Gravimetry

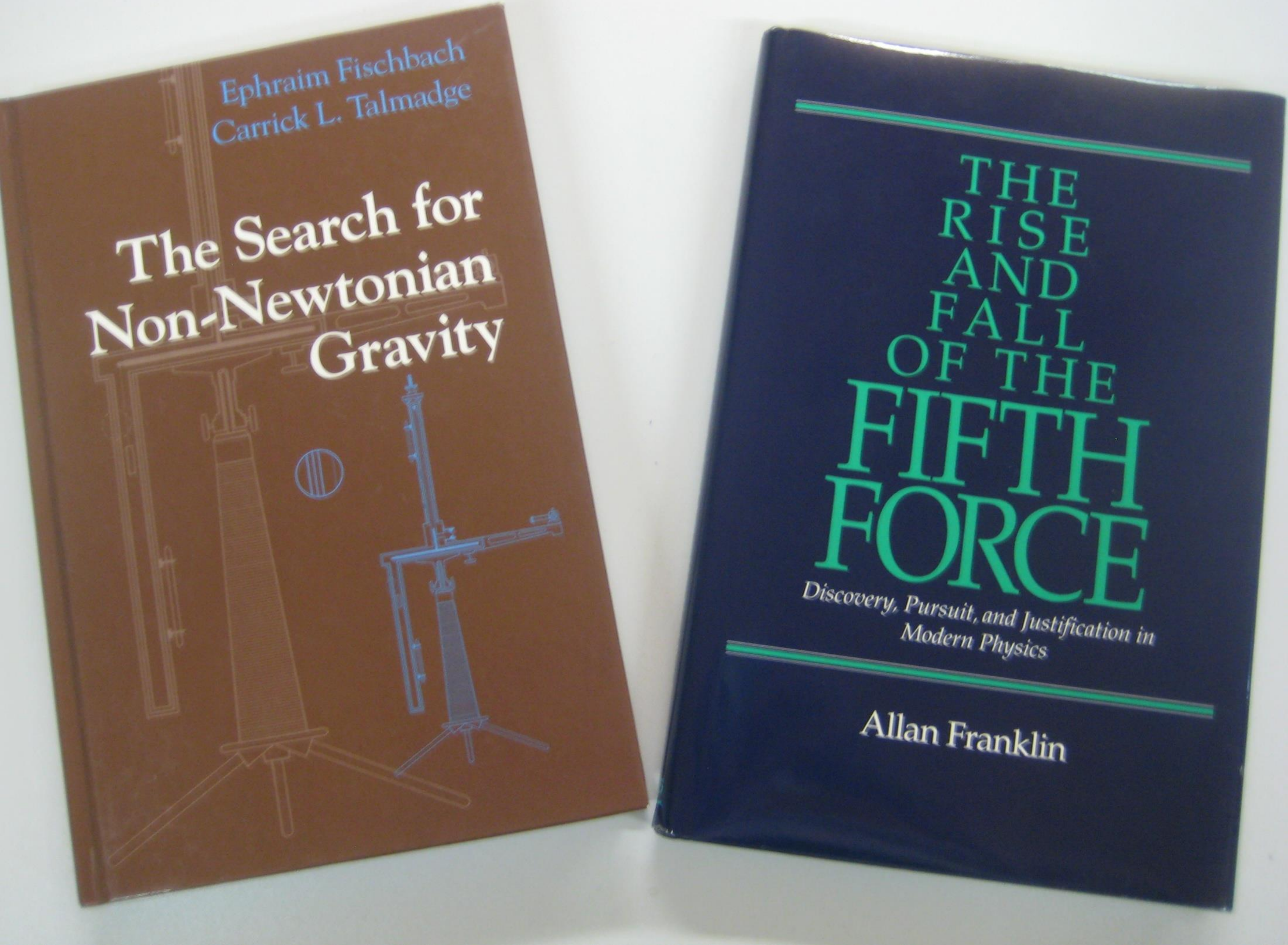
and

„The rise and fall of the 5. Force“

by

Walter Zürn, Black Forest Observatory

EOST Strasbourg --- NOV 19, 2014


Ephraim Fischbach
Carrick L. Talmadge
The Search for Non-Newtonian Gravity
THE RISE AND FALL OF THE FIFTH FORCE
Discovery, Pursuit, and Justification in Modern Physics
Allan Franklin

Contents

Two publications trigger a flurry of activities

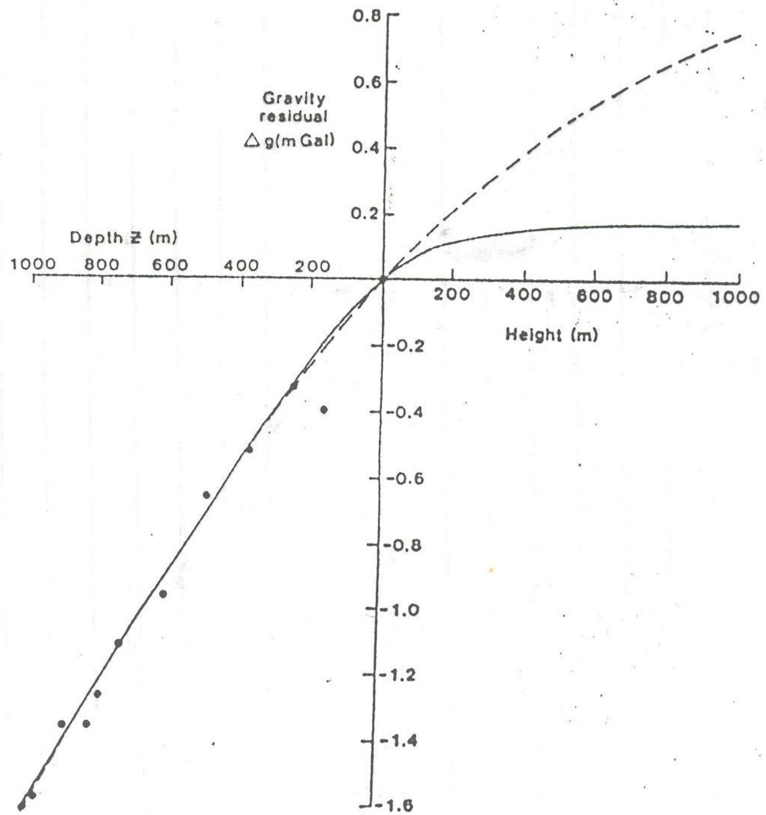
Material dependence of Big G:

Fischbach, E., Sudarsky, D., Szafer, A., Talmadge, C., Aronson, H. (1986)
Reanalysis of the Eötvös Experiment
Phys. Rev. Lett. 56, 2424

Range dependence of Big G:

Stacey, F. D., Tuck, G. J. (1981)
Geophysical evidence for non-newtonian gravity.
Nature 292, 230 - 232.

Stacey & Tuck, Nature 292, 1981, 230



Distance-dependence

FIG. 3. Plot of gravity residuals for the Hilton mine profile. These are differences between measured gravity and calculated values, assuming Newton's law with the laboratory value of G. The curves represent fits to Eq. (4.11) with different values of α and λ, demonstrating the difficulty in determining α and λ separately from mine data alone. Solid curve, $\alpha = -0.007656$, $\lambda = 200$ m; dashed curve, $\alpha = -0.010216$, $\lambda = 1000$ m. These are the least-squares-fitted values of α for the selected values of λ.

4 Interactions in Elementary Particle Theory:

Electromagnetism (Photon)
Strong nuclear force (Gluons)
Weak nuclear force (W & Z – Bosons)
Gravitation (Graviton)

5th Interaction (mimicking gravity) = 5th Force:

Range dependence of Gravitational Constant (Big G)
and/or Material dependence of Big G

Non - Newtonian Gravitation

Newtonian gravitational potential:

G = Universal gravitational constant (Big G)

$$U = G \cdot \frac{M_1 \cdot M_2}{r}$$

Fifth Force (Yukawa-Potential):

α **= (attractive) strength,** λ **= range**

$$W = G \cdot \frac{M_1 \cdot M_2}{r} \cdot [1 + \alpha \cdot exp(-r/\lambda)]$$

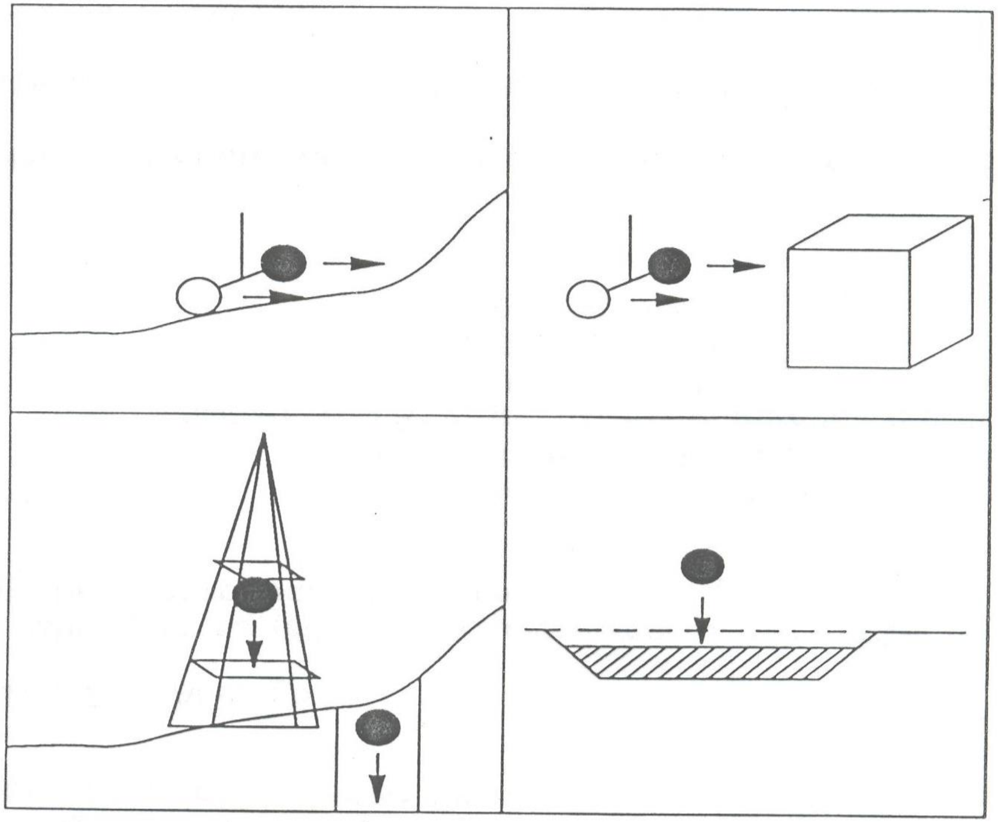
Modified law of gravitation:

$$F = -\frac{\delta W}{\delta r} = G \cdot \frac{M_1 \cdot M_2}{r} \cdot [1 + \alpha \cdot (1 + \frac{r}{\lambda}) \cdot exp(-r/\lambda)]$$

Big G as function of range:

$$G(r) = G_\infty \cdot [1 + \alpha \cdot (1 + \frac{r}{\lambda}) \cdot exp(-r/\lambda)]$$

$$G_{Lab} = G(0) = G_\infty \cdot [1 + \alpha]$$



Composition

range

FIGURE 14. Types of experiments to measure the Fifth Force. The upper row shows composition-dependence experiments. The bottom row shows distance-dependence experiments, or tests of the inverse-square law. The left column shows terrestrial sources, the right column shows laboratory/controlled sources. From Stubbs [1990a].

