geocentric one, (7) and (8) solve the B.V.-problem.

Using a model E' which has same k^2M' and same volume V' as S', and with W' identical for both S' and E', the integral equation (8a) can always be written with sufficient accuracy:

$$\delta G_{P'} = G_{P'} - \Gamma_{P'} \approx 2\pi\Delta\mu(P) - \iint_{E'} \frac{\cos(\Delta_{PQ}, \hat{n}_P)}{\Delta^2_{PQ}} \Delta\mu(Q) dE'_Q$$

where P and Q are ortogonal projections on E' of P' and Q'. The solution

$$T_y = \iint_{E'} \frac{\Delta\mu(Q)dE'_Q}{\Delta_{P_yQ}}$$

, is identical with the solution of the free B.V.-problem from

$$\Delta G_P = G_{P'} - \Gamma_{P'} = 2\pi\Delta\mu(P) - \iint_{E'} \left[\frac{\cos(\Delta_{PQ}, \hat{n}_P)}{\Delta^2_{PQ}} - \frac{1}{\Gamma_P}\left(\frac{\partial\Gamma}{\partial n_{E'}}\right)_P \cdot \frac{1}{\Delta_{PQ}}\right] \Delta\mu(Q) dE'_Q$$

or the solution of Bjerhammar - Zagrebin's ellipsoidal reference problem with the basic boundary equation

$$\left(\frac{\partial T}{\partial n_{E'}}\right)_P - \frac{1}{\Gamma_P} \cdot \left(\frac{\partial\Gamma}{\partial n_{E'}}\right)_P \cdot T_P = - \Delta G_P$$

The modelproperties are given from

$$V' = \frac{4}{3}\pi a^3_{E'}(1 - \alpha) \quad ; \quad k^2M' \text{ given by (5a)}$$

and the Somigliana formula for the external potential of E'.

Observe, that here, the slopes of S' to E' are negligable contrary to the F-case, where they are also indeterminate.

- XII -

S A T E L L I T E S

The first meeting on Thursday morning 5th September, was presided over by Prof. R.H. RAPP.

3 reports on various topics are presented : by Prof. R.H. RAPP, Prof. R.S. MATHER and Prof. D.B. DeBRA.

Prof. R.H. RAPP speaks on : Gravity Anomaly Data from Satellite Observations - Present and Future Results.

In the first part he deals with gravity anomalies derived from the SAO Standard Earth III and the Goddard Earth Models 5 and 6. These anomalies are compared to well determined terrestrial anomalies in 15°, 10° and 5° equal area blocks. From this analysis an accuracy assessment of these solutions is made.

In the second part he deals with results for gravity anomaly determination that may be made from satellite to satellite tracking data, altimeter data, and gravity gradiometer data. The accuracy of anomalies derived from such data for various size blocks and for various observation configurations is discussed. *

Prof. R.S. MATHER presents a paper : Sea Surface Topography from Satellite Altimetry - Requirements for Surface Gravity Data. (See p.I-86).

After this report, some remarks are made by the Delegates, especially, M.C.C. TSCHERNING points out that in most countries there is no correction between the first order levelling networks and the levelling used to determine the height of the gravity stations. So it will in fact be very difficult in practice to get valid geopotential height for the gravity stations as required according to R.S. MATHER's presentation.

Prof. D.B. DeBRA reports on : A Satellite Freed of all but Gravitational Forces : "TRIAD I".

The abstract and some pages of this report are published hereafter (See p. I-93).

* The complete text will be published in Zeitschrift für Vermessungswesen, 1975.

SEA SURFACE TOPOGRAPHY FROM SATELLITE ALTIMETRY - REQUIREMENTS FOR SURFACE GRAVITY DATA

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ABSTRACT

National Aeronautics & Space Administration (NASA) plans to launch a series of spacecraft equipped with altimeters for ranging to the ocean surface, as part of its Earth and Ocean Physics Applications Program (EOPAP). The first of these spacecraft is due for launch at the end of 1974. One of the goals of this program is the resolution of quasi-stationary sea surface topography.

It would appear that the separation of effects *other than* non-tidal Newtonian gravitation acting on the ocean surface using solutions of the geodetic boundary value problem, cannot be achieved without the use of gravity measurements of adequate accuracy on land and on the continental margins. This gravity data will have to satisfy certain stringent requirements on a global basis if unacceptable levels of systematic error in the computed values are to be avoided.

The dominant requirements to be met by the gravity control networks are the following:

1) The spacing of stations comprising the global gravity standardization network should be approximately 10^3 km in continental areas, the gravity values having been established with a resolution approaching ± 100 μGal and exhibiting no error correlation of significance between values at adjacent stations.
2) Regional gravity control networks should be established using techniques which will not introduce correlated errors at levels significantly above those given at 1) above, though larger magnitudes of purely accidental error are tolerable.

Free air anomalies as conventionally used, are inadequate for the task outlined above. The gravity anomaly required for this purpose should be computed from geopotential differences with respect to the datum for geodetic levelling. As the latter are not necessarily coincident with the geoid (the equipotential surface of the Earth's gravity field corresponding to the *mean value* of mean sea level for the epoch of determination), it is essential that computer files of gravity data to be used for this purpose, should contain reference to the sea level datum to which the levelling data is linked.

It will be difficult to determine the quasi-stationary sea surface topography with any degree of confidence unless all national organizations and/or global gravity data banks providing gravity information for geodetic purposes, were to correctly identify and describe the levelling datum when providing suitably "clean" gravity data.

1. INTRODUCTION

In the next decade, the United States Government's National Aeronautics & Space Administration (NASA) plans to launch a series of satellites equipped with altimeters for ranging to the ocean surface, as part of its Earth and Ocean Physics Applications Program (EOPAP) (NASA 1972; VONBUN 1974). A part of this effort will be directed towards the synoptic monitoring of the instantaneous location of the ocean surface and its variations with time. Apart from providing information on the nature of tides in the open oceans, it is hoped that the successful achievement of EOPAP objectives will give valuable information which could provide a better understanding of ocean circulation. Present notions of this phenomenon are largely based on temerature and salinity measurements as well as current determinations of the oceans and attendant inferences on the basis of models commonly adopted in physical oceanography.

Unfortunately the quasi-stationary sea surface topography inferred from these concepts provide a picture of the oceans which disagrees with that afforded by the connection of tide gauges to geodetic levelling networks. The discrepancies are largely in the north-south direction (e.g., see MATHER 1973c, Appendices 1 & 2 for an up-to-date summary). While these discrepancies may be construed as either coastal aberrations of the principles of physical oceanography on the one hand, or some hitherto unrecognized source of systematic error in geodetic levelling on the other, the correlation with latitude is too commonplace to ignore. Satellite altimetry provides a potential source of independent data which could well give the scientific community fresh insights into the problem.

The altimetry can provide useful information only if carried out under carefully controlled conditions. The magnitude of the stationary sea surface topography is not expected to exceed ±2 m. This calls for a precision approaching ±10 cm in the spatial definition of the Newtonian gravitational effects to which the undisturbed sea surface is expected to respond, in the absence of periodic tide-producing forces, steric effects and other non-gravitational consequences.

Two types of data which contain information about Newtonian gravitational effects are *surface gravity* determinations and *elevations of the ocean above the reference surface* deduced from satellite altimetry. The required determination could be obtained from surface gravity data alone (MATHER 1973a) provided a global sampling of the surface gravity field were available with an error of representation at the ±3 mGal level (equivalent to a 10 km grid in non-mountainous regions). This gravity coverage is unlikely to be achived within the time-frame of EOPAP (i.e., before 1985).

The prognosis for the achievement of adequate coverage in oceanic areas using satellite altimetry with a precision which is appropriate for the definition of quasi-stationary sea surface topography is by no means pessimistic. The 1-2 m low energy mode altimetry expected from the GEOS-C mission, due to commence in late-1974, if obtained under conditions of appropriate tracking, has the potential to define the stationary Newtonian gravitational effects on the ocean surface to 1-2 m (MATHER 1974a). The data collected under conditions of adequate tracking by an altimeter with the capability specified for the SEASAT mission due to commence in 1978, has the potential to resolve quasi-stationary sea surface topography with wavelengths greater than 100 km. It is questionable whether shorter wavelengths are of any significance in the stationary sense due to a variety of local effects.

The above statements are based on a formulation of the solution of the geodetic boundary value problem so that the following types of input data could be accommodated:

a) gravity anomalies in continental and shelf areas; and

b) "geoid heights" from satellite altimetry in ocean areas.

The object of this presentation is to review the requirements to be met by the gravity data measured at the surface of the Earth, and to be used in quadratures evaluations of the geodetic boundary value problem for the determination of quasi-stationary sea surface topography.

2. SURFACE GRAVITY DATA REQUIREMENTS

Gravity measurements are used in the solution of the geodetic boundary value problem in the form of gravity anomalies. These differ from free air anomalies by small amounts which are, nevertheless, significant in the context of high precision geodetic determinations. The structure of gravity anomalies is described in Appendix I. The gravity anomaly data should be in the form of an array which represents continental and shelf areas (i.e., 40% of the Earth's surface area) in the quadratures evalutaions, the surface being divided into elements as mentioned in section 1. The dominant problem which has to be overcome in achieving a successful quadratures evaluation, is the control of systematic errors of long wavelength in the data array. The major sources of systematic error can be assessed to be the following (MATHER 1973a,p.68):

1) Errors in the global gravity standardization network used to calibrate the instruments used in regional gravity surveys.
2) Errors in the geopotential network used in computing the gravity anomalies.
3) Errors arising from the use of *regional* geodetic co-ordinates instead of *geocentric* co-ordinates in the computation of normal gravity.

While the power in the global representation of gravity anomalies and geoid heights are not similarly influenced through terms of equivalent wavelength, it could be stated that a precision of ±5 cm in the sea surface topography would call for a precision of ±50 μGal in the gravity anomaly. If, however, the former is computed from the latter using quadratures methods, this figure would only represent *one factor* in assessing the extent of systematic error which could be tolerated in the data. It does *not* refer to the precision with which individual gravity anomalies in the global array should be established for the following reason. The effect of an error e in the gravity anomaly data set which holds its magnitude and sign over an (n°× m°) area *but behaves as an accidental error over the rest of the globe*, has an effect e_N on the quadratures evaluation of the ocean geoid, given by the inequality (IBID)

$$e_N^{(cm)} \not> K \; e^{(mGal)} \; (n°\times m°)^{\frac{1}{2}} \qquad (1),$$

where K is a constant, due to the kernel function being bounded between well defined limits. The smaller the extent over which the systematic error occurs, the larger the magnitude of the error which can be tolerated before its effect on a quadratures evaluation exceeds the prescribed error limit. Thus purely local errors characteristic of individual gravity anomaly values can be relatively large (e.g., ±3 mGal for representation on a 10 km grid in non-mountainous regions for 5 cm ocean geoid determinations) provided the errors of adjacent values were not correlated over significant wavelengths.

In practical terms, this would mean that low order levelling connections (±1-2 kGal m) to gravity stations would not cause the result to deteriorate provided each determination were independently linked to a regional geodetic levelling network in which the systematic error propagation were held to below the 0.15 kGal m level. Any first order geodetic level network should meet this criterion in terms of internal consistency. This would, of course, not necessarily apply to the datum adopted for the levelling network. Quadratures evaluations, as commonly used, require that the levelling datums all lie on the same equipotential surface of the Earth's gravity field – the geoid. The effect of this not being the case can be formulated (MATHER 1973b).

By the same token, it is quite important to ensure that sampling of the gravity field with the ±3 mGal error of representation in land areas is unbiased in terms of the local topography.

The second* most exacting requirement physical geodesists can make on gravimetrists is the establishment of global gravity standardization networks which will meet the requirements of sea surface topography determinations. In broad terms, quadratures evaluations for this purpose are likely to require standardization networks with a density of one station per 10^3 km in continental areas with errors in individual values being uncorrelated at the 100 µGal level if 10 cm resolution is to be achieved. To the writer, it would appear that the most promising way in which this goal can be reached within the time-frame of the EOPAP program is by the use of transportable gravity measuring systems like the system modeled on the B.I.P.M. apparatus (SAKUMA 1973), unless it is clearly established that the multiple-gravimeter approach

a) is capable of the required precision; and
b) does not introduce intolerable systematic error into the net.

A wider station spacing would require a proportionate increase in the resolution of determinations at stations in the standardization network. This would still be acceptable if the quality of the regional connections did not result in a marked deterioration in the quality of the individual gravity values in terms of the criteria set out above. For example, the establishment of gravity values at stations in the fundamental network with a resolution of 10 µGal would permit a relaxation in the station spacing to approximately 5000 km. This would, of course, throw a greater strain on the regional networks like the Isogal network in Australia which would have to be carefully controlled to ensure that systematic error does not occur with amplitudes of 100 µGal and wavelengths of 2000 km.

On reflection, it would not only be desirable but also well within the realms of practical possibility to establish absolute gravity values using instruments similar to the transportable apparatus of the type to be marketed shortly in France, provided the systems are not time consuming to operate. It is envisaged that an area like Australia (5% of the global land area) will require approximately 15 stations. It is not inconcievable that such a regional network could well be established in approximately one year.

3. CONCLUSION

It is not unrealistic to expect that the gravity data of adequate precision which is necessary for the representation of land and continental shelf areas in quadratures evaluations of the geodetic boundary value problem could be assembled within the time-frame of EOPAP (i.e., in the next decade).