Franklin, 1993

Ongoing Experiments, July 15, 1988

7 Laboratory Eötvös Experiments
5 Eötvös Experiments near a cliff
6 Repetitions of the Galileo Experiment
3 Floating Ball Differential Accelerometer Experiments
18 Searches for Non-Newtonian Gravity (mines, boreholes, towers, lakes, ocean)
7 Other Tests

Additional experiments started afterwards

Gravimeters
and
Material Dependence of
Gravitation

Niebauer et al. (1987): Phys. Rev. Lett. 59, 609-612
Goodkind et al. (1993): Phys. Rev. D, 47, 1290-1297

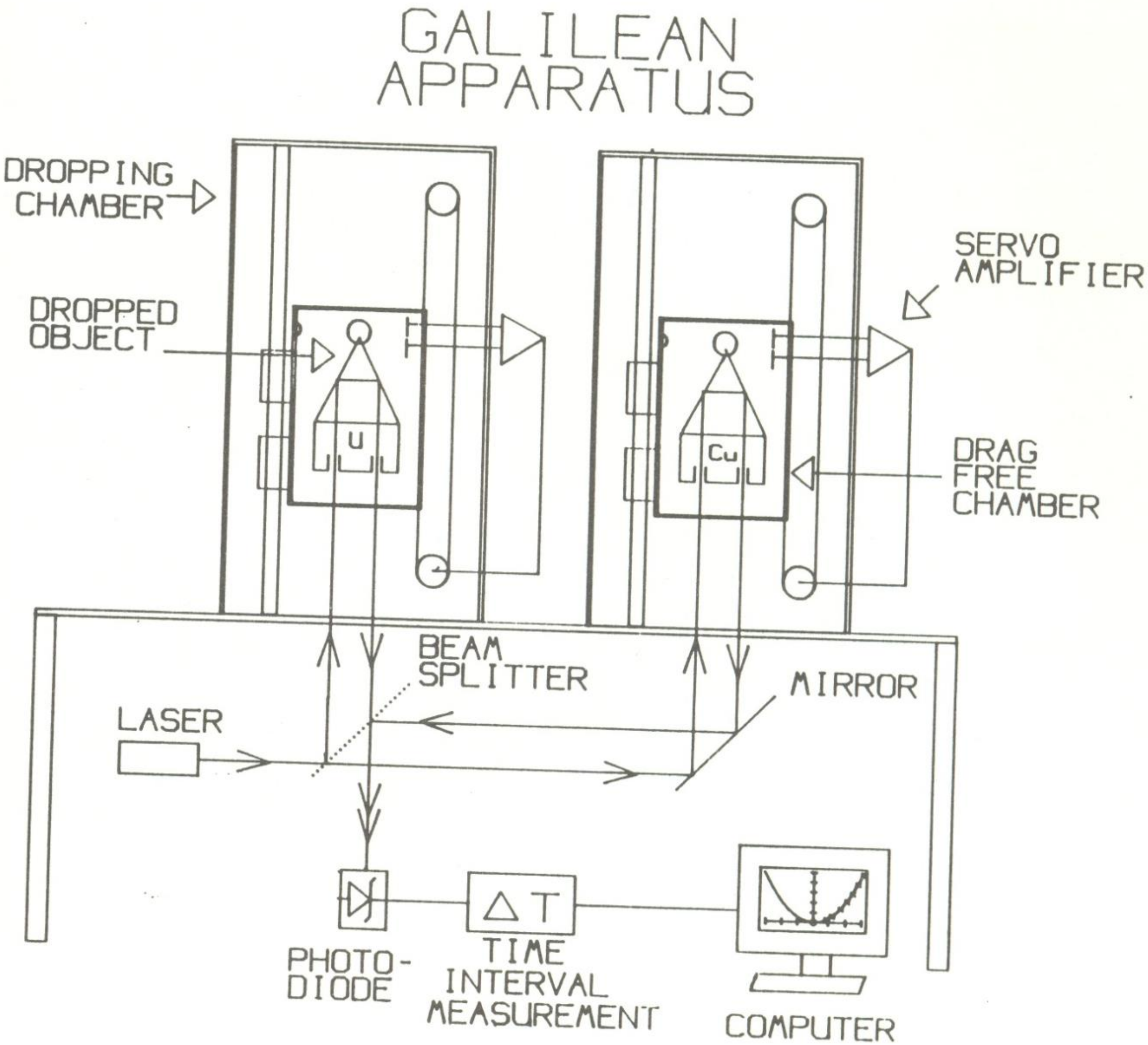


FIGURE 23. The experimental apparatus of Niebauer, McHugh, and Faller [1987]. A repetition of the Galileo experiment.

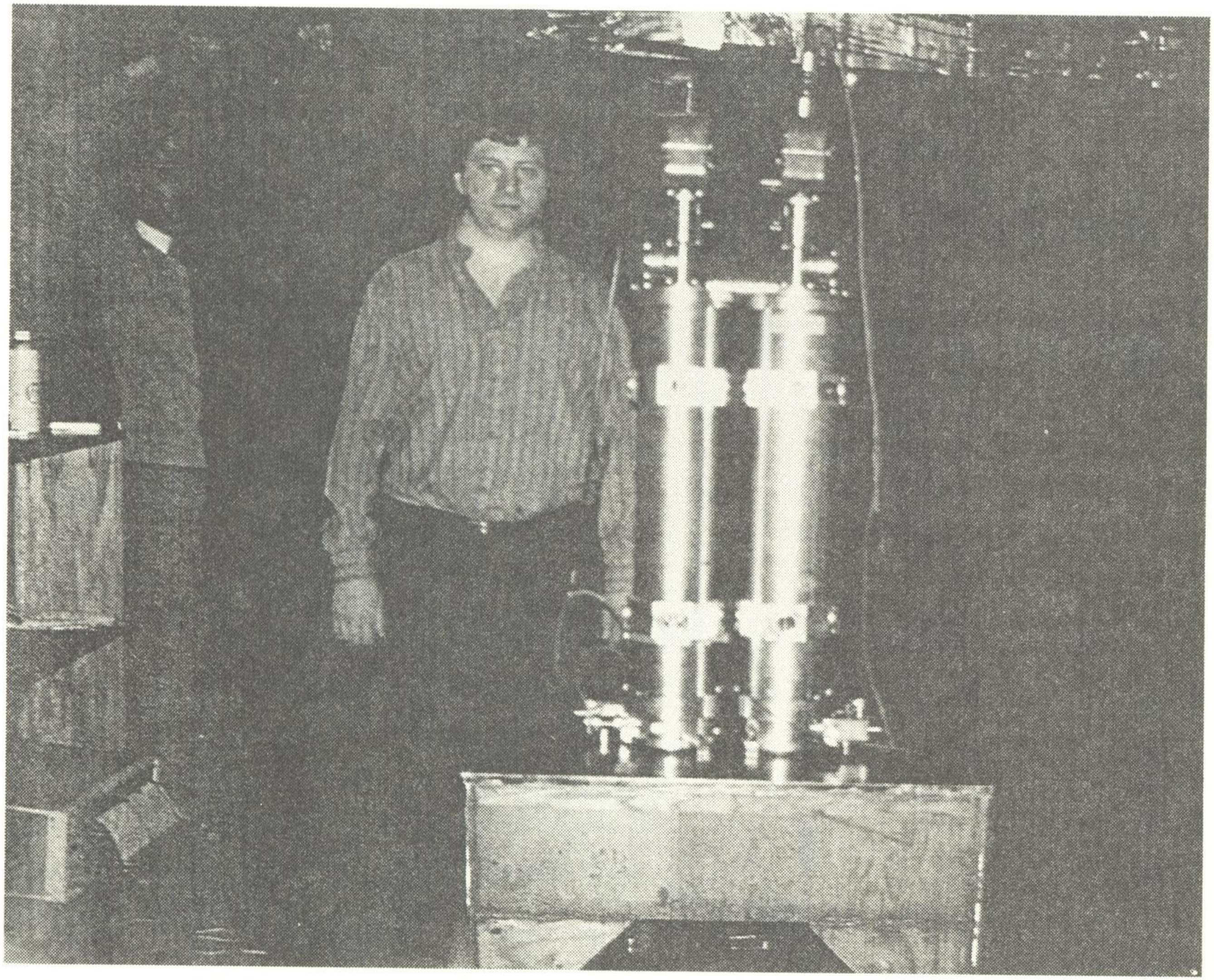


FIGURE 24. Tim Niebauer and the apparatus for the Galileo experiment. Courtesy of Jim Faller.

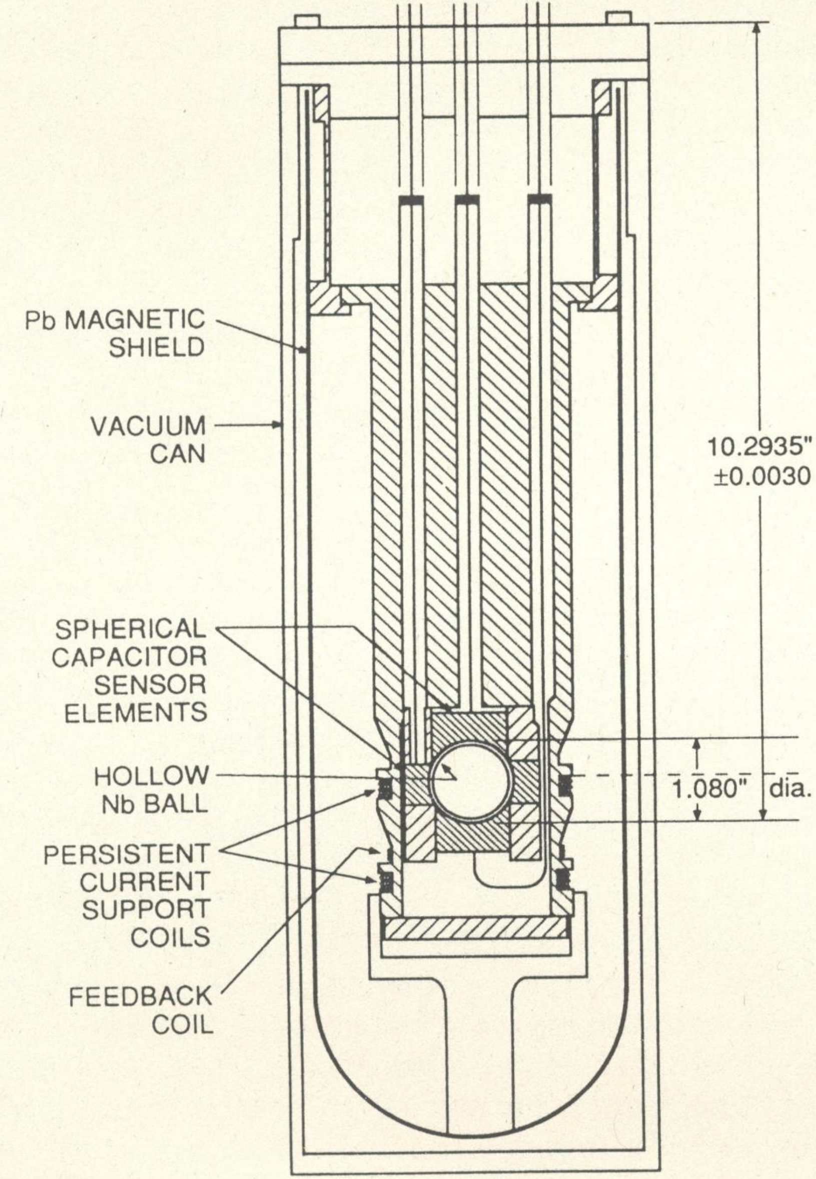


FIG. 1. Superconducting gravimeter, consisting of a hollow Nb ball that is suspended by persistent currents in vacuum.

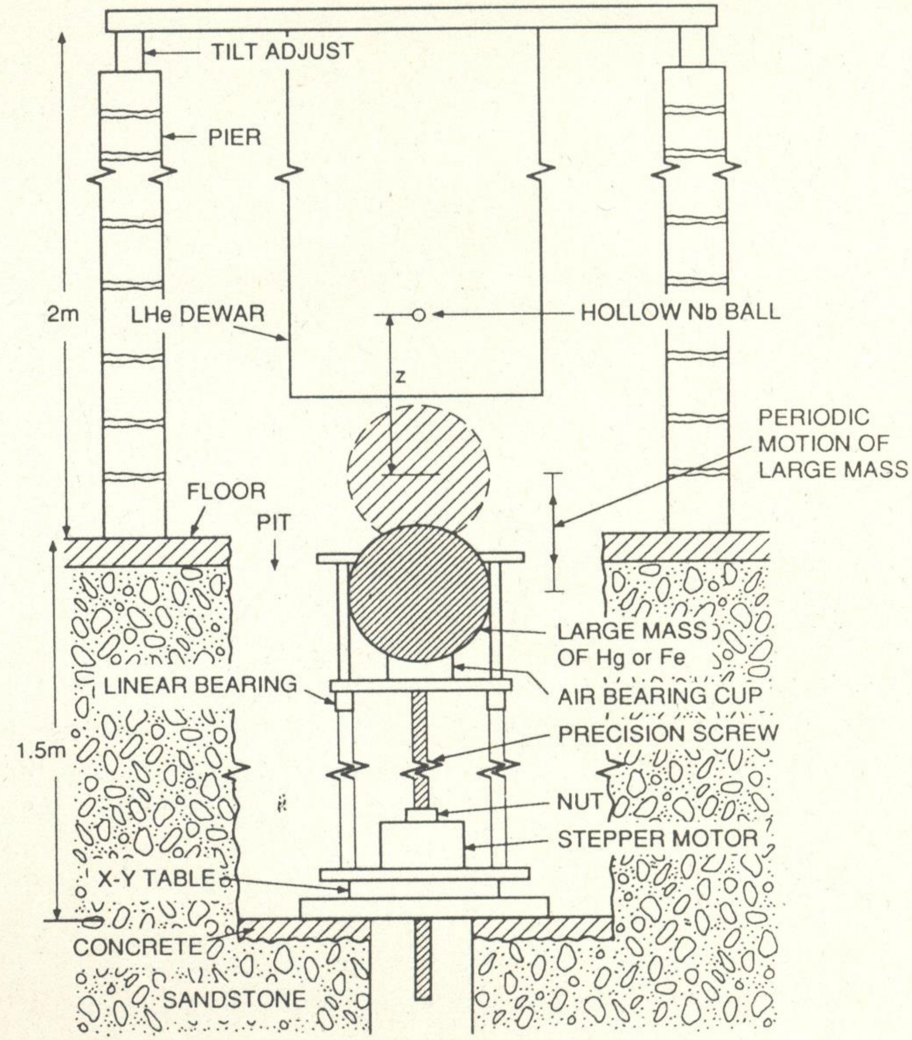


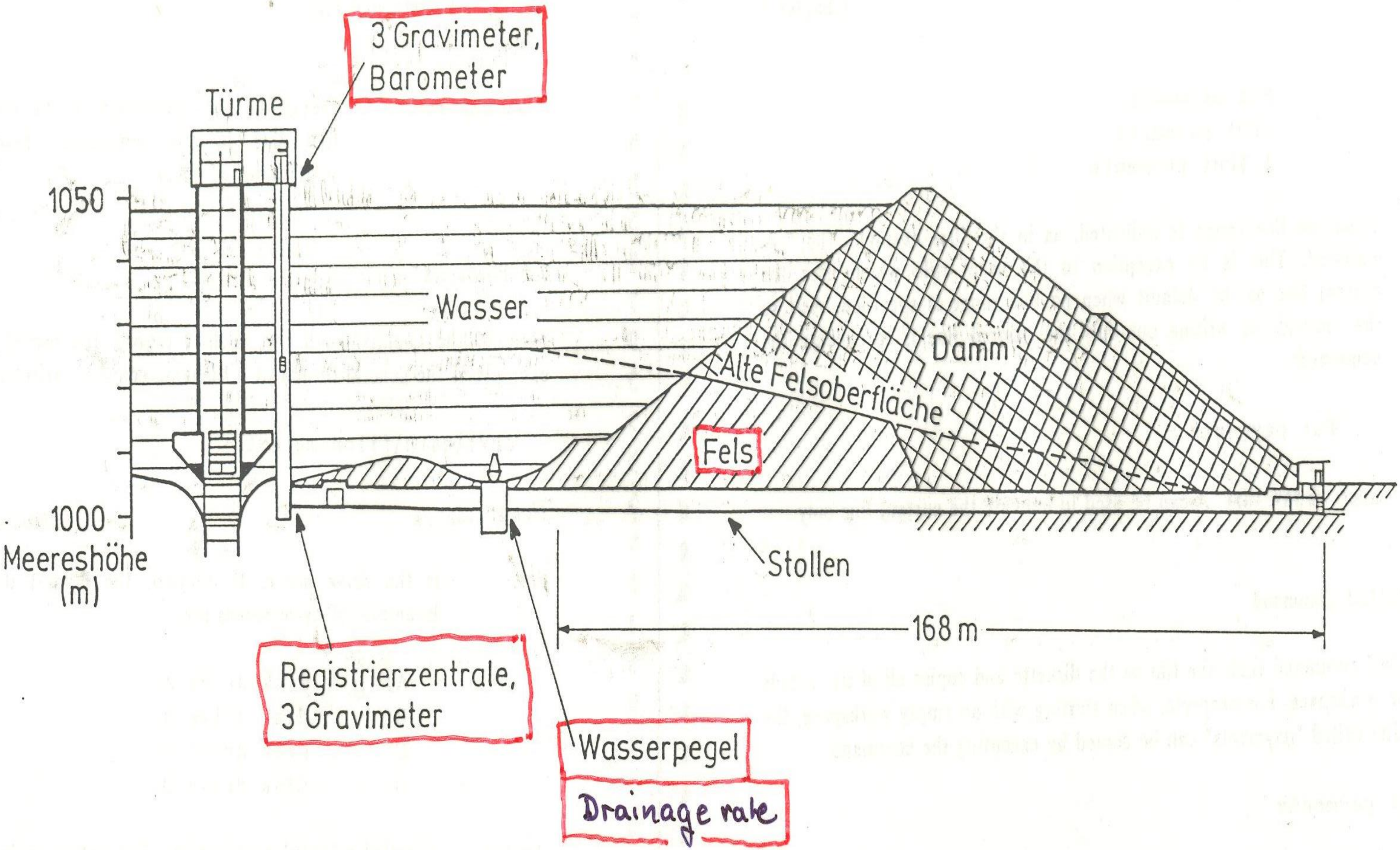
FIG. 2. Experiment for measuring the acceleration caused by a large mass that moves up and down on an elevator beneath the superconducting gravimeter.

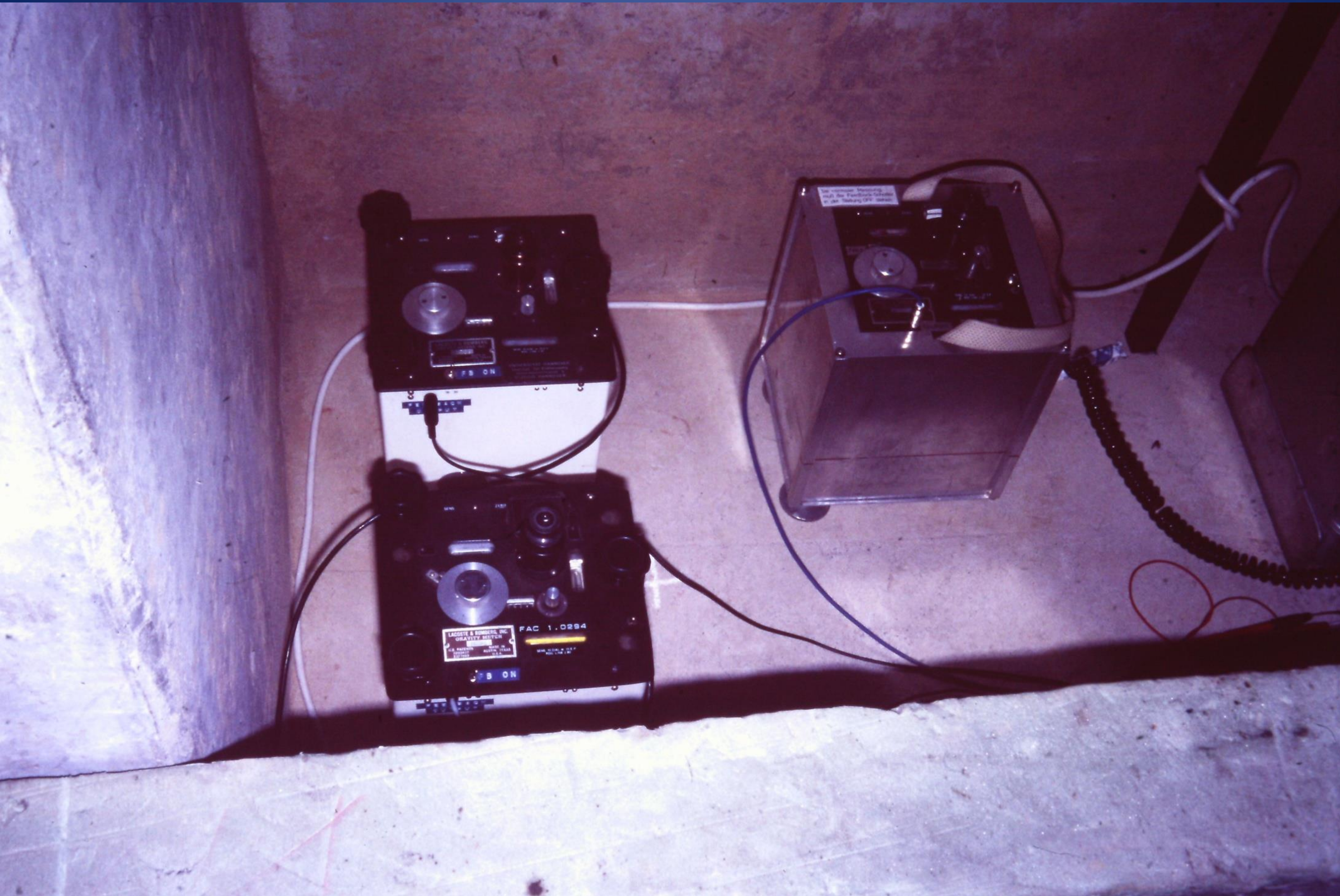
Lake Experiments

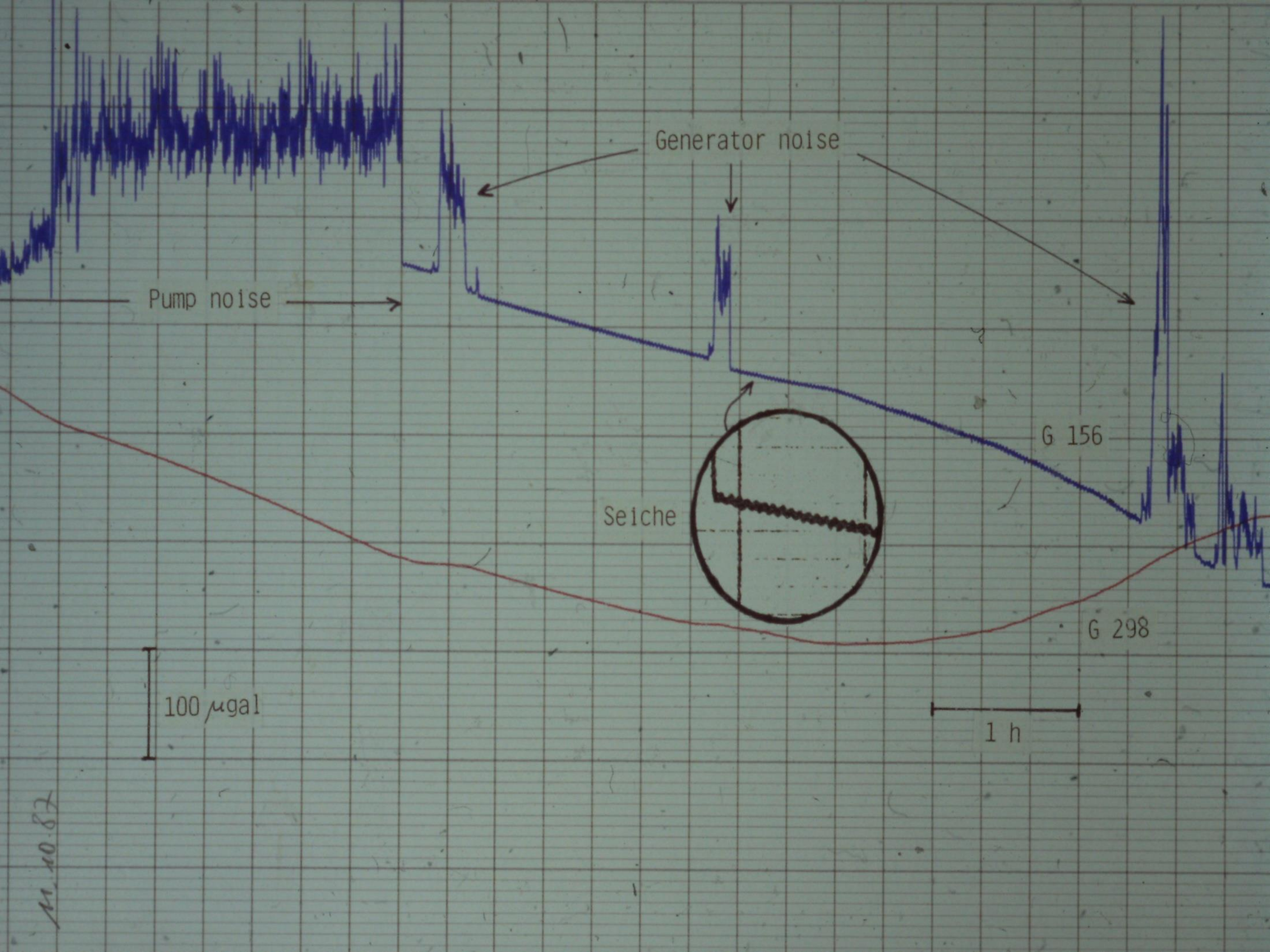
Moore et al. (1988): Phys. Rev. D., 38, 1023-1029
Müller et al. (1989): Phys. Rev. Lett. 63, 2621-2624
Edge & Oldham (1991): Proc. 11th ISET, 415-424
Oldham et al. (1993).: Geophys. J. Int., 113, 83-94
Hubler et al. (1995): Phys. Rev. D. 51, 4005-4016
Achilli et al. (1997): Nuovo Cimento, 112B, 775-804