* The first is the collection of data to monitor the motion of the geocentre

This would make it possible to resolve the quasi-stationary sea surface topography to ±10 cm *if an appropriate effort is made.*

It must be emphasized that this goal cannot be achieved by the use of the gravity data banks available at present. In the first instance, the International Gravity Standardization Network (IGSN71), based largely on gravimeter connections, has been assessed as having an accuracy of ±0.2 mGal (MORELLI ET AL 1971). It is not clear what the estimate of systematic error in this network is. The techniques used do not rule out the possible existence of error correlation with 2000 km wavelengths at the 0.1 mGal level in continental areas. Secondly, what is required for the quadratures evaluation is the gravity anomaly as defined by equation 2 in Appendix 1, and not the free air anomaly as commonly used at present. For this purpose, levelling information should be retained and used in the form of geopotential differences with respect to the levelling datum. It can be shown that the latter can be calculated with a precision adequate for quadratures evaluations from observed gravity on a grid where the error of representation is ±3 mGal (10 km in non-mountainous regions); gravity readings are not necessary on terminal benchmarks for this purpose (MITCHELL 1972).

It is also extremely important that the datum of levelling be identified on all gravity information which is to be used in quadratures evaluations. This would enable the data to to correctly identified when determining the stationary sea surface topography.

The basic requirements to be met by gravity data to be used in quadratures evaluations of the geodetic boundary value problem leading to evaluations of the global stationary sea surface topography at the 10 cm level are summarized in Appendix 2. The purpose of this presentation is to make a plea to all national organizations maintaining gravity data banks, to "clean up" their gravity data in the manner described above so that gravity information of adequate quality will be available for the representation of land and continental shelf areas for the quadratures evaluations outlined earlier. *It is virtually impossible for organizations not involved in the calibration and assembly of the gravity data to be able to make the appropriate corrections which would permit their use in such solutions with resolution at the 10 cm level.* This information, when combined with the satellite altimetry data NASA plans to obtain from the GEOS-C and SEASAT missions should provide a feasible basis for resolving the quasi-stationary sea surface topography.

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5. APPENDIX 1

The Gravity Anomaly Δg at a point P at the surface of the Earth is given by

$$\Delta g = g - \gamma - \frac{2\,\Delta W}{a}\left[1 + f + m + \frac{1}{2}\frac{\Delta W}{a\gamma} - 2f\,\sin^2\phi + o(f^2)\right] \qquad (2),$$

where
- g is observed gravity
- γ is normal gravity computed to ±50 µGal on the ellipsoid of reference
- $m = a\omega^2/\gamma_e$
- a, f are parameters defining the reference ellipsoid
- γ_e is equatorial normal gravity
- ω is the angular velocity of rotation of the Earth

ΔW is the difference in geopotential between the general point P and the datum O for the geodetic levelling, being given by

$$\Delta W = -\int_0^P g\,dz \qquad (3),$$

dz being the observed increment in orthometric elevation.

6. APPENDIX 2

Summary of Requirements to be Met by Gravity Data for Use in Quadratures Evaluations of the Geodetic Boundary Value Problem in Sea Surface Topography Determinations

1. Land and continental shelf areas to be represented by a grid of surface gravity measurements with an error of representation approaching ±3 mGal (10 km in non-mountainous regions).

2. Values to be based on a consistent global gravity standardization network with a station spacing of 10^3 km in continental areas and absolute errors held to less than ±100 μGal without significant error correlation.

3. Gravity anomalies to be computed from geopotential differences with respect to levelling datum (see Appendix 1). The levelling datum used should be indicated for each gravity anomaly required for the representation at 1.

4. Normal gravity should be computed from geocentric and not regional geodetic co-ordinates.

5. The particulars defining the relation of each levelling datum to mean sea level should be maintained with all gravity anomaly data.

July 1 1974
Sydney, Australia

A SATELLITE FREED OF ALL BUT GRAVITATIONAL FORCES: "TRIAD I"

The Staff of the Space Department of
The Johns Hopkins University
Applied Physics Laboratory

The Staff of the Guidance and Control Laboratory of
Stanford University

ABSTRACT

Under the sponsorship of the U.S. Navy, we have collaborated in the design of a "drag free" satellite; a satellite in which surface forces (drag and radiation pressure) are cancelled by jets.

The satellite was launched into a polar orbit on September 2, 1972. The surface-force cancellation system has performed faultlessly since launch.

The satellite and its in-orbit performance are described.

Using tracking data we have:

1. Shown that the satellite follows an orbit in which the non-gravitational disturbances are less than 10^{-11}g.
2. Improved the APL MK-5 geopotential model.
3. Shown, using telemetry data, that the biases in the external forces balanced by the force-compensation system are less than 10^{-11}g along-orbit and approximately 10^{-9}g in the radial direction.
4. Confirmed that the analytical model of radiation pressure is correct both in the main and in detail [Ref. 4]. Because the drag force at this altitude is much smaller than the radiation pressure force, no similar statement can be made for the

atmospheric density model [Ref. 6]. The strongest statement we can make is that the data does not give any indication of a needed change to the density model.

INTRODUCTION AND SUMMARY

As part of an on-going effort to improve navigation by satellite, the U.S. Navy sponsored the experimental TRIAD satellite.

An important experiment aboard the satellite is a disturbance (or surface force) compensation system (DISCOS).* This system was first proposed about 10 years ago [Ref. 1]. The basic idea is that a tiny satellite is completely enclosed in a cavity of a larger satellite. The inner satellite (or proof mass) is shielded from all external surface forces, drag and radiation pressure. As a part of the design it is necessary:

1. To eliminate all possible force-interractions between the two bodies,
2. To sense the relative displacement between the two, and
3. To use this displacement-signal to modify the motion of the (outer) satellite. As a result, the satellite is constrained to the orbit of the proof mass which is free of all external surface forces.

If the control system and design were perfect, then the equations of motion of the satellite would be identical with that of the proof mass:

$$\ddot{\bar{r}} = -\bar{\nabla}U$$

where U is the gravitational potential.

* An exploded view of the DISCOS as built is shown in Fig. 1.

We sought, in the design, to limit departures from this ideal to accelerations of 10^{-11}g. The largest error sources were

a. the mass-attraction assymetries between the proof mass and the near-parts of the satellite, and

b. the electrical attraction between the proof mass and the capacitive position-sensing plates.

The satellite design was also influenced by errors due to:

c. magnetic gradient forces,

d. residual gas in the proof mass cavity, and

e. temperature gradients.

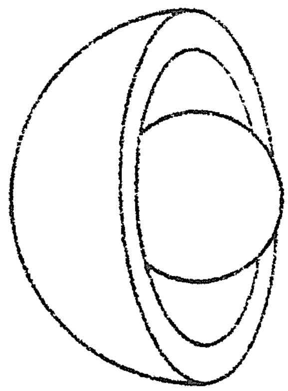
The satellite mass is 86.6 kg. It was launched in a "collapsed" configuration; roughly a cylinder 1.6 m high, 0.75 m diameter. In orbit, it expanded into three bodies (a "TRIAD"). The center body, containing the DISCOS unit, is separated from the two end bodies by 2.7 m booms. The top body contains the power supply while the lower unit contains transmitter, receiver, telemetry, and antenna. This configuration was chosen

a. to minimize the fabrication problems associated with controlling the mass-attraction assymetries on the proof mass, and

b. to take advantage of the simplicity of gravity-gradient stabilization.

A small spinning wheel was included to enforce a 3-axis stabilization relative to a locally level system of coordinates.

The proof mass and cavity are shown below, schematically but to scale:



The proof mass, 22 mm in diameter, resides in a 40 mm cavity. The proof mass is a 70/30 gold-platinum alloy weighing 111 gms or 0.0013 of the satellite mass. This alloy was chosen for its high density and nearly zero magnetic susceptibility.

In orbit, the proof mass freely "floats" in the cavity; its position (relative to the cavity) is sensed by a set of 3 capacitance bridges (2 plates on each of 3 orthogonal coordinate axes). These three independent pairs of signals are used (in a control loop) to turn on (and off) three corresponding pairs of cold-gas jets. Simply put; if the satellite approaches one side of the proof mass then the thrusters (on the opposite side) accelerate the satellite to restore the gap symmetry.

The thrust from a single jet is either on or off. Only the on-off modulation is changed by the nearness of the proof mass to the cavity wall. Among other advantages, this scheme minimizes the valve-leakage and reliability problems.

It was intended that the satellite be placed in a near circular orbit ($\epsilon = 0.006$) at an average altitude of 874 km ($a = 1.1371$). Because of a malfunction of the launch-vehicle guidance, the actual orbit has an average altitude of 783 km ($a = 1.1236$) and the correct eccentricity. This difference has had no significant effect on the DISCOS experiment.

A failure in the satellite telemetry system, two months after launch, has drastically reduced the aeronomy data of this particular experiment -- but not before its promise had been shown. The DISCOS unit has been on almost continuously since launch (7 months) and continues to function normally.

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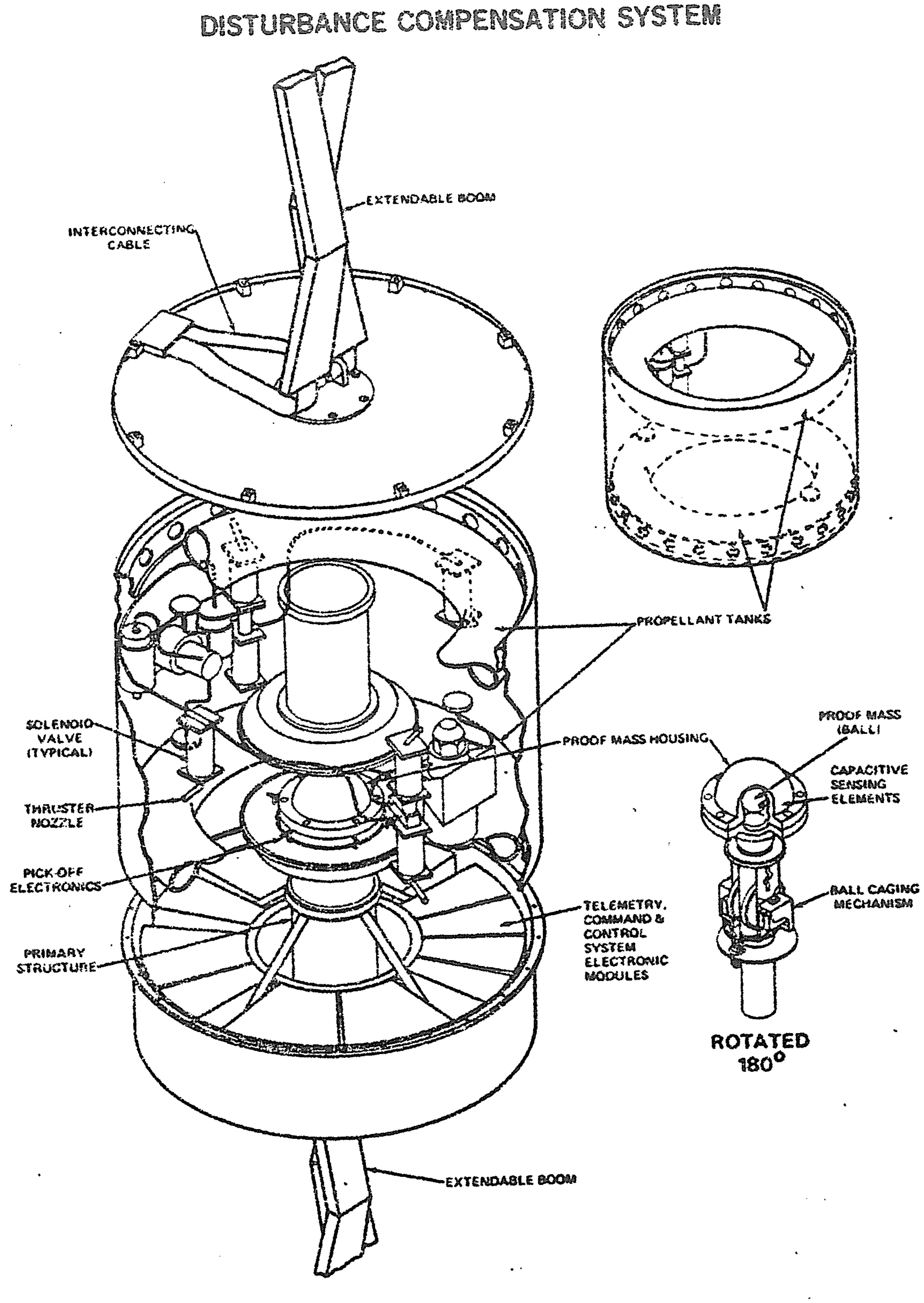
DISTURBANCE COMPENSATION SYSTEM
EXTENDABLE BOOM
INTERCONNECTING CABLE
PROPELLANT TANKS
SOLENOID VALVE (TYPICAL)
PROOF MASS HOUSING
PROOF MASS (BALL)
CAPACITIVE SENSING ELEMENTS
THRUSTER NOZZLE
PICK-OFF ELECTRONICS
BALL CAGING MECHANISM
TELEMETRY, COMMAND & CONTROL SYSTEM ELECTRONIC MODULES
PRIMARY STRUCTURE
ROTATED 180°
EXTENDABLE BOOM

Figure 1.

- XIII -

GEOPHYSICAL INTERPRETATION of GRAVITY DATA

Special Study Group n° 5.11

General discussion in view of the newer concepts of tectonic plates and the role of the physical Geodesy in this connection

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On Monday afternoon, 2nd September, Dr. S. SAXOV, Chairman of this Special Study Group makes a communication on this subject, pointing out particularly the necessity to compare gravity results with other data, geophysical or geological. (See p. I-100).

At the end of this session, Dr. T. HONKASALO adds a recent information saying that :

"In the International Symposium on Recent Crustal Movements in Zurich, August 1974, a paper on : "Gravity and Temperature Anomalies in the Wales of Drifting Continents"was presented by H.G. KAHLE.
This may be one such idea which should be considered".