Hornberg Experiment

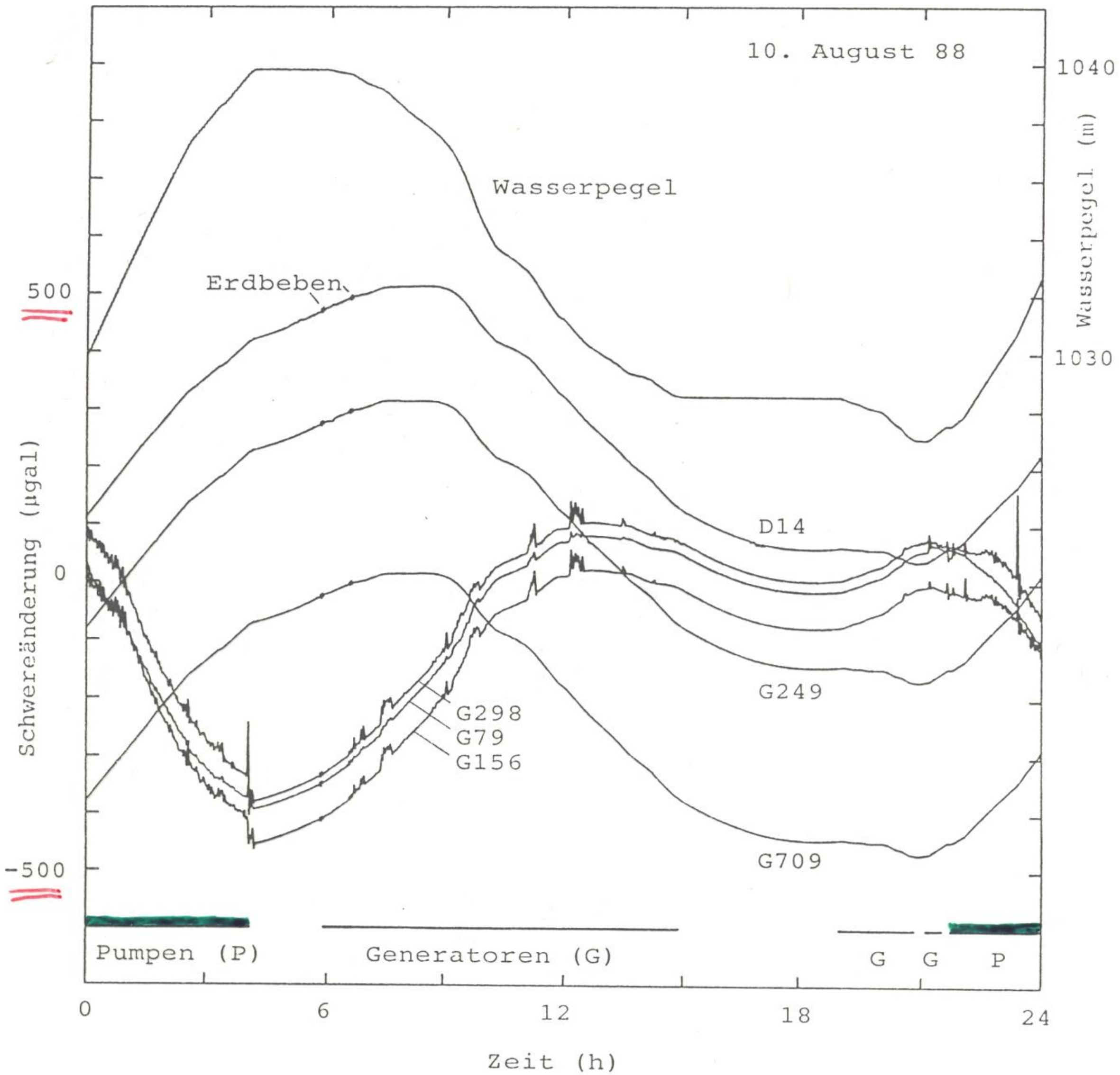
Müller et al. (1989): Phys. Rev. Lett 63, 2621-2624
Müller et al. (1990): Geophys. J. Int. 101, 329 - 344


3 Gravimeter,
Barometer
Türme
1050
Wasser
Damm
Alte Felsoberfläche
Fels
1000
Meereshöhe
(m)
Stollen
168 m
Registrierzentrale,
3 Gravimeter
Wasserpegel
Drainage rate


LACOSTE & ROMBERG, INC.
GRAVITY METER
FAC 1.0294



Generator noise
Pump noise
Seiche
G 156
G 298
100 µgal
1 h
11.10.87



Newtonian water signals ~ 32 µgals/m, ≙ 800 µgals/25 m
($2\pi G\varrho$ ~ 42 ")

Earth tide ~ 230 µgals$_{pp}$

Air pressure effect ~ .42 µgals/mbar

Hornberg: Additional Measurements

besides gravity (2 x 3), water level and air pressure

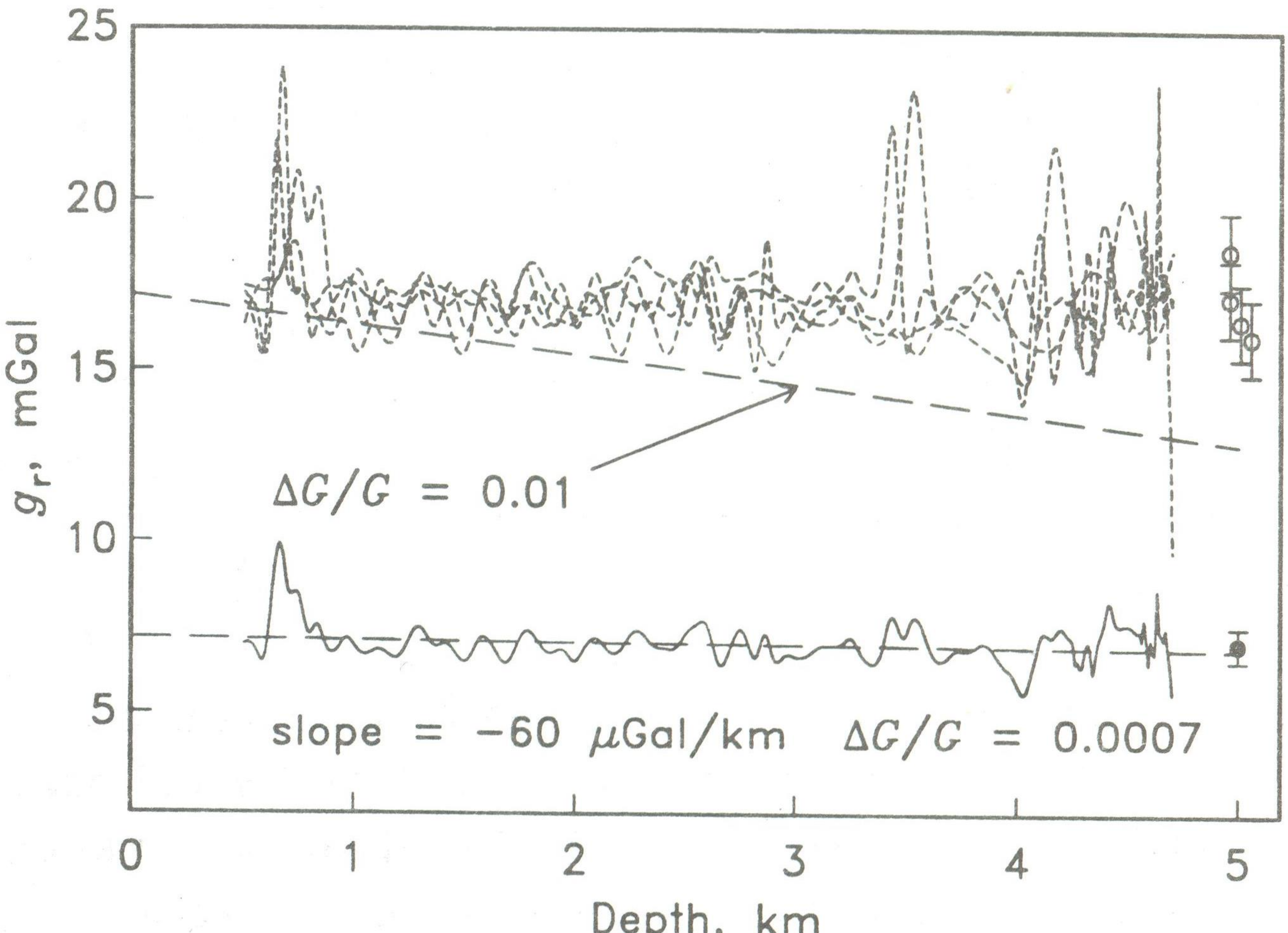
- Calibration of 6 gravimeters on Hannover vertical line before and after experiment 1)
- Relative calibration of gravimeters in vicinity of lake
- Calibration of water pressure transducer with water tube in the elevator shaft 2)
- Comparison of all voltmeters involved
- Calibration of all transfer functions
- Check of all coordinates by geodetic methods
- Fine leveling in adit tunnel at two extreme water levels (loading) 3)
- Seismic measurements to locate vibration minima on top of tower
- Selection of least vibration sensitive gravimeters for upper station
- Vertical temperature profile in the lake at different times
- Water samples at different depths and density measurements
- Inspection of drainage rate monitors
- Recording of lake oscillation amplitudes (seiches)
- Seiche period as function of lake level by high-speed analog recording

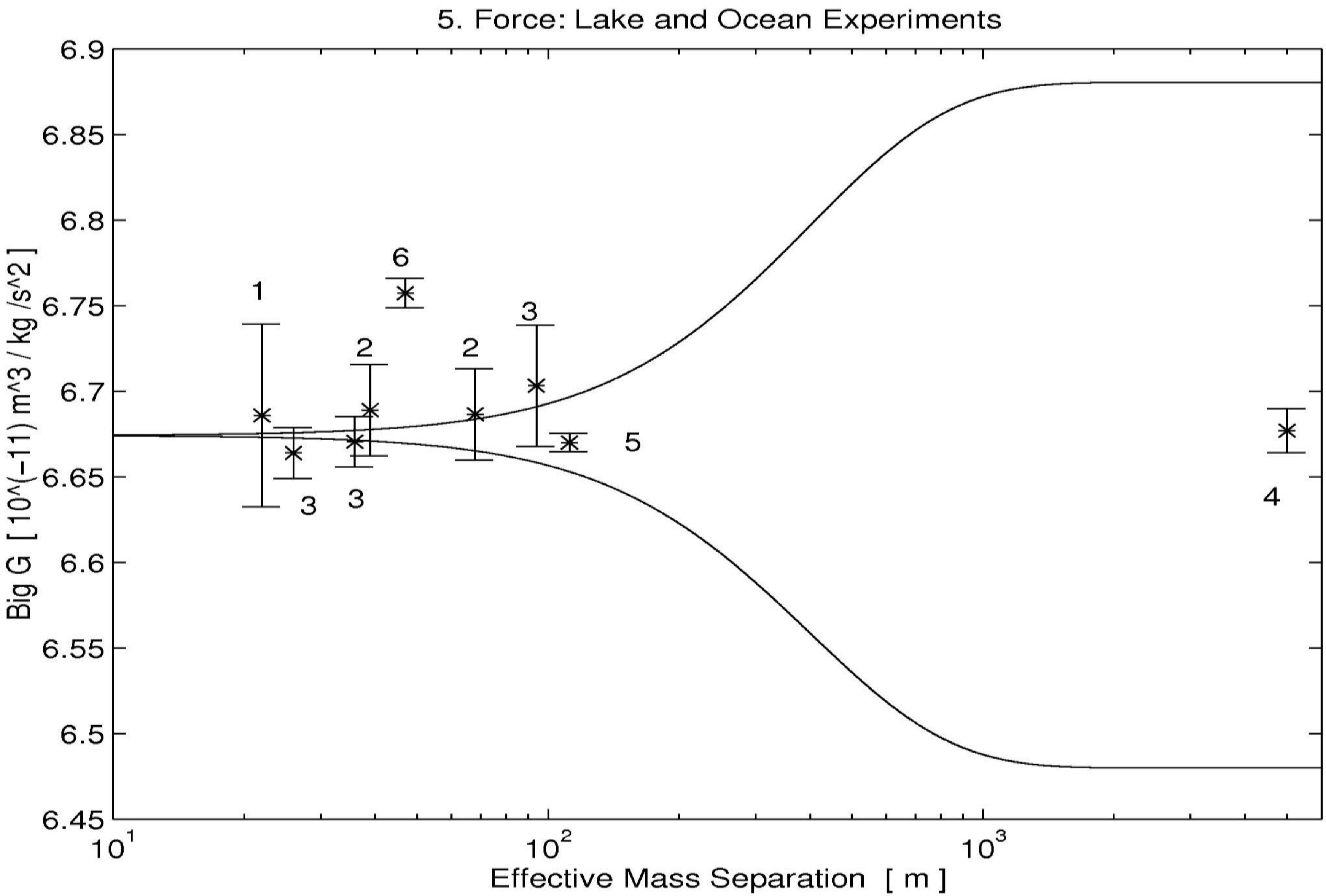
1) $\leq 0.16\,\%$
2) $\sigma = .74$ cm
3) $\Delta q \leq 1$ mm