It is to be noted that during the I.G.C. meeting, interest was expressed for :

1) Gravitational interpretation of plate boundaries and structure ;
2) Geophysical prediction of gravity anomalies ;
3) Gravity and uplift / subsidence.

Special Study Group 11 will include these points in its program.

In this topic, it is mentioned the report presented by Prof. G.P. WOOLLARD on : <u>Regional Changes in Gravity and their Relation to Crustal Parameters.</u>

We publish in this Bulletin only the abstract and some pages. (See p. I-106).

Geophysical Interpretation of Gravity Data

S. SAXOV

Special Study Group 11 is concerned with Geophysical Interpretation of gravity anomalies. The Study Group was initiated by professor Heiskanen, who - as you all know -had a special relationship to isostatic problems. Unfortunately, professor Heiskanen's illness and his premature death prevented him from being effective in the work of SSG 11. Professor Honkasalo, who was closely related to professor Heiskanen, then very kindly took upon himself the task of SSG 11 also, and in the following I am keeping very close to the report presented by professor Honkasalo at the XV General Assembly in Moscow 1971.

"The purpose of this Study Group is to determine the sizes, forms, densities and depths of the disturbing masses in the earth's crust which have caused gravity anomalies. All these quantities cannot be compared solely on the basis of gravity anomalies. Other data, geophysical or geological, is necessary. In some simple cases the solution can be based on pure hypothesis".

Let us consider for a moment the gravity anomalies. We assume that the gravity measurements are carried out correctly with respect to calibration factors and reference values; that the geographical position is correct and that the proper theoretical value has been applied. The only parameter left in order to obtain an anomaly is the density value. Depending on the purpose and on the anomaly type the density is chosen. It is customary to apply 2.67 gr/cm^3 at continents and 1.00 at oceans. But let us take a look at other groups working with gravimetry. In mining geophysics it is used to measure in a grid system, lines 40 to 80 metres apart, and stations 20 to 40 metres apart; the grid system is of a limited size, which means that the interest is concentrated on very local features. Therefore, gravity influence from regional sources is filtered. The residual anomaly obtained is then studied by model computation, but in these models the density values applied are obtained from direct determinations of samples and the values are usually different from 2.67 gr/cm^3.

In oil geophysics the procedure is similar even if the grid distance is somewhat larger, the interpretation, however, is the same.

In geological applied geophysics you may find detailed investigations which will then be similar to the prospecting ones; however, you may also find the opposite situation, namely an interest in the gross features which means that you filter the local effects; the further interpretation is the same, you apply to your model the density values you know from sampling.

Turning to physical geodesy I wonder where you have to put the geodetic interest. Is it in the very detailed picture, e.g. in relation to the deflection of the vertical, or to local crustal movements? Or is it in the global picture, e.g. continents or oceans? Furthermore, is the density value of 2.67 gr/cm^3 the value to be preferred.

This last problem was discussed at the joint meeting of SSG 11 and SSG 16 in Uppsala, Sweden, in the beginning of November 1972. The meeting recommended that special attention should be paid to the question of determining subsurface density distributions by new measuring techniques and new theoretical approaches.

Prior to the Uppsala meeting I had made the first efforts to establish a small working group which first of all could consider the density problems. The group consists of Dr. Gantar, Trieste; Professor Torge, Hannover; Professor Honkasalo, Helsinki; Professor Tengström, Uppsala, chairman SSG No. 16, and myself. It turned out immediately that many difficulties would occur; firstly, most density values originate from geological studies; the geological samples are not collected with the purpose to obtain representative values for a certain area; they represent usually special geological occurrences; secondly, most samples available are surface samples; thirdly, subsurface samples are often on files with oil companies and prospecting companies and may not be released; fourthly, the distribution of samples and especially subsurface samples is very uneven; it may better be characterized as sporadic.

One, therefore, has to look for other possibilities.

It is a wellknown fact that there exists a relationship between density and seismic velocity, in fact the product of density and P as well as S waves is described by the elastic moduli. It is also a well-known fact that the elastic moduli increase in value with depth, which actually means that seismic velocities as well as density increase with depth. Several investigations have been carried out during the last 20 years, especially for the conditions in sedimentary basins. One result is that the density is not constant in a specific geological formation but will increase with depth. Another result is that a plot density-velocity gives a large spread of points, and depending on the number of points different functions can be worked out. However, the trend of the lines is the same. Even if we do not get a definite value of density with depth we get values within a small range. A further result is that Wollard in 1959 (and Drake & Nafe, also in 1959) concludes that for sedimentary basins (including marine basins) a minimum density of 2.74 gr/cm^3 should be applied. For sediments it has been customary to use values from 2.34 to 2.50 gr/cm^3.

When we turn to the continental crust the number of data available is more limited. Wollard (1959) has for North American data mainly estimated the mean density of the continental crust to be in the range of 2.87 to 3.00 gr/cm^3.

In both cases the value is larger than the one used traditionally. Which value or values are we going to apply in physical geodesy?

Turning again to seismology and to seismics not much support is to be obtained. From the long profiles with deep seismic soundings we have inconsistencies; one result is the establishment of low velocity channels. Actually, that is contradictory to the seismic theory which requests higher velocity with depth. With the low velocity channels we are also getting low density zones. That is well-known from sedimentary basins, where Zechstein - rock salt - has a lower density and also a lower velocity than the surrounding geological formations. Apparently, the phenomena also occur at larger depths.

In the plate-tectonic-theory, we have plates moving, not only horizontally, but also vertically, or maybe more correctly at some inclination angle. However, lighter material is going down, heavy material is going up. That gives rise to large problems in seismology, and also in gravity.

In other words, we will have to obtain support from other sources. One possibility is palaeomagnetic investigations, but again the results so far have been ambiguous.

I believe that we have to obtain information not only from traditional seismology and seismics, but also from free oscillations, deep magnetic soundings and magneto-telluric. Further support may come from geothermics and earth tides, and I also believe that geochemical evidence must be included.

This is an enlargement of the problem as such, and it has given no answer to the question of density. I feel that we have to continue with the traditional 2.67 gr/cm^3 value and continue to apply more specific values when computing models. It is obvious that in some cases we can deal with Free Air Anomalies and then avoid the density problem. However, as soon as we have to deal with practical problems we have to apply one or another density. Therefore, in my opinion the density problem is the most urgent one for the Study Group.

It is difficult, however, to keep a restricted line of geophysical/geodetical policy in the Study Group 11, because problems connected with geophysical interpretation of gravity anomalies are interconnected with several other problems in physical geodesy, not only with Study Group 16, and may give some overlapping. Nevertheless I feel that the density problem is of outmost importance and must be given special attention by SSG 11.

There are other problems also to be dealt with e.g. prediction of gravity anomalies, however, I believe that firstly we have to deal with specific problems as plate boundaries and areas of uplift/subsidence before we are able to contribute satisfactorily to prediction. I have only referred to two pages from 1959; in recent years more papers have occurred.

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Regional Changes in Gravity and their Relation to Crustal Parameters

G.P. WOOLLARD

Abstract

Data are presented that indicate satellite-defined long wave length free air gravity anomalies correlate closely with overall long wave length changes in crustal and upper mantle parameter values both in continental areas and in oceanic areas. Both local and regional anomaly values are shown to be related to the mass of the crust as defined by its thickness and implied density as deduced from mean crustal seismic velocity values, and the density of the upper mantle as implied in the observed seismic velocity values. Where these values are high there are positive free air and isostatic gravity anomalies, and conversely where they are low there are negative gravity anomalies. An integration of the resulting surface anomaly field as represented in 12° x 12° average values to give an equivalent areal representation to that embodied in satellite anomalies derived using degree sixteen coefficients closely duplicates the satellite-defined free air anomaly field. Although these relations do not rule out a possible underlying cause for the near surface mass distribution that also influences gravity, it is shown that in the United States at least values of P_n are in opposite sign on the whole to changes in mantle velocity and the satellite-defined free air anomaly pattern.

Near Surface Controls of the Satellite-Defined Gravity Field:

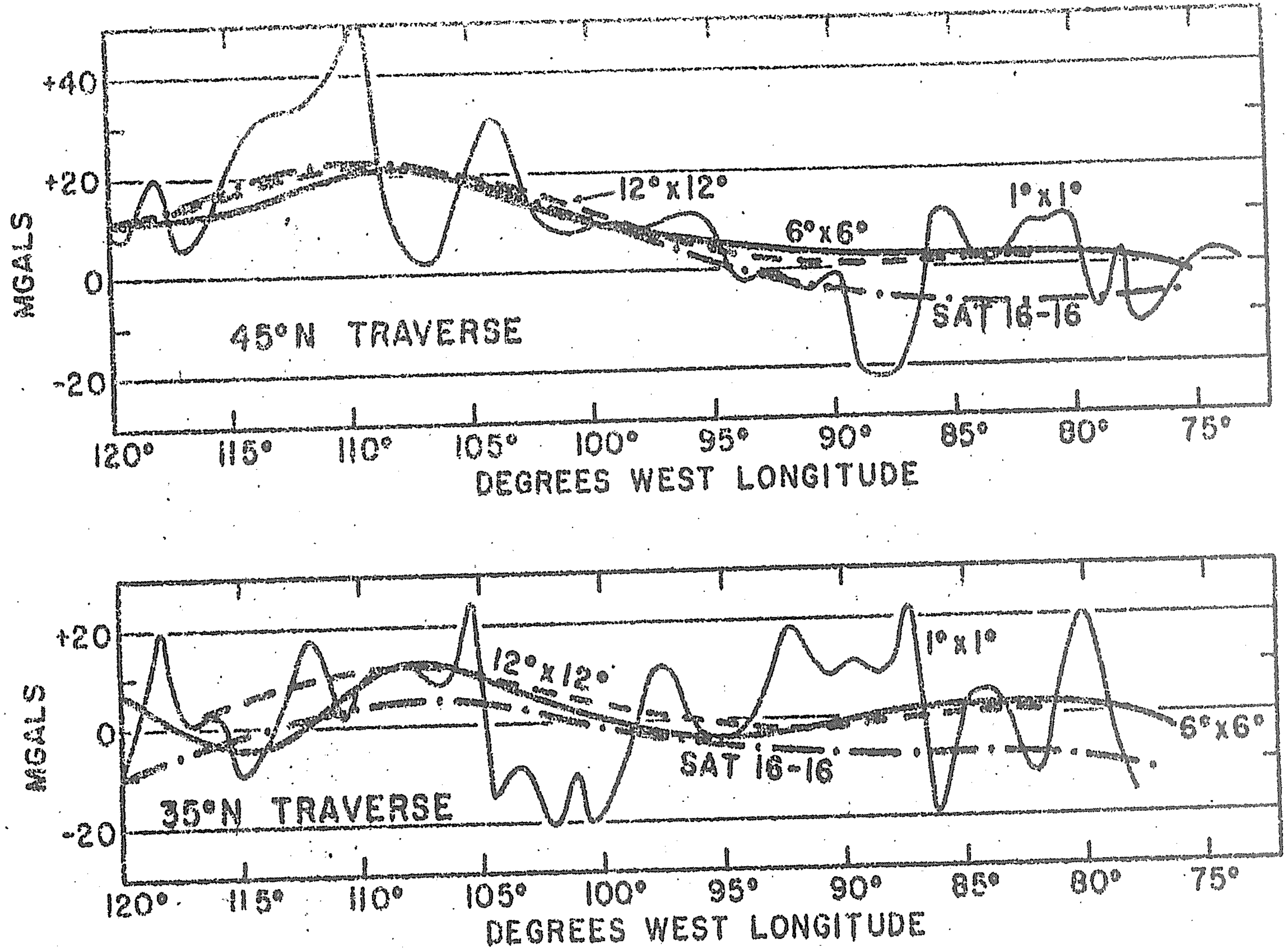
That there are apparent correlations of the satellite-defined gravity anomaly field with certain classes of geologic features has been noted by various investigators (Strange, 1966; Kaula, 1969, 1972; Talwani and LePichon, 1969; Menard, 1973). That these relationships are not always consistent was also noted by these investigators. Kaula (1972), for example, who has made the most extensive study of this type, shows that although there is a high degree of consistency in the association of satellite-defined gravity anomaly "highs" with Cenozoic orogenic belts, mid-ocean spreading centers, and zones of crustal plate convergence, these relations are not always found. The mid-Atlantic Ridge, for example, which correlates well with a pronounced satellite-defined gravity "high" in the northern hemisphere, has, as shown in Figure 1, no expression in the satellite-defined anomaly field in the southern hemisphere. Kaula to explain these inconsistencies concluded that the anomalies are not related to the surficial geological expression so much as to the mechanism that caused them, and whether it is still active or dormant. He attributes the anomalies to underlying vertical asthenospheric flow or accelerations or decelerations in horizontal asthenospheric flow with the origin of the associated surface features being consequent products of upwelling or down flow in the asthenosphere and induced crustal plate movement.

To date, Kaula's (1972) explanation for the more than casual association of satellite-defined gravity anomalies to certain classes of geologic features, and for the inconsistencies noted, is the most logical and convincing one that has been proposed.

However, there is evidence also of mass inequalities having long wave lengths similar to those defined by satellite data which appear to definitely have their origin in the earth's outer shell. The evidence for this is the correlation of long wave length isostatic and free air anomalies defined by surface data with satellite-defined gravity anomaly "highs" and "lows", and the relation of crustal and upper mantle parameter values to isostatic anomaly values and regional (1° x 1° averaged) free air anomalies.