Ocean Experiment

Zumberge et al. (1991): Submarine Measurement of the Newtonian Gravitational Constant

Phys. Rev. Lett. 67, 22, 3051 – 3054


25
20
15
10
5
g_r, mGal
ΔG/G = 0.01
slope = −60 μGal/km ΔG/G = 0.0007
0
1
2
3
4
5
Depth, km



5. Force: Lake and Ocean Experiments
Big G [10^(−11) m^3 / kg /s^2]
6.9
6.85
6.8
6.75
6.7
6.65
6.6
6.55
6.5
6.45
10^1
10^2
10^3
Effective Mass Separation [m]
1
2
2
3
3
3
4
5
6

Tower Experiments

AFGL - 600 m high!

first positive, claiming fifth and even sixth force, later corrected to negative

BREN tower - 465 m

Erie tower – 300 m

Mines and Boreholes

Hilton mine, Australia

Dye 3, Greenland

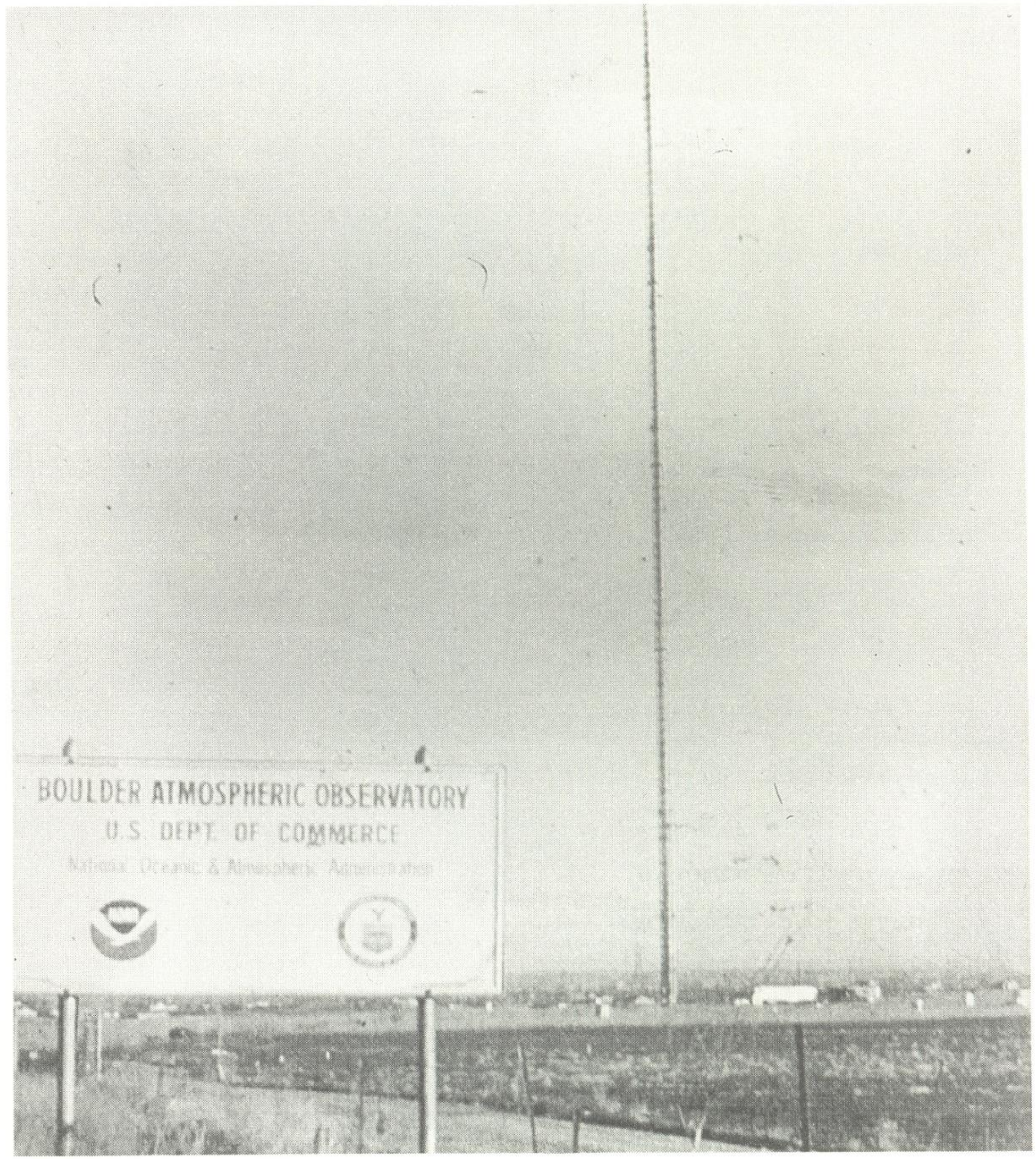
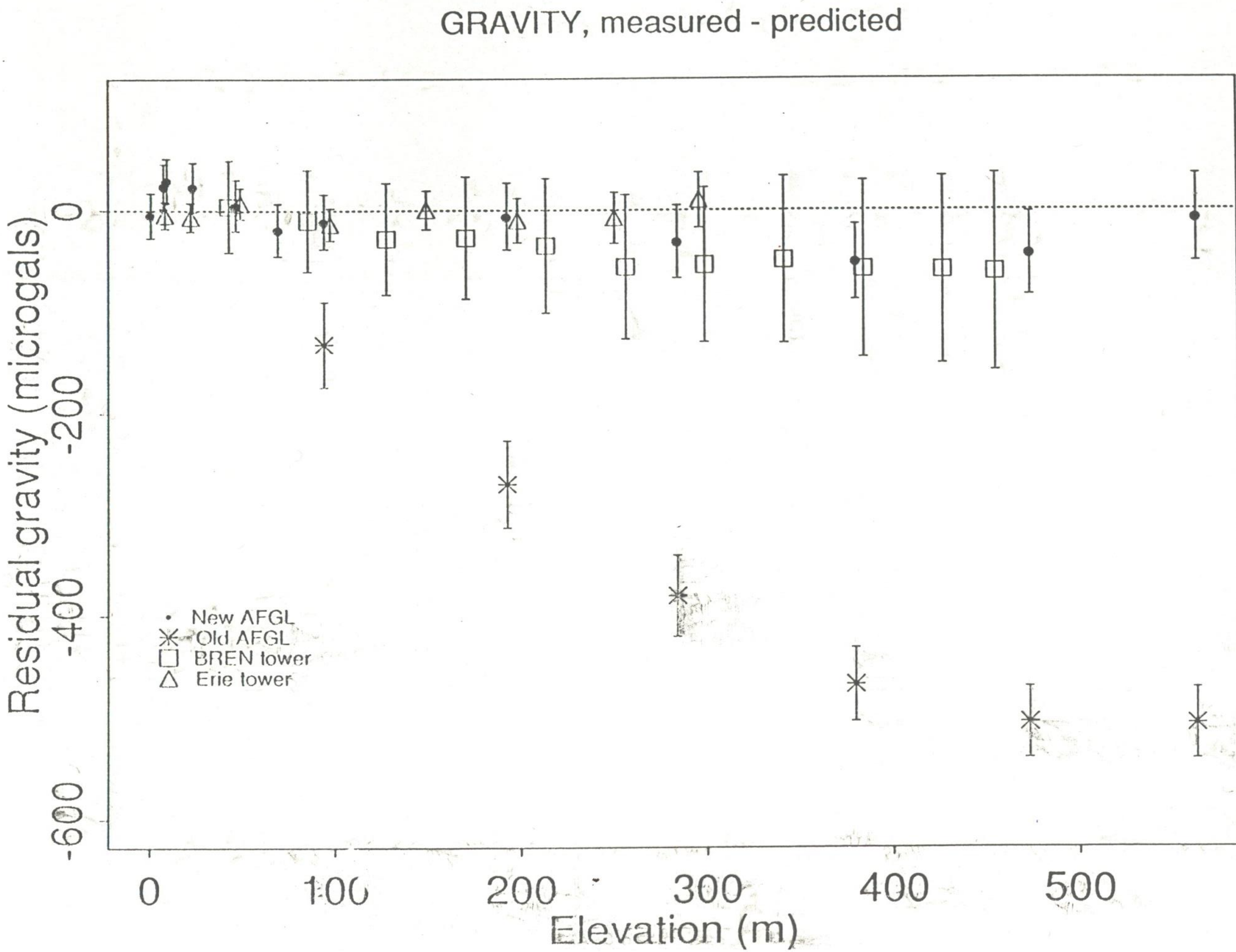


FIGURE 41. The 300 m tower in Erie, Colorado used by Speake *et al.* [1990a,b] for their gravity measurements. Courtesy of Jim Faller.

… and there are psychological disadvantages to making measurements in the dark on small elevated platforms. …


GRAVITY, measured - predicted
Residual gravity (microgals)
0
-200
-400
-600
Elevation (m)
0
100
200
300
400
500
New AFGL
Old AFGL
BREN tower
Erie tower

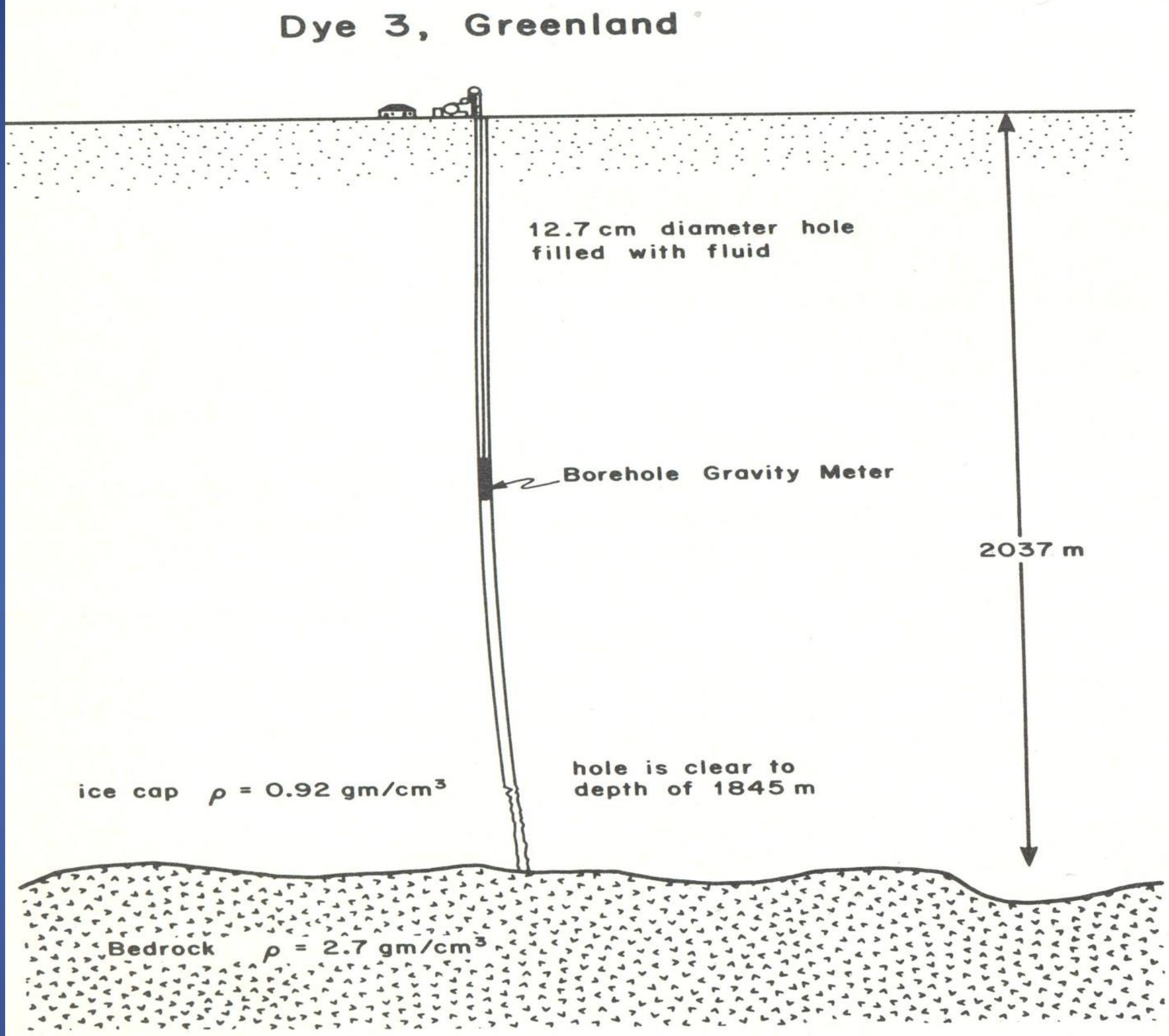


Fig. 2. Cross section of the ice sheet. The borehole is filled with a mixture of perchlorethylene and diesel fuel to prevent its closure. At the depth corresponding to the Holocene-Wisconsin boundary, a mechanical discontinuity occurs and results in deformation of the borehole. In the upper 100 m the snow gradually is compressed into firn and then ice containing trapped air bubbles.

Summary of 5th-Force Tests

1) All negative within confidence limits, except
   3 unexplained : Thieberger, Boynton & Achilli
2) At submillimeter scale we don‘t know
3) Experiments were very useful because they
   explored an unexplored regime .... and
4) They triggered new interest in Big G

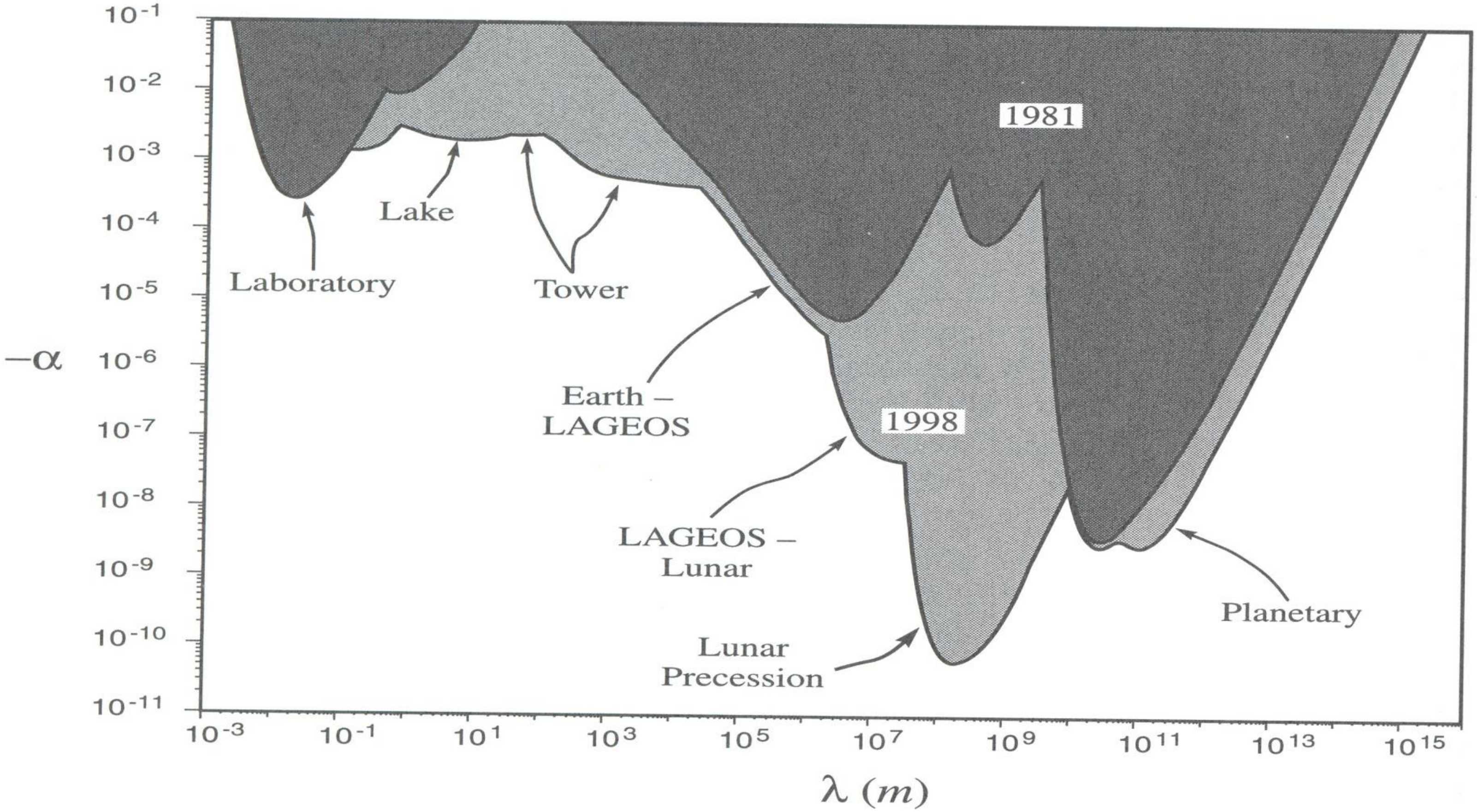


Figure 2.13: Constraints on the coupling constant α as a function of the range λ from composition-independent experiments. The dark shaded area indicates the status as of 1981, and the lighter region gives the current limits. Note that only the most sensitive results are exhibited in each regime in λ, and that all limits are quoted at the 2σ level. For references to the earlier experiments which contribute to the curves, see [TALMADGE, 1988] and [DERUJULA, 1986].

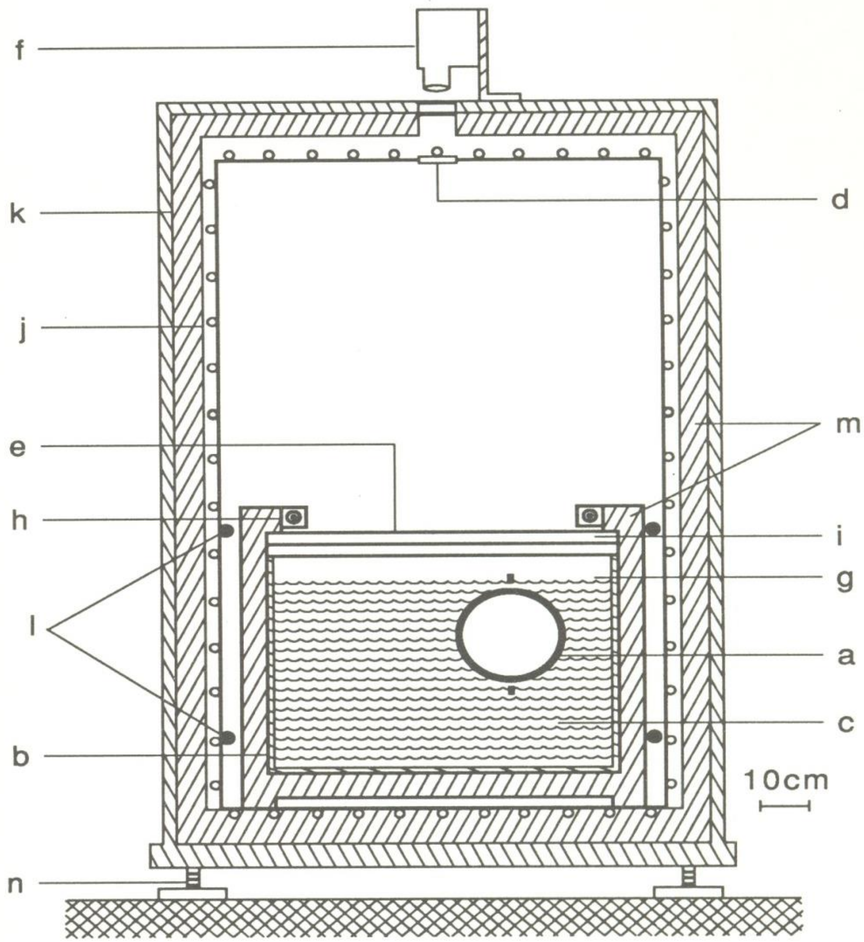
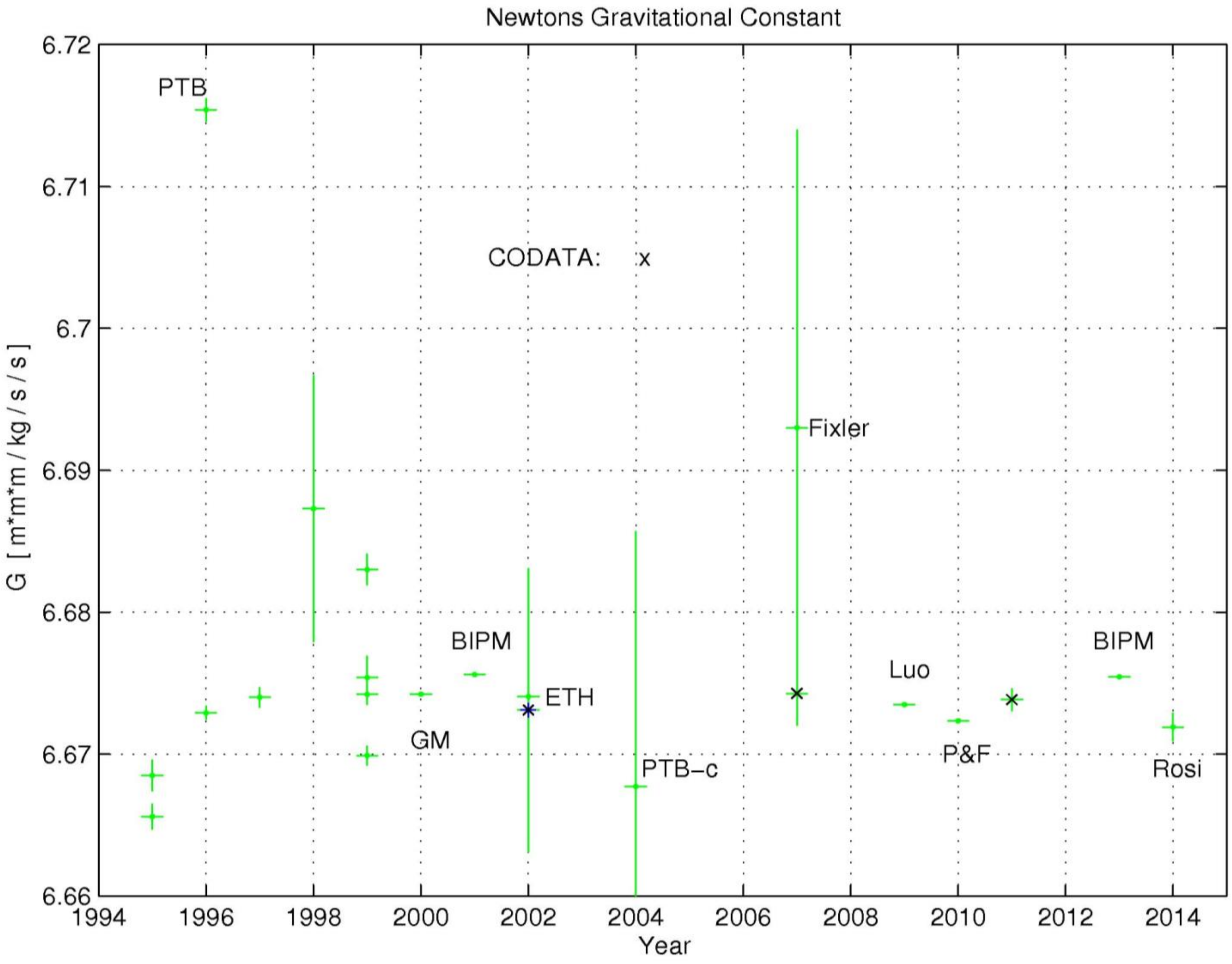
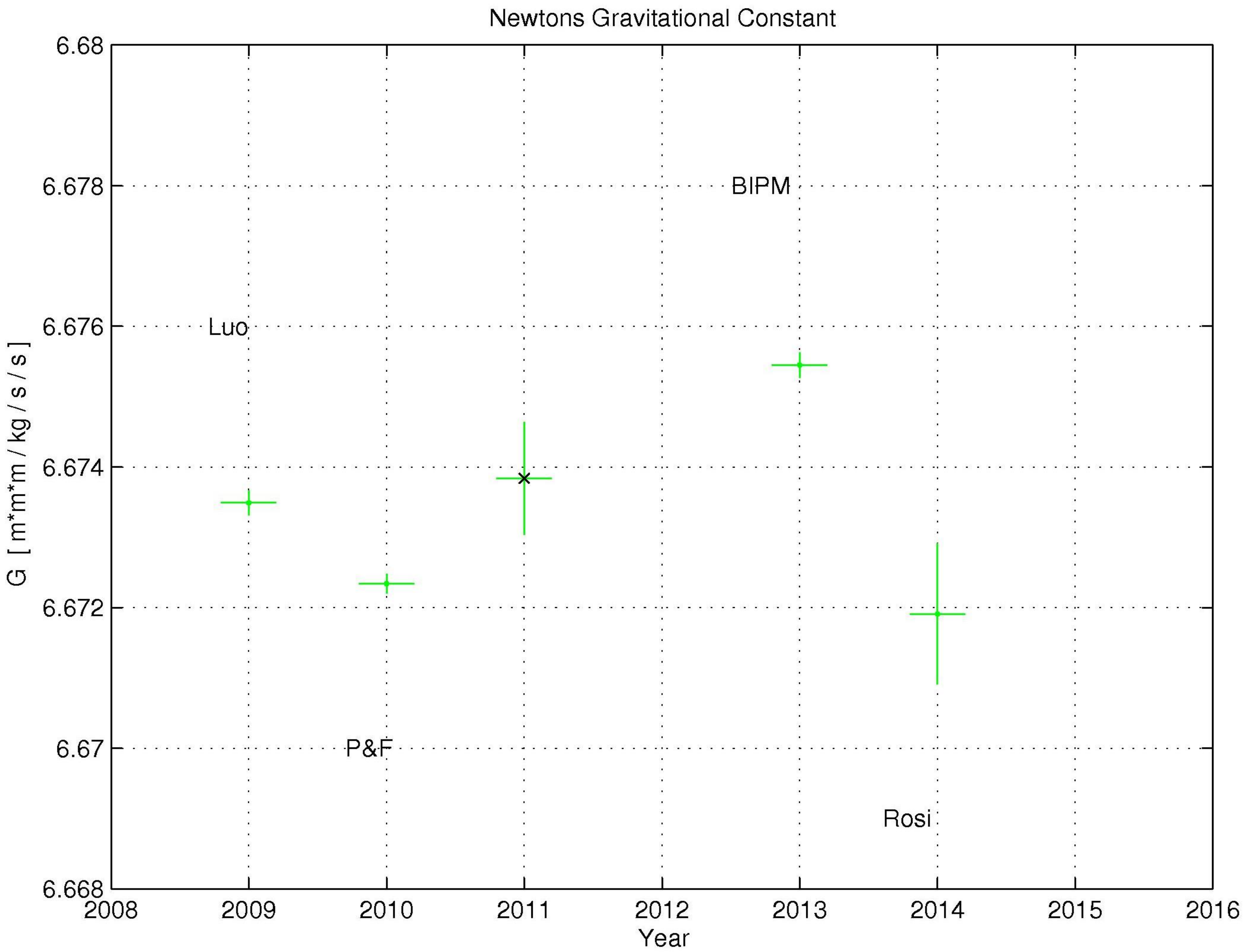