Conclusion:

Although it is not possible at this time to conclusively demonstrate that the satellite-defined gravity anomaly pattern has predominantly a shallow rather than a deep source, sufficient data do exist to suggest this is the case. As shown, the surface gravity anomaly pattern can be accounted for in large measure by surface and near surface mass variations which are age-dependent on both the continents and in the ocean basins. Also, as shown, an integration of the surface anomaly field to an equivalent areal representation as defined by satellite data and corresponding to 12° x 12° average values of the surface data duplicates closely the satellite anomaly pattern.



COMPARISON OF SATELLITE AND SURFACE FREE AIR ANOMALIES ACROSS THE UNITED STATES

Fig. 4. Comparison of satellite-defined free-air gravity anomaly profiles across the United States at 45° and 35°N latitude with 1° x 1°, 6° x 6°, and 12° x 12° averaged values of surface data.

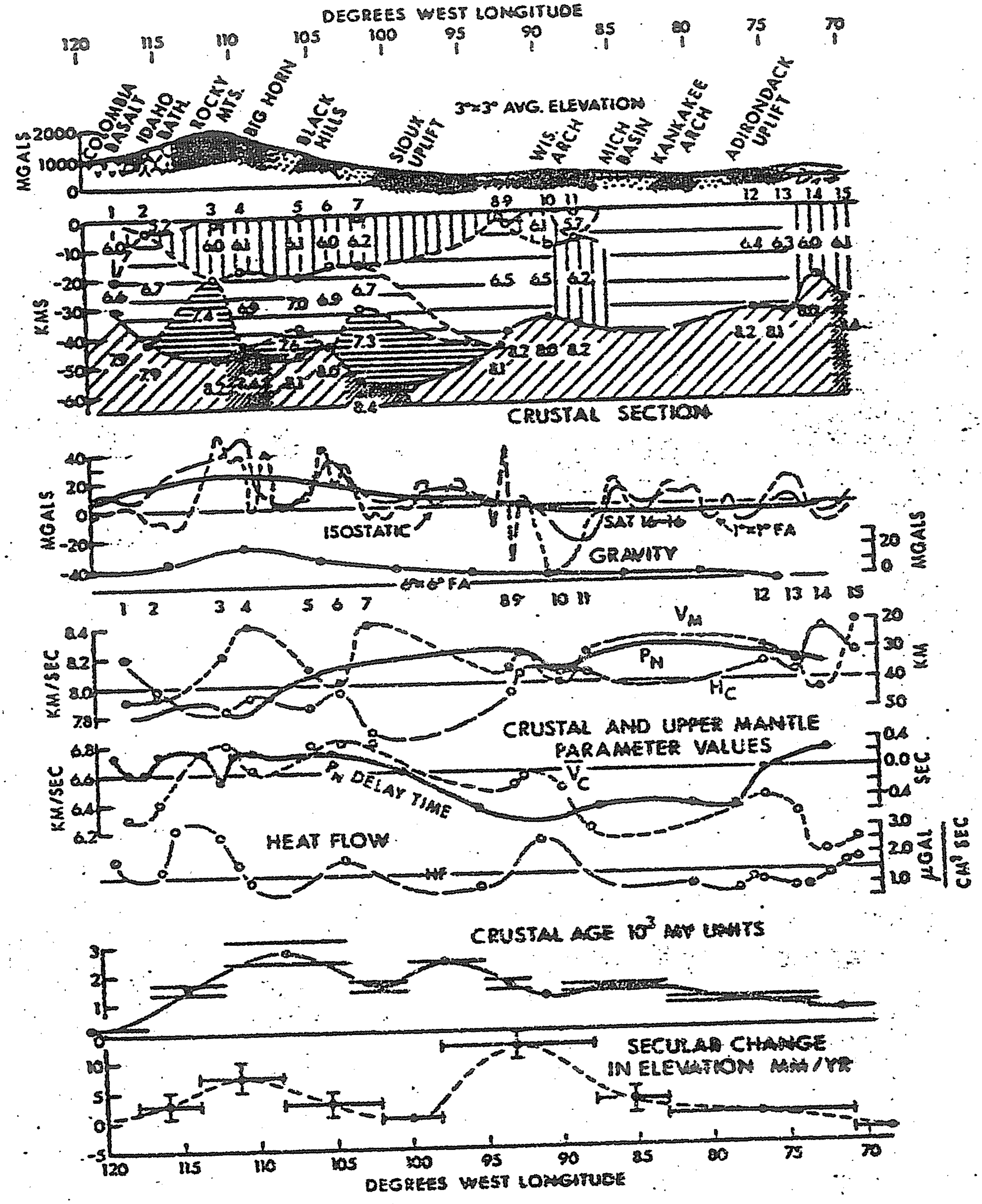


Fig. 6. Comparison of geophysical parameter changes along the 45°N parallel of latitude across the United States.

— C —

DETAILED GRAVIMETRIC GEOID OF FINLAND

by

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1. INTRODUCTION

The astrogeodetic geoid of Finland has been well determined on the basis of 321 astronomic latitude and longitude determinations and 201 astronomical azimuth measurements in the first order triangulation. The first order triangulation does not cover the whole country as a net but consists of chains. The form of the geoid inside the chain loops is thus somewhat inaccurate. The gravity station net of 20 000 stations covers the whole country with 5 km spacing. Using this gravity material and published data from the surrounding areas and from the whole world the gravimetric geoid has been determined with Stokes' formula and deviations of the vertical with the Vening Meinesz formula for 4161 points. These form a net of equal 10 km spacing. The results have been compared with astrogeodetic ones.

This is a preliminary report. A complete report will be published by the Finnish Geodetic Institute.

2. GRAVITY MATERIAL

2.1 Mean free air anomalies of 10 x 10 km squares on the Gauss-Krüger (transversal Mercator) map with 27° EG longitude as the Central Meridian in Finland were computed on the basis of the c. 20 000 gravity stations ([5] and data not yet published). Taking the correlation coefficient between elevation and free air anomaly into consideration the mean anomalies were computed to the mean height of the square. The anomaly field was described with a Taylor polynomial of the third degree. This was adjusted with the method of least squares to the observed gravity anomaly values of the square in question and its eight neighbouring squares. Weight one was taken for observed anomalies at less than

5 km from the centre of the square and the weight for the surrounding stations inversely proportional to the square of the distance. The polynomial was then integrated over the 10 x 10 km square and divided by its area. The standard error of the mean anomalies are in most cases < 0.5 mGal.

2.2 Mean free air anomalies of 1° x 1° squares outside Finland at

$$45° \leqq \varphi \leqq 85° \text{ N}$$
$$15° \leqq \lambda \leqq 65 \text{ EG}$$

published by the International Gravity Bureau [3] completed by some cruises in the North Atlantic and in the Arctic Ocean. The ACIC list of 1° x 1° anomalies [1] and updated anomalies by letter from Dr. R.H. Rapp [9] completed the field. The Arctic Ocean area, however, did remain weak.

2.3 Mean free anomalies of 5° x 5° squares outside the above area published by the International Gravity Bureau [2].

3. COMPUTATIONS

Computation of the geoid and the deviations of the vertical were carried out with a Univac 1108 computer in three phases. The influence of the anomalies inside Finland were computed using 10 x 10 km mean anomalies. The geoid height was computed for every central point of these squares, thus for 4161 points in Finland. When computing the deviations of the vertical with the Vening Meinesz formula the Taylor polynomials of the nine squares nearest to the computation point were integrated using approximated function ([4], p.121).

The 1° x 1° square mean anomalies were then used for computing. This was carried out for points in geographical coordinates. From these points the geoid height and deviation of the vertical were interpolated for all the 4161 points in question. The 10 x 10 km square and 1° x 1° square boundaries did not agree with each other. Though it is easy to compute the influence of the broken squares, this was not done since the change from 10 x 10 km squares to 1° x 1° squares caused much greater inaccuracies to points near the state boundaries.

A similar method was used for distant areas using 5° x 5° mean free air anomalies [2] . The geoid on the international ellipsoid 1924, with flattening 1:297 is illustrated with the attached map.

4. ACCURACIES

The standard errors were also computed in three phases. The influence of the distant areas, the 5° x 5° mean anomalies, was ±2.0 m for the geoid and ±0".13 for the components of the deviation of the vertical. This estimation is obviously too optimistic. The correlation between the estimated anomalies could not be taken into consideration since the material used for computing the published mean anomalies was unknown to the author. The same problem concerns the 1° x 1° square mean anomalies. The standard errors for ΔN vary from 0.33 to 0.42 m and for $\Delta \xi$ and $\Delta \eta$ from 0".07 to 0".18 but these can also be too small.

The standard errors caused by the 10 x 10 km square anomalies are in most of the country $\Delta N \leqq$ 5 cm. The accuracy of $\Delta \xi$ and $\Delta \eta$ varies a great deal depending on the density of the gravity field in the immediate surroundings.

5. COMPARISON WITH ASTROGEODETIC DETERMINATION OF N, ξ And η

A realistic estimation of standard errors of geoid and deviations of the vertical variations in Finland gives the c o m p a r i s o n o f g r a v i m e t r i c g e o i d a n d t h e g e o i d c o m p u t e d b y a s t r o g e o d e t i c l e v e l l i n g [6]. The gravimetric geoid heights were interpolated from the computation points to the triangulation stations. After the mean astrogeodetic geoid was moved and tilted to the mean of the gravimetric geoid we obtained the quadratic mean of differences at 264 first order triangulation stations ±19 cm. Agreement is good, but there are large areas of positive or negative difference. Thus the distribution of differences is not random. The change of N-difference between of two neighbouring stations is in most cases < 5 cm.

KORHONEN [7] has computed the a s t r o g e o d e t i c g e o i d i n F i n l a n d a s a T a y l o r p o l y n o - m i a l o f 17 d e g r e e s. (170 unknowns). A similar comparison with this and as was made above with the geoid computed by astrogeodetic levelling gives ±20 cm as the quadratic mean of ≈ 291 differences. From the 321 astrogeodetic stations used by KORHONEN, some on the islands and those now in the SSSR, have not compared because of the lacking gravity net around these stations.

A third comparison was made with the astrogeodetic geoid of Finland computed by LACHAPELLE [8].

The quadratic mean of 263 differences was ±22 cm.

The comparison with the observed astrogeodetic deviations of the vertical on 235 triangulation stations, after elimination of the tilting difference of the geoids, gave the quadratic mean of differences $\Delta\xi = \pm 0''.73$ and $\Delta\eta = \pm 0''.69$. The interpolation from computed points to the triangulation points has increased the standard errors. The accurate gravimetric deviation of the vertical needs a dense gravity station net in the immediate surroundings of the station. Earlier computation of gravimetric deviation of vertical for 21 stations with a dense net in the immediate surroundings [6] gave the difference $\pm 0''.35$. Interpolation for these same stations now gave $\pm 0''.48$.

6. ACKNOWLEDGEMENTS

This study was performed at the Finnish Geodetic Institute with financial support from the Academy of Finland, which I gratefully acknowledge. I would like to express my appreciation for the work done by H. PARVIAINEN in 1972, V. KNUUTI in 1973 and M. HEIKKINEN in 1974, who made all the programmings and computations with the Univac 1108 computer of the State Computer Centre.

The computer office of Outokumpu Oy made the drawing of the geoid maps with their IBM computer, for which I would like to express my gratitude.

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[2] CORON, S.: Carte d'anomalie à l'air libre par 5° x 5° Bureau Gravimetr. International, Bull.d'Inf. No 29, Paris 1972.

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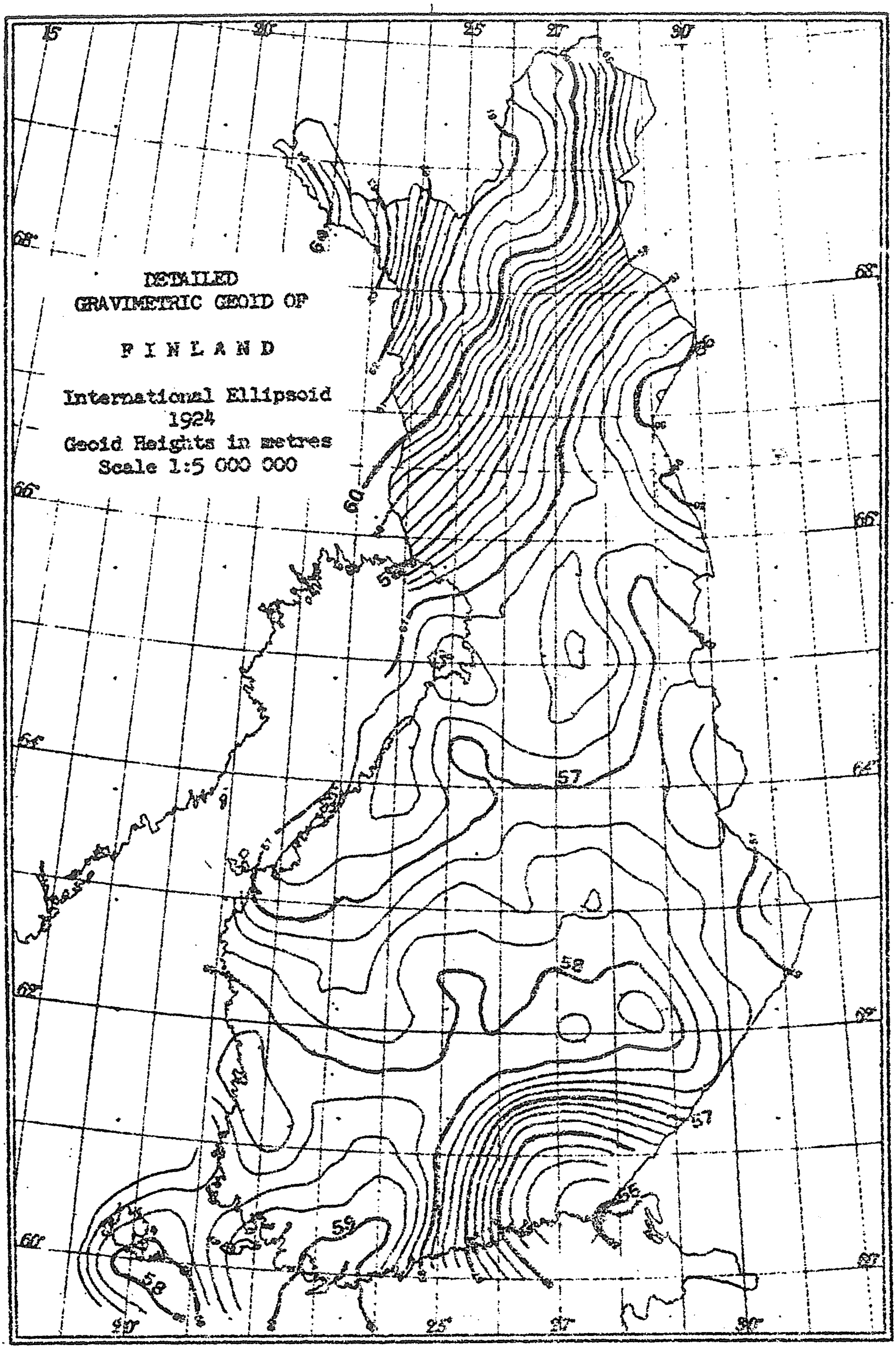
[5] HONKASALO, T.: Gravity survey of Finland in the years 1945-1960. Publ.Finn.Geod.Inst. No 55, Helsinki 1962.