FIGURE 15. Schematic diagram of the differential accelerometer used in Thieberger's experiment. A precisely balanced hollow copper sphere (a) floats in a copper-lined tank (b) filled with distilled water (c). The sphere can be viewed through windows (d) and (e) by means of a television camera (f). The multiple-pane window (e) is provided with a transparent *x-y* coordinate grid for position determination on top with a fine copper mesh (g) on the bottom. The sphere is illuminated for 1 s per hour by four lamps (h) provided with infrared filters (i). Constant temperature is maintained by means of a thermostatically controlled copper shield (j) surrounded by a wooden box lined with Styrofoam insulation (m). The Mumetal shield (k) reduces possible effects due to magnetic field gradients and four circular coils (l) are used for positioning the sphere through forces due to ac-produced eddy currents, and for dc tests. From Thieberger [1987a].

Big

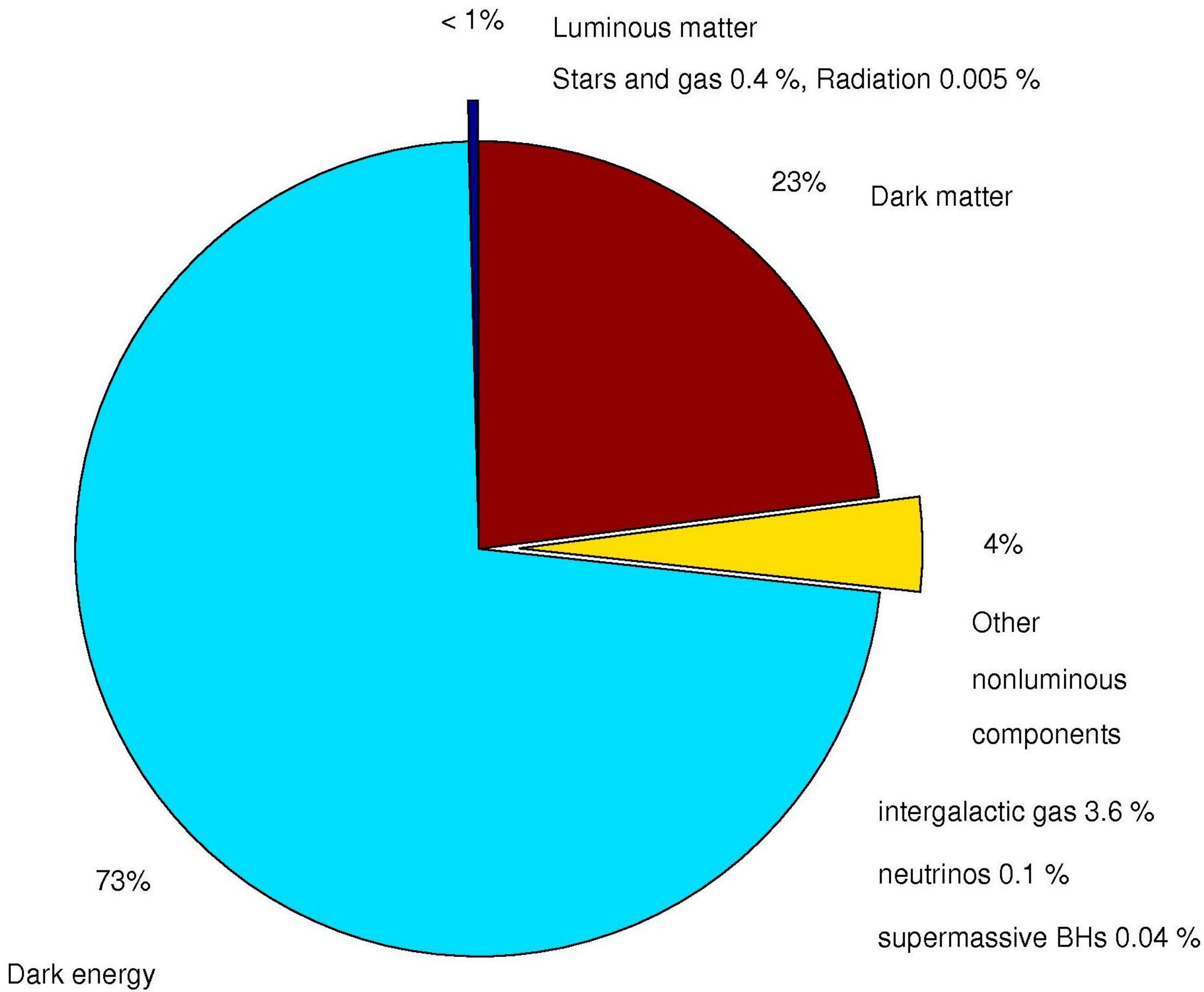
G


Newtons Gravitational Constant
G [m*m*m / kg / s / s]
Year
6.72
6.71
6.7
6.69
6.68
6.67
6.66
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
PTB
CODATA: x
Fixler
BIPM
ETH
GM
PTB−c
Luo
P&F
BIPM
Rosi


Newtons Gravitational Constant
6.68
6.678
6.676
6.674
6.672
6.67
6.668
G [m*m*m / kg / s / s]
2008
2009
2010
2011
2012
2013
2014
2015
2016
Year
Luo
P&F
BIPM
Rosi

Trouble with Big G

Accuracy and Consistency of Determinations?
< 1 mm? (Rolled-up additional dimensions?)
What makes up Cold Dark Matter?
What is Dark Energy?
Pioneer anomaly?
Planetary flyby anomalies?


< 1%
Luminous matter
Stars and gas 0.4 %, Radiation 0.005 %
23%
Dark matter
4%
Other
nonluminous
components
intergalactic gas 3.6 %
neutrinos 0.1 %
supermassive BHs 0.04 %
73%
Dark energy

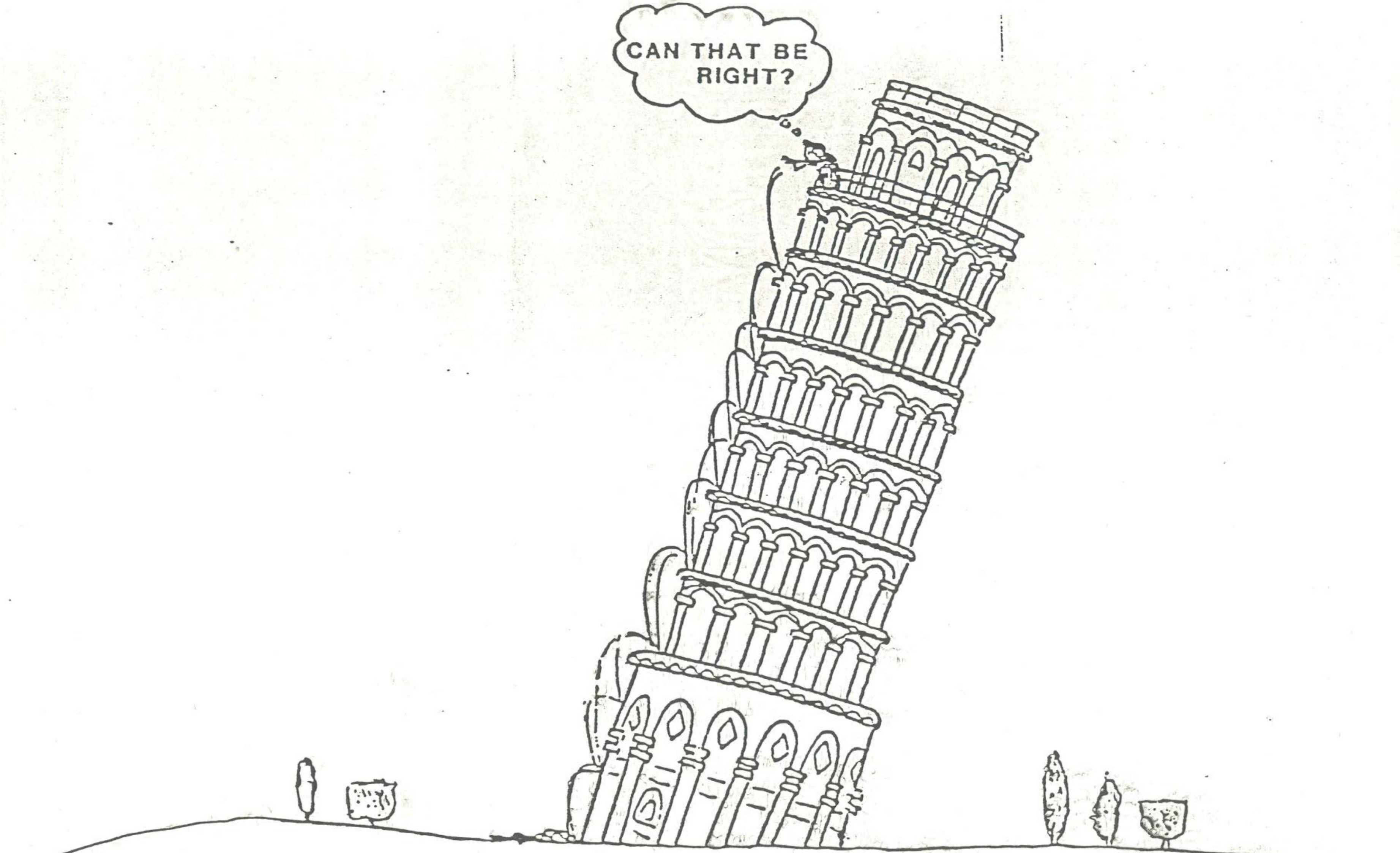
The dark side

..... **DARK ENERGY** has now been added to the already perplexing question of **DARK MATTER**. One is tempted to speculate that these ingredients are add-ons, like the Ptolemaic epicycles, to preserve an incomplete theory.......