[6] HONKASALO, T.: Physical geodesy, Geodetic Operations in Finland 1967-1970. Helsinki 1971.

[7] KORHONEN, J.: Om beräkningen av geoidhöjder med tillhjälp av lodavvikelserna. Nordiska Kommissionen för Geodesi. Helsinki 1971.

[8] LACHAPELLE, G.: Estimation of the accuracy of the astrogeodetic geoid in Finland. Thesis for Licentiate of Science degree in the University of Helsinki 1973.

[9] RAPP, R.H.: 1° x 1° updated anomalies. Private communication Dec. 1972.


DETAILED
GRAVIMETRIC GEOID OF
F I N L A N D
International Ellipsoid
1924
Geoid Heights in metres
Scale 1:5 000 000
15
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LISTE des PUBLICATIONS

reçues au

BUREAU GRAVIMETRIQUE INTERNATIONAL

(Janvier à Juin 1974)

CONCERNANT LES QUESTIONS DE PESANTEUR

LISTE des PUBLICATIONS

* 261 - GOODACRE A.K., L.E. STEPHENS & R.V. COOPER - "A gravity survey of the Scotian Shelf".
Earth Sci. Symposium on Offshore Eastern Canada, Geol. Surv. Can., Paper 71-23, p.241-252, 1973.
Earth Physics Branch, Contr. n°464, Ottawa.

During the summer of 1970, 692 underwater gravity stations were established on the Atlantic continental shelf of Canada. The areas surveyed include the Laurentian Channel, Cabot Strait, and parts of St. Pierre Bank and the Scotian Shelf. Stations were located on a 15 km grid and detailed profiles run across the Orpheus anomaly and across a diapiric structure northeast of Sable Island. During all three cruises of CNAV SACKVILLE, standard marine Decca and radar were used as primary navigation aids but tests were also made to evaluate the accuracy of differential Omega navigation. The gravity data are presented in the form of a Bouguer anomaly map. The anomalies generally strike in an easterly direction across the continental shelf and the dominant feature is the linear Orpheus anomaly which extends 250 km eastwards from Chedabucto Bay and is flanked to both north and south by positive anomalies. The northern positive anomaly appears to be related to Proterozoic metavolcanic rocks with interspersed Devonian basic intrusions. A broad negative anomaly south of the Orpheus anomaly is probably underlain by a Devonian granite batholith. Between Cape Breton Island and the Miquelon Islands a broad positive anomaly area appears to delineate the underwater extent of the Avalon Platform and in this area density variations within the pre-Carboniferous basement are probably the primary source of variations in the gravity field. Several gravity anomalies are distorted or terminate at one of both margins of the Laurentian Channel ; this observation suggests that deep-seated structure may have been a factor in the formation of the Channel.

262 - QURESHY M.N. - "Relation of gravity to elevation, geology and tectonics in India".
Proc. of the Second Symposium on Upper Mantle Project, Dec. 1970, Hyderabad. Nat. Geophys. Res. Inst., Contr. n°71-222, 23 p, 1970.

Bouguer anomaly map of India prepared from the data of Oil and Natural Gas Commission, Survey of India, Hawaii Institute of Geophysics and the National Geophysical Research Institute brings out correlation between near surface geologic variations and gravity anomalies. It is thereby concluded that bulk of the variation in Bouguer anomaly values can be accountered for by isostatic effect and intra crustal density variations.

* Les numéros font suite à ceux indiqués dans le Bull. Inf. N° 35, Novembre 1974.

The regression analyses of free-air, Bouguer, Pratt-Hayford and Airy-Heiskanen anomalies against elevation and the correlation of isostatic anomalies with geology indicate that isostatic equilibrium prevails in India, at least in a general way.

An approximate crustal thickness map prepared from Bouguer anomaly and elevation data shows the crustal thickness to vary between 36 and 40 km over the bulk of the sub-continent. Higher values are obtained over the Himalayas (40-80 km), Nilgiris (50 km), Eastern Ghatts (44 km) and Western Ghats (40-50 km).

From the regression between crustal thickness and elevation, a standard column for India is inferred which is presumed to have a sea level thickness of 35 km, and an average density of 2,88 gm/cm^3 with an underlying Upper Mantle having a density of 3,47 gm/cm^3.

263 - DEFENSE MAPPING AGENCY, AEROSPACE CENTER - "World relative Gravity Reference Network : IGSN 71". (North America, Asia, Australia, Africa, West Indies, Central America, South America, Antarctica, Atlantic Ocean). DoD Gravity Library, 223 p, St-Louis, 1973.

Enclosed is one copy of the new gravity reference base station values for all volumes of Reference Publication N°25, "World Relative Gravity Reference Network", previously forwarded to your Office during the past three years. These new values are keyed to the IGSN 71 adopted by the International Association of Geodesy in 1971. All gravity data requested from the DoD Gravity Library will now be keyed to IGSN 71.

265 - TSCHERNING C.C. - "An Algol-Program for prediction of height anomalies, gravity anomalies and deflections of the vertical". Geod. Inst. Rep. n°2, 40 p, Copenhagen, 1972.

266 - REMMER O. - "A stability investigation of least squares adjustment by elements". Geod. Inst., Med. n°49, 11 p, Copenhagen, 1973.

This paper deals with least squares adjustment by elements.

The classical treatment of this subject was fully developed already in the last century by men like Gauss and Helmert.

Provided that the observations are normally distributed and that the relative accuracy of the observations is known, the classical works give us a beautiful and complete theory.

This object of the present investigation is the method of least squares when these conditions are no longer fulfilled. Roughly speaking, the approach to the problem is this : How robust is the method of least squares when we use non-normally distributed observations and a false weight matrix or variance matrix. (A more stringent formulation of the approach to the problem is given in Chapters II and III) ... .

267 - KAARLAINEN J. - "Uber die 50-M lange Rohrlibelle zur Untersuchung der Neigung der Erdkruste". Finnish Geod. Inst., Rep. n° ISBN 951-711-002-2, 26 p, Helsinki, 1973.

268 - HYTONEN E. - "Absolute gravity measurement with long wire pendulum".
Finnish Geod. Inst., Pub. n°75, 146 p, Helsinki, 1972.

269 - KAHMEN H. - "Untersuchung von analogen und digitalen Phasenmessystemen in der elektrooptischen Entfernungsmessung".
D.G.K., Reihe C : Dissert., H. n°186, 68 S, München, 1973.

270 - KOLBL O. - "Kombinierte Auswertung von Satelliten und Lufbildern für die topographische Kartierung".
D.G.K., Reihe C : Dissert., H. n°188, 118 S, München, 1973.

"Combined restitution of aerial and satellite photographs for topographic mapping".
It is shown how topographic mapping especially for the needs of developping countries can be rationalized by the incorporation of satellite photographs. The considerations are mainly concerned in map scales between 1:50.000 and 1:100.000.
The satellite photographs are used both for bridging and for supplying the geometric information for topographic mapping. For topographic photo-interpretation aerial photographs are used with picture scales between 1:50.000 and 1:100.000.
A mosaic of rectified satellite photographs represents the first stage of a photo-map, although there are only a few topographic details which can be interpreted in this "map". Only by the use of aerial photographs and by careful coordination with the satellite photographs, sufficient topographic interpretation is possible. This controled mosaic of aerial photographs can serve as a base for further cartographic amendments or for the derivations of a line map.

As satellite-photographs in the proposed scales can not be used to supply adequate height control for a topographic map non-photogrammetric survey methods have to be incorporated for instance statoscope and electronic altitude measurement(laser altimeter). Plotting of reliable contour lines can be achieved with such heigh control.

271 - GRAFAREND E. & N. WECK - "Tagung Freie Randwertaufgaben".
Mit. Inst. Theor. Geod. Univ. Bonn, n°4, 84 S, 1972.

a) KOCH K.R. - "Method of integral equations for the geodetic boundary value problem".
p. 38-48.

The geodetic boundary value problem, i.e., the determination of the shape of the Earth and its gravitational field from gravity anomalies, is investigated using the method of integral equations. To derive the integral equations, an approximate surface of the Earth, the telluroid, as boundary and boundary values with an accuracy of the order of the flattening of the Earth are assumed to be known. The resulting integral equation is known as Molodensky's basic integral equation. It is shown in contrast to Molodensky's results that the conditions of the existence of solutions of the basic integral equation can only be given for a boundary which is a sphere, i.e., for an Earth without topography.

b) LAURITZEN S.L. - "On the stochastic approach to the determination of the gravity potential".
p. 50-59.

It is well-known among geodesists, that it is possible to use statistical methods to determine the potential of the Earth.

Kaula (1959) tried to use time-series analysis techniques on gravity measurements and determined an estimate of the covariance function of gravity anomalies.
Krarup (1969) showed how to use a covariance function for the potential to derive covariances between other linear functionals, so that it became possible to use. e.g., gravity anomalies and deflections of the vertical simultaneously.

A sufficiently precise mathematical model was never made. The guess on the uncertainty of the by Kaula determined covariance function was founded only on heuristic arguments.

The present lecture summarizes a paper to appear in the publications of the Danish Geodetic Institute, trying to formulate a precise model and prove, that the uncertainty of the covariance function is too large even if the potential of the Earth happened to be completely known.

c) GRAFAREND E. - "Die freie geodätische Randwertaufgabe und das Problem der Integrationsfläche innerhalb der Integralgleichungsmethode".
S. 60-66.

10 propositions (P) collect the typical features of the geodetic boundary value problem. (GBVP)

P. 1 : The GBVP is not a classical BVP, but a free, oblique BVP of the LAPLACE-POISSON equation.

P.2,3 : The natural or astronomical coordinate system is anholonomic. The gravity g is the basic integrating factor within PFAFFian forms to find holonomic coordinates.

P. 4 : Assuming the given gravity g or gravity disturbance Δg on the known Earth surface, the BVP is of CARTAN - GIRAUD type.

P.5,6 : But knowing instead of the real gravity g only the approximative normal gravity γ, the γ- holonomic coordinates give not the real Earth figure. Their approximative surface differs by longitude, latitude, and height anomalies from the real surface. The anomalies are found from the geometro-dynamical equation, a generalisation of BRUNS' formula.

P. 7 : The geometro-dynamical equation is the necessary and sufficient condition to solve the GBVP.

P.8,9 : Within the integral equation method for solving BVP the typical problem for a free BVP is the missing a priori information of the integration surface which has to be determined within the solving procedure. The integration surface is via the geometro-dynamical equation dependent of the potential.

P. 10 : Therefore, the integral equation solving the GBVP with singular surface density is of HAMMERSTEIN nonlinear type.

272 - CHOJNICKI T. - "Ein Verfahren zur Erdgezeitenanalyse in Anlehnung and das Prinzip der kleinsten Quadrate".
Mit. Inst. Theor. Geod. Univ. Bonn, n°15, 59 S, 1973.

A method for elaborating tidal observations was presented, based on the principle of least squares and which, because of the possibilities of its utilization, was devised as the possibly most universal one among those applied up to date.

273 - TENGSTROM E. - "Uber das Short-Arc-Satelliten beobachtungsvorhaben im Bereich des "Europäischen Datums".
Mit. Inst. Theor. Geod. Univ. Bonn, n°16, 7 S, 1973.

The aims of the International Short-arc campaigns are explained and a report is given on the success of 4 campaigns as performed hitherto. Then, plans for future work are developed and certain problems are discussed.

274 - BONATZ M. - "Gravimetrische Erdgezeitenstation KERGUELEN (Indischer Ozean) Ergebnisse des ersten Registrierzeitraumes Januar bis Mai 1973".
Mit. Inst. Theor. Geod. Univ. Bonn, n°20, 17 S, 1973.

In cooperation with the "Laboratoires scientifiques du territoire des Terres australes et antarctiques français", Paris, and with support of the "Deutsche Forschungsgemeinschaft", Bonn, in December 1972 at Port-aux-Français, archipelago of Kerguelen in the South Indian Ocean, a gravimetric earthtide station was established...

The situation of Kerguelen-Islands amidst the ocean gives a good possibility for the study of the loading effect of the oceanic tides. It is of interest too, that the station is relative to the equator symmetrically situated with regard to the mentioned Westeuropean stations. In addition, it is possible to study eventual correlations with other geophysical phenomena by using the data of the numerous geophysical stations at Port-aux-Français.

The recordings obtained until 17. May 1973 were analysed in three separate parts (corresponding to the arrival of the data at Bonn) after Chojnicki's method. A total analysis was computed too.

275 - BONATZ M. & W. ROCHOLL - "Gesamtauswertung der mit Horizontalpendeln in der Testation ERPEL, gewonnenen Messungsergebnisse 1965 bis 1971".
Mit. Inst. Theor. Geod. Univ. Bonn, n°21, 10 S, 1973.

From December 1965 until October 1970 in the test station Erpel near Bonn the clinometric tides were measured with horizontal pendulums of the type Verbaandert-Melchior... .

276 - BONATZ M. - "Gezeitenregistrierung mit einem auf kapazitiven Angriff umgerüsteten Askania-Gravimeter GS 12".
Mit. Inst. Theor. Geod. Univ. Bonn, n°22, 11 S, 1973.

Comparing the measurement results obtained by modern Earth tide gravimeters Askania GS 15 with those using the older types GS 11 and GS 12 an augmentation of the inner accuracy by the factor three to four is to be stated. As the spring system of the meter in principle has not been changed the benefit of accuracy is only due to the applied transducer system instead of photocells. This fact led to the consideration whether it is possible by installing a capacitive transducer system into an old type meter to transform it as a modern efficient earth tide gravimeter...

278 - CESKOSLOVENSKA AKADEMIE VED - Studia Geophys. & Geod. t.17, n°1, Praha, 1973.

a) BURSA M. - "Gaussian curvature of smoothed equipotential surface from satellite orbit dynamics".
p. 1-6.
Stokes's constants $J_n^{(k)}$ and $S_n^{(k)}$ of the Earth's body, determined from satellite orbit dynamics up to a comparatively high degree, give an unified description of the fundamental features of the geopotential field. In the present paper, they were used to derive the Gaussian curvature of the external equipotential surfaces of the geopotential.

279 - CESKOSLOVENSKA AKADEMIE VED - Studia Geophys. & Geod., t.17, n°2, Praha, 1973.

a) BURSA M. - "The mean curvature of the external equipotential surface and the vertical gravity gradient as functions of Stokes's constants".
p.74-80.
The mean curvature of the equipotential surface and the vertical gradient of gravity are expressed in terms of a development into a series of spherical harmonics, neglecting terms of the order of 10^{-8}. The curvature anomalies have been computed using the satellite data. The symbols used are the same as in n°278(a) above.

b) KOLBENHEYER T. - "On a method of computing the gravitational fields of inhomogeneous bodies".
p.111-114.
A solution of the direct gravity problem for a finite body with variable density is given. The method is based on Green's formula and is applicable when a particular solution of Poisson's equation is known. The attraction due to the body is expressed by integrals over its surface. The exact solution of the direct gravity problem, as known from the theory of two-dimensional fields is closely connected with the problem of the analytic continuation of the exterior field of the attracting mass system into its interior. In the first place, this is a problem of determining the singularities of the exterior field, their distribution within the system and their nature. This approach to the solution of the direct problem is also meaningful from the point of view of determining the characteristics of the attracting system and, therefore, also of solving the inverse problem. In the case of two-dimensional fields the methods of analytical continuation were widely developed in a series of well-known papers by V.N. Strakhov, and they are mainly based on the methods of the theory of the functions of the complex variable. These methods were also successfully applied by Tsirulskii and Golizdra in treating the homogeneous and inhomogeneous, two-dimensional direct problem by means of Cauchy's integrals. However, as regards three-dimensional fields a number of fundamental problems has not been solved in this respect.

e) PICK M. - "On the boundary condition of the gravity disturbing potential".
p.173-176.
The boundary condition for the gravity disturbing potential was derived up to the second-order terms and the influence of the second-order terms was investigated.

d) TRAGER L. - "Zeitliche Konstantenveränderungen der Gravimeter GS 12 n°129 und n°181".
p.177-179.

280 - CESKOSLOVENSKA AKADEMIE VED - Studia Geophys. & Geod. t.17, n°3, Praha, 1973.

a) BURSA M. - "Geoidal curvature radii from satellite data for different degrees of smoothing".
p.193-198.
Radii of curvature and their anomalies of a smoothed geoidal surface are computed using Stokes's constants $J_n^{(k)}$, $S_n^{(k)}$ of the Earth's body, obtained from satellite orbit dynamics. Different degrees n of smoothing are used (n = 8, 12, 21). The notation are the same as in n°278(a) above.

281 - TRAVAUX de l'INSTITUT GEOPHYSIQUE de l'ACADEMIE TCHECOSLOVAQUE des SCIENCES. N° 345-362, 1971 ; v.XIX, Praha, 1973.

a) BURSA M. - "Undulations of the geoid due to deep anomalous masses on the territory of Czechoslovakia".
p.9-58.
The paper deals with the results of determining partial undulations of the geoid due to masses deeply deposited on the territory of Czechoslovakia. Components of the deflections of the vertical, corrected for the effect of topographic masses, were used at about 1000 discrete points of a territory 128.000 km^2 in area.

b) KUBACKOVA L. - "Some mathematical problems of discrete optimum (Wiener) filtering of anomalous gravity fields".
p.101-108.
The method of discrete filtration of a homogeneous random field in an additive noise of the same nature is discussed. In the first part a system of linear equation is derived defining the optimum filter, and the uniqueness of its solution is proved. The independence of the coefficients of this filter at the filtered point follows from the homogeneity of the fields considered. In the second part certain problems are considered which are connected with the use of statistical estimates of correlation coefficients instead of the real values in computing the filter.

c) CHARAMZA F. & L. TRAGER - "Bearbeitung der Messungsergebnisse auf den Schwerepolygonen".
p.109-120.
An untraditional method of treating the results of measurements on gravity polygons is described. The difference between the method presented and other procedures, used currently, is in the simultaneous determination of the unknown values of the acceleration of gravity at the individual points of the polygon, the dimensional coefficients of the selected gravity meter, and the parameters of the drift of the gravity meters during the individual periods of the day. After giving the fundamental relations, some of results of the adjustment of a gravity polygon, which was carried out in the way described, are mentioned.

d) DIVIS K. - "Determining vertical gradients of the acceleration of gravity mountainous regions".
p.121-132.

The values of the vertical gradient of the acceleration of gravity $\partial g/\partial z = \partial^2 W/\partial z^2$, were determined in two independent ways at 17 points in the Velka Fatra Range. The first method is based on deriving the values of the vertical gradient from the observed values of the acceleration of gravity at two or more points of the real vertical. The second method is based on computing the anomalous part of the vertical gradient, $\partial^2 T/\partial z^2$, from a map of gravity anomalies. The computations were carried out using a procedure derived by Yurkina for a plane reference surface, which allows the computation to be carried out by means of successive approximations. In this case the computation is rectricted to the first approximation. Most of the computing was done by computer. The results yielded by both the methods were compared, and the differences were used to estimate the accuracy of the vertical gradients in the zero and first approximations ... .

282 - BOTT M.H.P. & D.S. DEAN - "Stress systems at young continental margins".
from : Nature Phys. Sci., v.235, n°54, p.23-25, 1972.
Dept. Geol., Pub. n°398, Univ. Durham.

A study of stresses associated with young continental margins shows that differential loading across major surface features of the Earth may cause tectonic activity within lithospheric plates.

283 - BOTT M.H.P. - "Interpretation of global gravity anomalies".
from : Nature Phys. Sci., v.236, n°63, p.23-24, 1972.
Dept. Geol., Pub. n°401, Univ. Durham.

284 - AL-CHALABI M. - "Interpretation of gravity anomalies by non-linear optimisation".
from : Geophys. Prospecting, v.XX, n°1, 16 p, 1972.
Dept. Geol., Pub. n°406, Univ. Durham.

The interpretation of a gravity anomaly in terms of the shape of the anomalous body is a non-linear problem and may, therefore, be carried out using non-linear optimisation techniques. The formulation is extended to include cases where the density contrast and the regional background are also unknown. For a given model the objective function is provided by the discrepancy between the observed anomaly and the calculated anomaly due to the model. Given an initial model, the optimisation procedure searches for a minimum of the objective function by an iterative adjustment of the parameters. A number of suitable objective functions is given. The behaviour of these functions in the parameter hyperspace is quite complex. Accordingly, direct search methods should be employed at the early stages of the search, changing to gradient methods at later stages. The use of constraints is also necessary to ensure the geological feasibility of the model. The required computer time may be largely reduced by careful programming. Two examples of interpretation by optimisation methods are given.

285 - LONG R.E., R.W. BACKHOUSE, P.K.H. MAGUIRE & K. SUNDARLINGHAM - "The structure of East Africa using surface wave dispersion and Durham seismic array data".
from : Tectonophysics, v.15, n°1/2, p.165-178, 1972.
Dept. Geol., Pub. n°415, Univ. Durham.

As a background to the discussion of the array data some results of studies on teleseismic P-wave delays and surface wave dispersion within the rift zone are presented. This work uses data from permanent stations. The deep structure of the Gregory Rift is subsequently discussed using data from the Kaptagat array station installed by the University of Durham in Kenya in 1968. A compressional velocity model for the Gregory Rift is presented.

286 - BOTT M.H.P., J.G. HOLLAND, P.G. STORRY & A.B. WATTS - "Geophysical evidence concerning the structure of the Lewisian of Sutherland ; N.W. Scotland".
from : J. Geol. Soc., v.128, p.599-612, 1972.
Dept. Geol., Pub. n°422, Univ. Durham.

Interpretation of two new gravity profiles across the Ben Stack line and of the I.G.S. aeromagnetic map indicates that the Lewisian biotite-gneisses occurring to the north of this line are underlain at a depth of about 3 km or less by rocks possessing similar density and magnetic properties to the pyroxene-granulites which crop out south of the line. The Ben Stack line forms the fundamental division between these two metamorphic assemblages of the Lewisian and its plane dips steeply towards the south. The gravity profiles also indicate that both the biotite-gneisses and pyroxene-granulites in the vicinity of the Ben Stack line are anomalously low in density. This is attributed to the penetration of both formations by granitic and pegmatitic intrusions of low density. The evidence suggests that the granitic material concentrated in the vicinity of the Ben Stack line occupies too great a volume to be derived solely from the host biotite-gneisses in the immediate vicinity and may therefore possibly be of more extensive origin.

287 - BOTT M.H.P. & A. INGLES - "Matrix methods for joint interpretation of two-dimensional gravity and magnetic anomalies with applications to the Iceland-Faeroe Ridge".
from : Geophys. J. R. Astr. Soc., n°30, p.55-67, 1972.
Dept. Geol., Pub. n°423, Univ. Durham.

Gravity and magnetic anomalies caused by a body satisfying the Poisson condition can be inter-related by linear algebra through use of a fictitious equivalent layer. Computer programs using this formulation have been written to carry out two-dimensional pseudogravimetric and pseudomagnetic transformations, to estimate the direction of magnetization, and to compute the ratio of magnetization to density within an assumed equivalent layer. The method is applicable to other problems of direct interpretation of gravity and magnetic anomalies and can be extended to three-dimensional interpretation. It is amenable to irregularly spaced field data.

The methods have been used to show that the complicated magnetic anomalies over the Iceland-Faeroe Ridge are partially related to the gravity anomalies. The correlation is attributed to substantial variations in the depth to the layer 1/layer 2 interface.

288 - GUNN P.J. - "Application of Wiener filters to transformation of gravity and magnetic fields".
from : Geophys. Prospecting, v.XX, n°4, p.860-871, 1972.
Dept. Geol., Pub. n°429, Univ. Durham.

Consideration of the spectral representation of gravity and magnetic fields shows the field to be the result of the convolution of factors depending on the parameters of the field Wiener filters, calculated using model transformations, provide an optimum method for altering these factors and hence effecting field transformations.

289 - BEN-AVRAHAM Z., C. BOWIN & J. SEGAWA - "An extinct spreading centre in the Philippine Sea".
from : Nature, v.240, n°5382, p.453-455, 1972.

An extinct ocean floor spreading centre identified by a topographic ridge has been discovered in the West Philippine Basin. Evidence of active spreading during the Mesozoic explains the early evolution of the Western Pacific and some marginal seas.

295 - LAUDON T.S. - "Land gravity survey of the Solomon and Bismarck Islands".
from : Geophys. Monograph n°12, Crust & Upper Mantle of the Pacific Area, 1968.
Contr. 196 of the Geophys. & Polar Res. Center, Univ. Wisconsin, p.279-295, 1968.

Bouguer isogal maps of the Solomon and Bismarck Islands are characterized by large, extremely steep positive anomalies. Local anomalies can be related to near-surface geological features. Basement rocks and Quaternary volcanic centers are expressed as gravity highs ; Upper Tertiary sedimentary basins are expressed as gravity lows. The regional gravity field of the Solomons consists of a broad low, elongated parallel to the trend of the islands, with smaller highs, corresponding to individual islands, superimposed on its flanks. The gravity results suggest that regional isostatic compensation of the Solomons has occurred. However, the gravity fields of the individual islands suggest significant departures from isostasy. These are attributed to : support of Quaternary volcanic piles by the strength of the Earth's crust without isostatic compensation ; higher than normal crustal densities ; and upwarping of the mantle beneath the islands.

296 - MALAHOFF A. - "Gravity anomalies over volcanic regions".
from : Geophys. Monograph n°13, The Earth's crust and Upper Mantle, Contr. 249 from the Hawaii Inst. of Geophys., 1969.

DEPARTMENT of SCIENTIFIC & INDUSTRIAL RESEARCH, Geophysics Division, Wellington
Gravity Map of New Zealand, 1/250.000.

297 - Bouguer anomalies, isostatic anomalies, isostatic vertical gradient anomalies, sheet 25 : DUNEDIN, 1969.
(3 maps, regional type anomalies)

298 - Bouguer anomalies, isostatic anomalies, isostatic vertical gradient anomalies, sheet 3 : AUCKLAND, 1971.
(3 maps, regional type anomalies)

299 - Bouguer anomalies, isostatic anomalies, isostatic vertical gradient anomalies, sheet 4 : HAMILTON, 1971.
(3 maps, regional type anomalies)

300 - Bouguer anomalies, isostatic anomalies, sheet 26: STEWART ISLAND, 1971.
(2 maps, regional type anomalies)

301 - Bouguer anomalies, isostatic anomalies, isostatic vertical gradient anomalies, sheet 2 : WHANGAREI, 1972.
(3 maps, regional type anomalies)

302 - Bouguer anomalies, isostatic anomalies, isostatic vertical gradient anomalies, sheet 6 : EAST CAPE, 1972.
(3 maps, regional type anomalies)

303 - Bouguer anomalies, isostatic anomalies, isostatic vertical gradient anomalies, sheet 9 : GISBORNE, 1972.
(3 maps, regional type anomalies)

304 - Bouguer anomalies, isostatic anomalies, isostatic vertical gradient anomalies, sheet 24 : INVERCARGILL, 1972.
(3 maps, regional type anomalies)

305 - Isostatic vertical gradient anomalies, sheet 21 : CHRISTCHURCH, 1972.
(1 map, regional type anomalies)

306 - KLINGELE E. - "Contribution à l'étude gravimétrique de la Suisse Romande et des régions avoisinantes".
Thèse, Univ. Genève, Dept. Minéralogie & Géophysique, 94 p, Genève, 1972.

307 - RECHENMANN J. - "Etude d'une anomalie gravimétrique et magnétique dans le Nord-Est de la Mauritanie".
Ann. Geophys., t.28, fasc. 4, p.871-877, 1972.

Les résultats de la campagne gravimétrique et magnétique dans le Nord de la République Islamique de Mauritanie montrent une large anomalie gravimétrique superposée à une anomalie magnétique dont l'interprétation pose le problème de l'origine des anomalies régionales. Les solutions classiques conduisent à des origines profondes, ce qui, pour l'anomalie magnétique, est incompatible avec la profondeur de la température du point de Curie.

Une interprétation au moyen d'un modèle dont l'aimantation serait croissante des bords vers le centre est proposée.

308 - MAKRIS J., U. ZIMMERMANN, H.C. BACHEM & B. RITTER - "Gravity survey of South Afar, Ethiopia".
Zeit. f. Geophys., Band 39, S.279-290, Physica-Verlag, Würzburg, 1973.

Early in 1970 South Afar in N.E. Ethiopia was gravimetrically surveyed by the Institutes of Geophysics, University of Hamburg and Theoretical Geodesy, Technical University of Hannover.

In an area of approx. 80000 km^2 900 gravity stations have been established. The data were uniformly reduced. They were compiled in a Bouguer map of 5 mGal isolines. The main results show that :

The gravity field follows closely the topographic features.

The gradient towards the Ethiopian escarpment is 2 - 3 mGal/km and 1 - 1,5 mGal/km towards the Somalianescarpment

The crustal deformation from the Somali plateau to the depression represents a flexure, whereas the Ethiopian scarp is a zone of crustal rapture.

The Ethiopian rift continues NNE-SSW into Afar up to the Abbe and Gamori Lakes.

The crust thickness increases towards the escarpments, and it is most probably of the subcontinental type as indicated by a 2-D model that was simulated across the depression in EW direction.

Towards the Aisha Horst the crustal thickness increases, since the gravity field becomes more negative.

310 - BOTT M.H.P. & D. MASSON-SMITH - "The geological interpretation of a gravity survey of the Alston block and the Durham coalfield".
The Quart. J. Geol. Soc. London, v.CXIII, part I, n°449, p.93-117, 1957.

Problems of the deep structure of the Alston Blocks and the Durham Coalfield are outlined in relation to previous geophysical work. The gravity survey planned as the most expedient approach to these problems is briefly described. The results of a density survey undertaken in conjunction with the gravity survey are stated.

The main feature of the gravity survey is a large negative anomaly over the Alston Block. The earlier conclusion, that it is caused by an unexposed granite, is upheld by the detailed physical and geological interpretation. The postulated granite approaches closest to the surface in five bosses, some of which almost certainly reach within 5000 feet of the surface. The shape of the gravity anomalies bears remarkable resemblance to the zones of mineralization and the volatile content of the coal seams, and for these reasons a post-Carboniferous age seems likely. Possible modes of origin of the postulated granite are discussed.

The northward decreases of anomaly across the Stublick fault system is caused by fairly rapid thickening of the Lower Carboniferous succession, which continues eastwards across the line of the Ninety Fathom Dyke. A southward Bouguer decrease across the Butterknowle fault is similarly interpreted as a southward thickening of Lower Carboniferous rocks. The internal structural features of the Alston Block are interpreted in relation to the assumed granite below.

A study of the background Bouguer anomaly suggests a North Pennine crustal mass deficiency in addition to the granite. It is considered that the granite mass deficiency, if accompanied by an additional crustal deficiency, could account isostatically for the present North Pennine uplift, and for the general stability since the lower Carboniferous.

311 - BOTT M.H.P. & D.G.G. YOUNG - "Gravity measurements in the North Irish Sea".
The Quart. J. Geol. Soc. London, v.126, p.413-434, 1971.
Pub. n°372, Dept. Geol. Sci. Labo., The University of Durham.

This paper presents a Bouguer anomaly map of most of the north Irish Sea, based on underwater gravimeter measurements. The map incorporates earlier surveys in the northern part of the region and new work in the southern part. The new work reveals that the previously discussed Manx-Furness gravity "low" (now renamed the East Irish Sea "low") extends southwards to the coast of North Wales. Newly observed detailed profiles across the north-western margins of the "low" show that it is caused by a partially fault-bounded composite sedimentary basin between the Isle of Man, Lancashire and North Wales, with a local region of basement uplift 30 km southeast of Douglas. High Bouguer anomalies are observed over a wide area between the Isle of Man, Anglesey and Ireland, suggesting a region with relatively shallow basement rocks. A negative gravity anomaly of - 40 mGal amplitude occupies an elongated oblong area 40 x 30 km^2 in dimension off the east coast of Ireland near Dublin. The steep gravity gradients and other characteristics of the anomaly suggest that it is caused by a sedimentary basin about 3 to 4 km deep. The high density contrast required to explain the anomaly implies that Permo-Triassic and/or later sediments form the main infill of the basin. This anomaly is called the Kish Bank gravity "low".

312 - DAY A.A. - "Gravity anomalies in the Channel Islands".
Geol. Magazine, v.XCVI, n°2, p.89-98, 1959.

Bouguer gravity anomalies have been determined at seventy-nine stations on Alderney, Guernsey and Jersey. On Alderney the anomalies are clearly dependent on the nature of the outcropping rock-types, and permit approximate values for the thickness of two outcropping rock masses to be obtained. On Guernsey the anomalies are not closely related to the surface geology, and suggest that the north-eastern coastal area is underlain by a body of dense rock, possibly of ultra-basic composition. The anomalies on Jersey indicate that the sedimentary rocks of western Jersey are underlain at no great depth by rock of density comparable to that of granite. In eastern Jersey the dominating feature of the anomalies is a pronounced "high" centred near Grande Charrière. It is shown that this feature is most reasonably considered to be the effect of a large buried gabbro intrusion.

313 - BROOKS M. & M.S. THOMPSON - "The geological interpretation of a gravity survey of the Bristol Channel".
from : J. Geol. Soc., v.129, part 3, p.245-274, 1973.

A Bouguer anomaly map of the Channel and surrounding land areas is presented and interpreted. The main features of the map are :
1) a negative anomaly approaching - 20 mGal trending WNW across the southern half of the Channel and adjacent areas of west Somerset and north Devon ;
2) a broad flanking area of weak positive anomaly in the northern part of the Channel which may extend southeastwards across the Cothelstone fault into Bridgwater Bay ; and
3) a local positive anomaly of over + 20 mGal around Lundy Island. These anomalies are all superimposed on a strong regional gradient of + 0.38 mGal km^{-1} to the southwest.

The negative anomaly in the southern part of the Channel is due partly to Mesozoic strata in the Bristol Channel syncline but partly to underlying, low density, Upper Palaeozoic rocks which are probably preserved in a structural basin similar to the South Wales coal basin but overthrust by the Devonian succession of Exmoor. The parallel belt of positive anomaly in the northern half of the Channel is interpreted as overlying an anticlinorial zone, characterized by Old Red Sandstone at shallow depth, separating the South Wales coal basin to the north from the postulated basin to the south. The positive anomaly around Lundy Island is attributed to the effect of a large basic pluton of Tertiary age occurring at shallow depth, and the gravity field of Lundy is compared with that of other Tertiary igneous centres. A sketch structural section across the Bristol Channel is presented.

314 - CHOUDHURY S.K. & A.N. DATTA - "Bouguer gravity and its geologic evaluation in the Western part of the Bengal Basin and adjoining area, India".
Geophysics, v.38, n°4, p.691-700, 1973.

The Bouguer gravity anomalies in the western part of Bengal Basin and part of eastern Bihar, India, can be explained in terms of basement relief which controls the thickness of the Gondwanas. This relief, however, has no influence on structure within the sedimentary section overlying the Gondwanas. During Gondwana times, the Bengal Basin continued further north at least up to Purnea, but in early Tertiary times, the continuity was interrupted by a basement feature passing through Jangipur and Malda.

The main line of connection between peninsular India and the Shillong Plateau may be through the Rajmahal hills and the Darjeeling Himalayas.

315 - RABINOWITZ P.D. - "Gravity anomalies across the East African continental margin".
from : J. Geophys. Res., v.76, n°29, p.7107-7117, 1971.
Contr. n°1702 of the Lamont Doherty Geol. Obs.

A free-air gravity map along the east coast of Africa from about 1°S to 7°S is constructed. The most important features of this map are :

1. A relative free-air gravity high that approaches 10 mGal just seaward of Mombasa. This high is flanked to the west by a free-air low more negative than - 100 mGal and to the east by a low more negative than - 50 mGal. Isostatic calculations indicate that these anomalies do not arise from "edge" effects, but result from crustal structure. The high extends from Pemba Island and appears to represent a submarine extension of the island. Crustal models indicate thick sediment accumulations on either side of this submarine extension.
2. A free-air gravity low observed throughout the length of the map at water depths ranging from about 2000 to 3500 meters. Landward of this low is a free-air gravity high that appears to extend onshore at about 2°S. This high is interpreted as representing a continuous basement ridge, somewhat similar to the ridge observed off the east coast of the United States. However, unlike the basement ridge observed off the east coast of the United States, which appears to be generally located at the shelf break, the presumed basement ridge off the east coast of Africa does not follow any particular topographic contour. It is located beneath ocean depths exceeding 2000 meters in the south to possibly onshore in an area farther to the north. Previous refraction measurements taken seaward of the gravity high did not detect the presence of the ridge.

The widespread existence of basement ridges on nontectonic continental margins indicate their common origin regardless of how they are expressed. If they are the products of the initial demarcation of the continents, the location of such ridges and, hence, the gravity signature associated with the ridges may define the continental edge.

316 - S. CORON & A. GUILLAUME - "Etude gravimétrique sur le Golfe de Gascogne et les Pyrénées".
Extrait de l'ouvrage : Histoire structurale du Golfe de Gascogne, p.IV.9-1-15, Paris, 1971.

Cet article fait la synthèse des mesures de pesanteur connues sur le Golfe de Gascogne et les Pyrénées en présentant plusieurs cartes.

La première est une carte d'anomalies complètes de Bouguer du golfe de Gascogne. Les deux autres sont celles des tendances régionales et des résiduelles de la même région ; elles ont été obtenues par lissage double (moyennes mobiles et polynômes) des anomalies de Bouguer.

Les figures 4, 5 et 6 concernent les Pyrénées ; elles indiquent respectivement les anomalies de Bouguer, les anomalies isostatiques (Airy, 30 km) et un schéma structural.

Ce travail met en évidence :
1) La structure océanique du centre du golfe qui dans l'ensemble, est compensé isostatiquement (les anomalies de Bouguer atteignent 300 mGal).
2) Des différences d'épaisseur de croûte de part et d'autre de la faille nord-pyrénéenne, dans la partie centrale des Pyrénées (écart supérieur à 50 mGal).
3) Des variations probables de la profondeur du toit du socle dans la plaine abyssale et sur ses marges : minimums a... d et maximums tel que A (fig. 3, anomalies résiduelles).
4) L'accident majeur nord-sud de Santander F 3 qui forme vraisemblablement la limite occidentale de la zone continentale, vers le parallèle 44°30'.

5) Des accidents crustaux importants dans le secteur pyrénéen, indiqués par les variations de direction des isanomales et l'existence d'extremums gravimétriques particulièrement nets. Ces accidents sont :

- soit directionnels : faille nord-pyrénéenne F 1 ;
- soit transverses ou obliques, les principaux d'entre eux étant :
  . l'accident d'Hendaye F 4 ;
  . la faille de Bagnères F 5 qui limite la zone axiale pyrénéenne vers l'ouest ;
  . l'accident bordier des Cévennes et de la Montagne Noire F 6;
  . les accidents de type Perpignan-Nîmes (F 7 ...).

On notera la présence de nombreux épicentres dans les zones d'intersection entre les accidents directionnels et transverses.

317 - GAIBAR-PUERTAS C. - "Estudio preliminar sobre las anomalias de la pesantez en el Mar de Alboran".
Revista de Geofisica, n°1-2-3-4, p.87-156,
Talleres del Inst. Geog. y Catastral, Madrid, 1972.

Using the results obtained in 60 observations effected in the Alboran Sea, have been the corresponding anomalies of gravity : Faye, Bouguer and isostatics of Airy (R = 0, T = 30 km). To support the track of the corresponding isogams, we use an other 60 terrestrial observations (16 in N.african litoral and 44 in the spanisch sector situated at the South of the parallel of 38°) also from the spanish station of Alboran Island.

The analysis of these three fields of isogams appears to indicate a geostructural scheme that confirms the existence of a sialic root (with similar importance to the Bética range) that crosses from North to South the Gibraltar Strait. Towards the meridian 2°30'W.G., coinciding with the rapid amputation and total disapearance of the dorsal of Alboran Sea thus like the narrow fosse ascribed to the northern side it produces a sharp variation in the orientation of the anomalies as a possible geostructural reply. In the occidental depresion of Alboran Sea (W. of the meridian 2°30'W.G.) the elongated anomalies like the dorsal of Alboran Sea (height > 1.700 m) and its ascribed fosse present an alpine orientation : parallel to the emerging range of the South of Spain and of the North of Africa. On the contrary, in the oriental depression of the Alboran Sea (E. of the meridian of 0°30'W.G.) the disappearing drop of that dorsal and accompanying fosse seems related with geostructural traits of the orthogonal orientation of the occidental ones because the anomalies appear clearly lengthened in a direction next to the NNW-SSE.

The thickness of the sialic crust seems to diminish progressively from the Gibraltar Strait towards the East. Inside the occidental depression it seems to diminish from the spanish litoral to the South of the dorsal, reaches its minimum value in the abyssal plane extended between the dorsal and the continental slope of the Tres Forcas Cape ; the great dorsal and the deep canyon next to its septentrional flank does not seem to modify substantially that progression of the sialic thickness.

The diverse structural compartiments seems to show arising tendency in the occidental sectors (Strait) and northerly (between spanish litoral and the northerly slope of the narrow fosse next to the dorsal). On the contrary, the abyssal plane extended between the dorsal and the African litoral seems subject to subsidence, the same as the oriental depression of the Alboran Sea.

318 - LE PICHON X. & M. TALWANI - "Gravity survey of a seamount near 35°N 46°W in the North Atlantic".
from : Marine Geol. v.2, p.262-277, 1964.
Contr. n° 782 of the Lamont Geol. Obs.

Continuous gravity profiles were obtained over a seamount near 35°N 46°W in the North Atlantic Ocean. The seamount consists of two peaks but there are no individual Bouguer minima over each peak. Rather, a Bouguer minimum is centered over a saddle between the two peaks and cannot be attributed to a wrong choice of density in the Bouguer reductions. This minimum is interpreted as due to a secondary magma chamber.

319 - CORON S. - "Grandes zones d'anomalies de la pesanteur dans le Bassin Méditerranéen et ses bordures - Détails pour la région de Gibraltar". Symposium sur la Géodynamique de la région Méditerranéenne, Athènes Nov. 1972 ; C.I.E.S.M., v.22, fasc. 2a, p.31-33, 1973.

Sur la carte d'anomalies de Bouguer établie pour la région de Gibraltar, a été indiquée la position des épicentres (d'après BEUZARD, 1972) ; on constate qu'une zone aséismique coïncide avec la zone minimum gravimétrique d'orientation N.S. On en déduit :
- q'aucune fracture majeure profonde d'orientation Ouest-Est n'est décelée au niveau du détroit de Gibraltar ;
- qu'un bloc homogène et stable réunit les 2 continents ;
- que dans cette région, la croûte "continentale" doit avoir une forte épaisseur puisque les anomalies de - 80 mGal peuvent difficilement être expliquées par la seule présence des terrains superficiels légers.

320 - BONINI W.E., T.P. LOOMIS & J.D. ROBERTSON - "Gravity anomalies, ultramafic intrusions and the tectonics of the region around the Strait of Gibraltar".
J. Geophys. Res., v.78, n°8, p.1372-1382, 1973.

A new compilation of gravity data in the region surrounding the Strait of Gibraltar between 2° and 9°W and 34° and 37°30'N is presented in the form of a Bouguer anomaly map. Published data and new data obtained by Princeton University in southern Spain are included. There are four major features of the anomaly map :
1) An arcuate zone of negative anomalies more than 200 km wide, parallels the trend of the Betic and Rif orogens. The gravity low crosses the Strait of Gibraltar and included the Atlantic approach to the Strait and the western Alboran Sea. Values as low as - 130 mGal in Spain and - 150 mGal in Morocco were reduced.
2) Two coastal gravity high zones along the Moroccan and Spanish margins of the western Alboran Sea show steep gradients and closures as high as 110 mGal superimposed on the arcuate negative zone. The gravity highs in part coïncide with a belt of outcrop of ultramafic and associated metamorphic rocks.
3) A central high in the Alboran Sea begins about 90 km east of Gibraltar and extends eastward into the axial high of the western Mediterranean.
4) Positive anomalies trend WSW from southern Spain and westward from northern Morocco into the Atlantic approaches to the Strait of Gibraltar. All four major gravity features show a rough, symmetry about a plane striking E.W. through the Strait of Gibraltar.

The most important conclusions that can be drawn from the data are the following :
1) The steep gravity gradients and magnitude of the coastal highs require steeply dipping density discontinuities probably reaching the mantle. The data support recent petrological and structural evidence from Spain of diapiric intrusion of ultramafic rock from the mantle and conflict with previous hypotheses that propose a thin thrust sheet structure of these masses.
2) Continental crust extends across the Strait of Gibraltar in a belt more than 200 km wide, including the western Alboran Sea. The continuity and symmetry of the anomaly pattern across the Strait agree with similar geological observations and correlations of rocks as old as Paleozoic and imply that the Betic and Rif have been part of a single tectonic system including the Alboran Sea probably since Precambrian time. Neither gravity nor geological evidence supports proposals of a major zone of plate discontinuity (transform faulting) between Spain and Morocco as a continuation of the Azores-Gibraltar ridge from the Atlantic.
3) The central Alboran Sea high is consistent with either a crustal break or a crustal thinning model. Significant zones of thin crust and possible crustal extension are found also in the Atlantic approaches to the Strait of Gibraltar.

321 - BOTT M.H.P., C.W.A. BROWITT & A.P. STACEY - "The deep structure of the Iceland-Faeroe Ridge".
from : Marine Geophys. Res. 1, p.328-351, 1971.
Pub. n°382, Dept. Geol. Sci. Labo. The University of Durham.

Two long seismic refraction lines along the crest of the Iceland-Faeroe Ridge reveal a layered crust resembling the crust beneath Iceland but differing from normal continental or oceanic crust. The Moho was recognised at the south-eastern end of the lines at an apparent depth of 16 - 18 km. A refraction line in deeper water west of the ridge and south of Iceland indicates a thin oceanic type crust underlain by a 7,1 km/s layer which may be anomalous upper mantle.

An extensive gravity survey of the ridge shows that it is in approximate isostatic-equilibrium : the steep gravity gradient between the Norwegian Sea and the ridge indicates that the ridge is supported by a crust thickened to about 20 km rather than by anomalous low density rocks in the underlying upper mantle, in agreement with the seismic results. An increase in Bouguer anomaly of about 140 mGal between the centre of Iceland and the ridge is attributed to lateral variation in upper mantle density from an anomalous low value beneath Iceland to a more normal value beneath the ridge. Local gravity anomalies of medium aplitude which are characteristic of the ridge are caused by sediment troughs and by lateral variations in the upper crust beneath the sediments. A steep drop in Bouguer anomaly of about 80 mGal between the ridge and the Faeroe block is attributed partly to lateral change in crustal density and partly to slight thickening of the crust towards the Faeroe Islands : this crustal boundary may represent an anomalous type of continental margin formed when Greenland started to separate from the Faeroe Islands about 60 million years ago.

We conclude that the Iceland-Faeroe Ridge formed during ocean floor spreading by an anomalous"hot spot" type of differentiation from the upper mantle such as is still active beneath Iceland.

This suggests that the ridge may have stood some 2 km higher than at present when it was being formed in the early Tertiary, and that it has subsequently subsided as the spreading centre moved away and the underlying mantle became more normal ; this interpretation is supported by recognition of a V-shaped sediment filled trough across the south-eastern end of the ridge, which may be a swamped sub-aerial valley.

322 - SERVICE HYDROGRAPHIQUE de la MARINE - "Anomalies de la pesanteur en Mer de Norvège : résultats de mesures effectuées à bord du "Paul Goffeny", 1965-1968".
Cahiers Océanogr., v.XX, n°5, 11ème année, p.503-514, Paris, 1970.
Liste de 797 observations.

324 - KUBOTERA A., H. TAJIMA, N. SUMITOMO, H. DOI & S. IZUTUYA - "Gravity surveys on Aso and Kuju volcanic region; Kyrushu district, Japan".
Bull. Earthquake Res. Inst., v.47, p.215-255, 1969.

Gravity survey at 446 points in an area of about 4300 km^2 over the Aso and Kuju volcanic region occupying the central part of Kyushu Island of Japan was made by use of Worden and LaCoste and Romberg Geodetic Gravimeters from 1965 to 1966.

This survey was carried out as one of the branch projects of "Combined Aeromagnetic-Gravity Studies of Calderas in Japan"

Bouguer gravity anomalies over this area are characterized by :
1) a strong negative anomaly on the Aso caldera,
2) a circular negative anomaly over the Kuju volcano group on the north-eastern side of the Aso caldera,
3) positive anomalies on the south-western flank of somma of the Aso caldera and
4) a narrow belt of relatively high gravity running from Ooita to Kumamoto.

The gravity low of the Aso caldera shows characteristic feature of the "low anomaly type caldera" as is pointed out by Yokoyama.

The Kuju volcanic group also shows the similar feature of "low anomaly type caldera", though existence of caldera is not identified from topographical view point. This fact coïncides with the geological presumption of buried existence of the Kuju caldera which was once as gigantic as that of the Aso caldera.

On the south-western flank of the somma of the Aso caldera, the oldest formation consists of semi-schist (Sambagawa System) and the outcrop of basalt is also being found from geological surveys. The gravity high which reaches 22 mGal at the center coïncides with the distribution of basaltic formation. It reveals, therefore, the high density material such as basaltic or metamorphic rocks.

A narrow belt of relatively high gravity is remarkably observed. The tectonic line which is geologically presumed to run from Ooita westward to Kumamoto through the Kyushu Island just coïncides with this belt.

325 - TOMODA Y. - "Maps of free-air and Bouguer gravity anomalies in and around Japan".
Ocean Res. Inst., Univ. Tokyo, 1973.

Scale : 1/3.000.000 (lat. 35°), approximately 30° to 47°N ; 125° to 145° E.G., interval contour = 2 mGal.

326 - LOZANO CALVO L. - "Red de observaciones con gravimetro en la Provincia de Palencia".
Inst. Geog. y Catstral, Talleres del IGyC, 31 p, Madrid, 1966

Liste des résultats de 914 stations. Cartes des anomalies de Bouguer et des Anomalies isostatiques (Airy 20 et 30 km).

327 - RUIZ LOPEZ J. - "Red de observaciones con gravimetro en la Provincia de Santander".
Inst. Geog. y Catastral, Talleres del IGyC, 36 p, Madrid, 1968.
Liste des résultats de 506 stations.(3 cartes identiques au n°326).

328 - INSTITUTO GEOGRAFICO y CATASTRAL - "Mapas gravimetricos de la Provincias de Alava, Guipuzcoa y Vizcaya".
47 p, Madrid, 1969.

Liste des résultats de 303 stations. Cartes des anomalies de Bouguer et des anomalies isostatiques (Airy 20 et 30 km).

329 - INSTITUTO GEOGRAFICO y CATASTRAL - "Avance del Mapa gravimetrico de la Peninsula Iberica, escala : 1/2.000.000".
30 p, Madrid, 1972. (3 maps, Bouguer, Free-air, mean heights anomalies).

Scale : 1/2.000.000 ; gravity anomalies in 1967 Reference System.

330 - SERVICIO GEOGRAFICO MILITAR - "Red gravimetrica fundamental, resumen de valores". le edicion.
Republica oriental del Uruguay, 55 p, Montevideo, 1970.
Liste des mesures faites de 1962 à 1968 : coordonnées, altitude, valeur de g, anomalies à l'air libre et de Bouguer.
La station de référence est l'aéroport de Carrasco dont la valeur provisoire est : 979.747,47 mGal, déterminée par rapport à la station Fondamentale de Miguelete (Argentine) : 979.705,00 mGal.

331 - SOBCZAK L.W., L.E. STEPHENS, P.J. WINTER & D.B. HEARTY - "Gravity measurements over the Beaufort Sea, Banks Island and Mackenzie Delta, with map n°151 - Mackenzie Delta - Banks Island".
Earth Physics Branch, Gravity map Series, 16 p, Ottawa, 1973.

The Earth Physics Branch has made about 7.700 gravity measurements over the Beaufort Sea, Banks Island and Mackenzie Delta between 1969 and 1972. Measurements were made both on land and on the sea ice of the Beaufort Sea. The major feature of the free-air gravity anomaly map is an arcuate high of about 100 mGal which is one of many elliptical anomalies along the continental margin. These anomalies are explained by a thinning of the crust at the continental break.