Saul Perlmutter, Physics Today, April 2003, p. 59

Cartoons and Jokes

Yes, there is a remote possibility that gravity has changed, but maybe we have to look for other explanations, too.



Early evidence for anomalous gravity

Eckardt

Dear Abby:

..... I have a problem. I have two brothers, one who is a scientist doing research on the Fifth Force and another who is sentenced to death in the electric chair for a series of homosexual rapes and murders. My mother died from insanity when I was three years old. She had syphilis and I think I caught it from her. My two sisters are prostitutes, and my father is now selling pornography and kinky sexual paraphernalia following his bust for retailing narcotics. Recently I met a young girl who had just been released from an institution for the criminally insane where she had served time for smothering her illegitimate child. I love this girl very much and I want to marry her. She loves me too, even though I have AIDS.

My problem is this: should I tell her about my brother who is working on the Fifth Force?

Yours truly,
Bewildered

(Letter dated March 7, 1990 circulated in the community)

Sincere thanks go to the following people:

Gerhard Müller (+)
Heinz Otto
Walter Großmann
Klaus Lindner
Norbert Rösch
Manfred Schnüll (+)
Hans-Georg Wenzel (+)
Hans Schmidt
Gerhard Pfeifer
Peter Varga


TRANSPORTER

Thank you for your attention

Interaction	Particle	Mass	Range
		kg	m
Electromagnetism	Photon	0	∞
Strong force	Gluons	$3.51\cdot10^{-29}$ (?)	$\approx 10^{-14}$
Weak force	W,Z - Bosons	$\approx 1.5\cdot10^{-25}$	$\approx 2.3\cdot10^{-18}$
Gravitation	Graviton	0	∞
Higgs-Field	Higgs - Boson	$\approx 2.25\cdot10^{-25}$	$\approx 1.5\cdot10^{-18}$
5.Force	???	$1.76\cdot10^{-45}$	200

Standard model of elementary particle interactions

5. Force:

- Violation of inverse-square law - range dependence of Big G
- Weak material dependence of Big G (coupling to baryon number, isospin ...)

Yukawa potential:

Uncertainty principle: $\Delta t = \frac{\hbar}{m_0\cdot c^2}$

Uncertainty of energy: $\Delta E = m_0\cdot c^2$

Uncertainty of distance (=range): $\Delta x = \lambda = c\cdot\Delta t$

Range of force: $\lambda = \frac{\hbar}{m_0\cdot c}$

Fishbach et al., Phys. Rev. Letters 56, 1, 1985, 3-6

Reanalysis of Eötvös-Experiment

Material-dependence

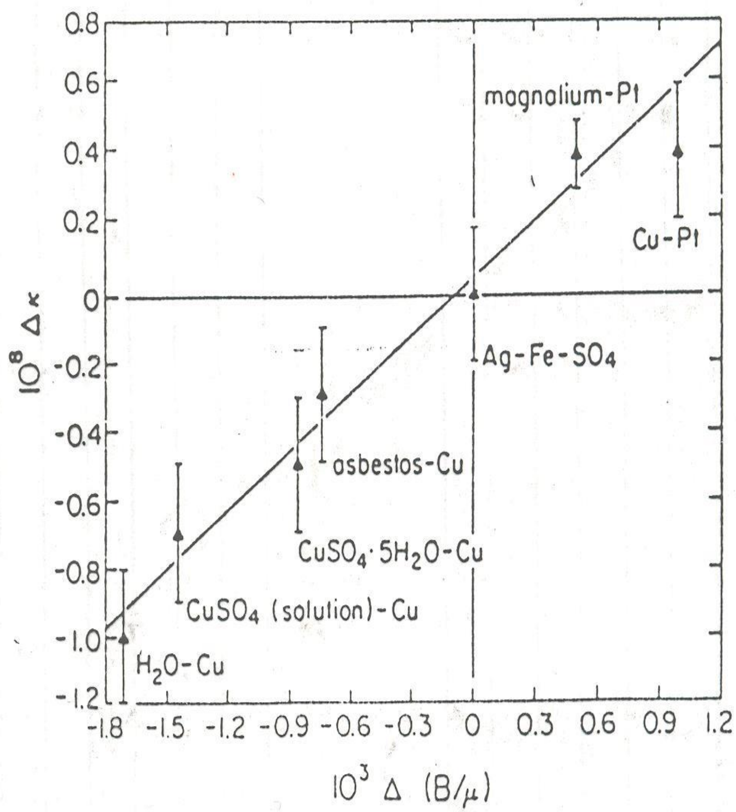
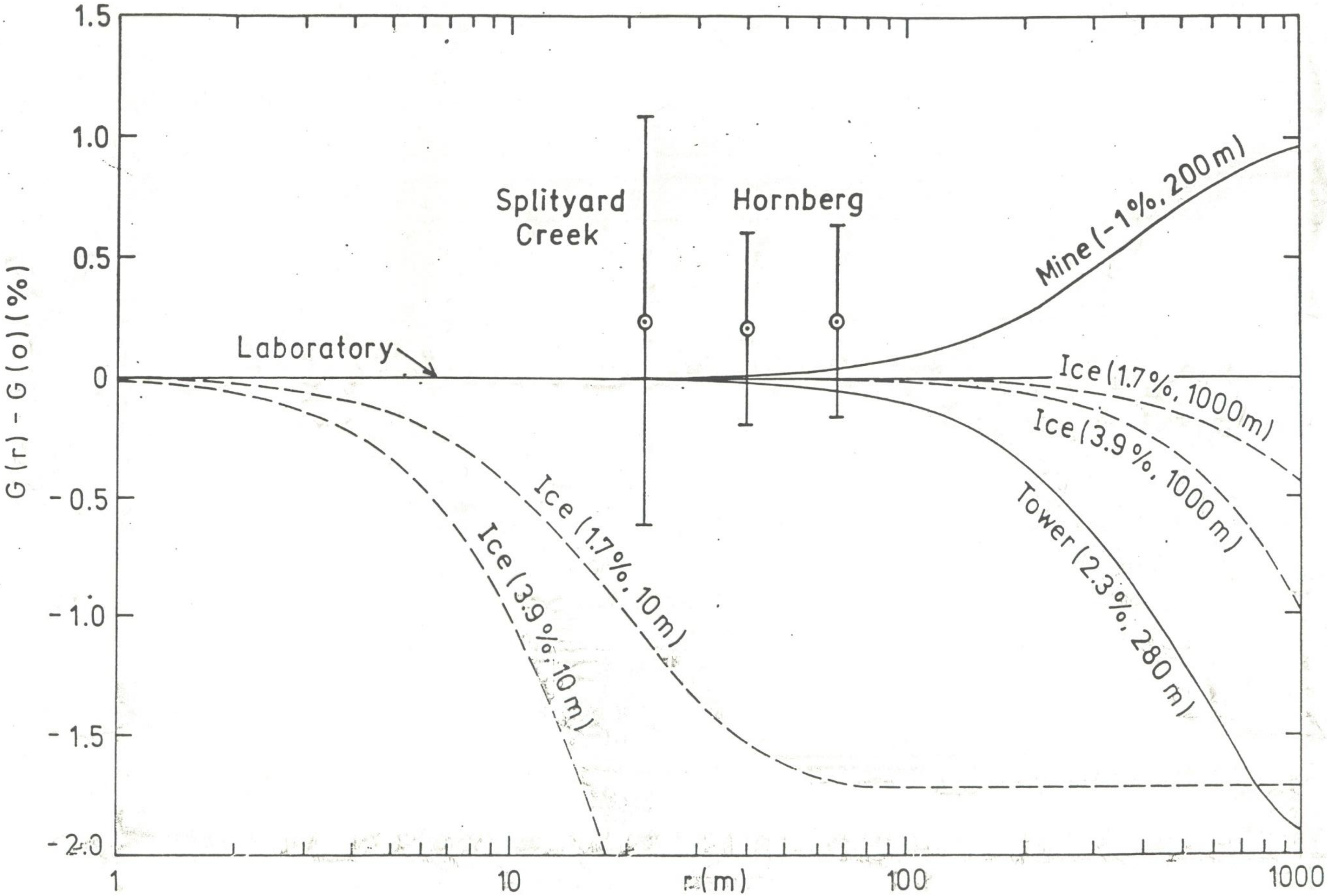
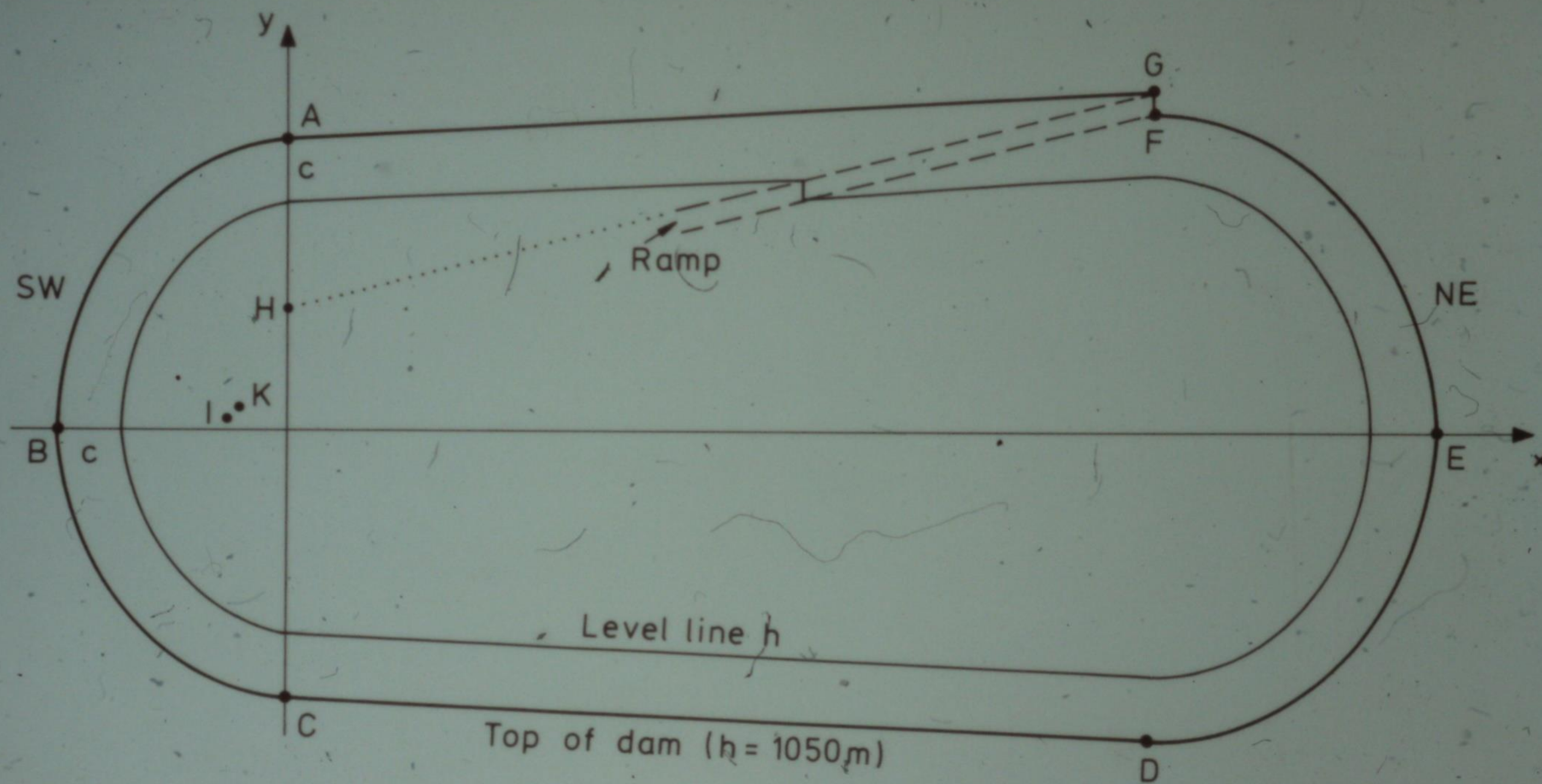


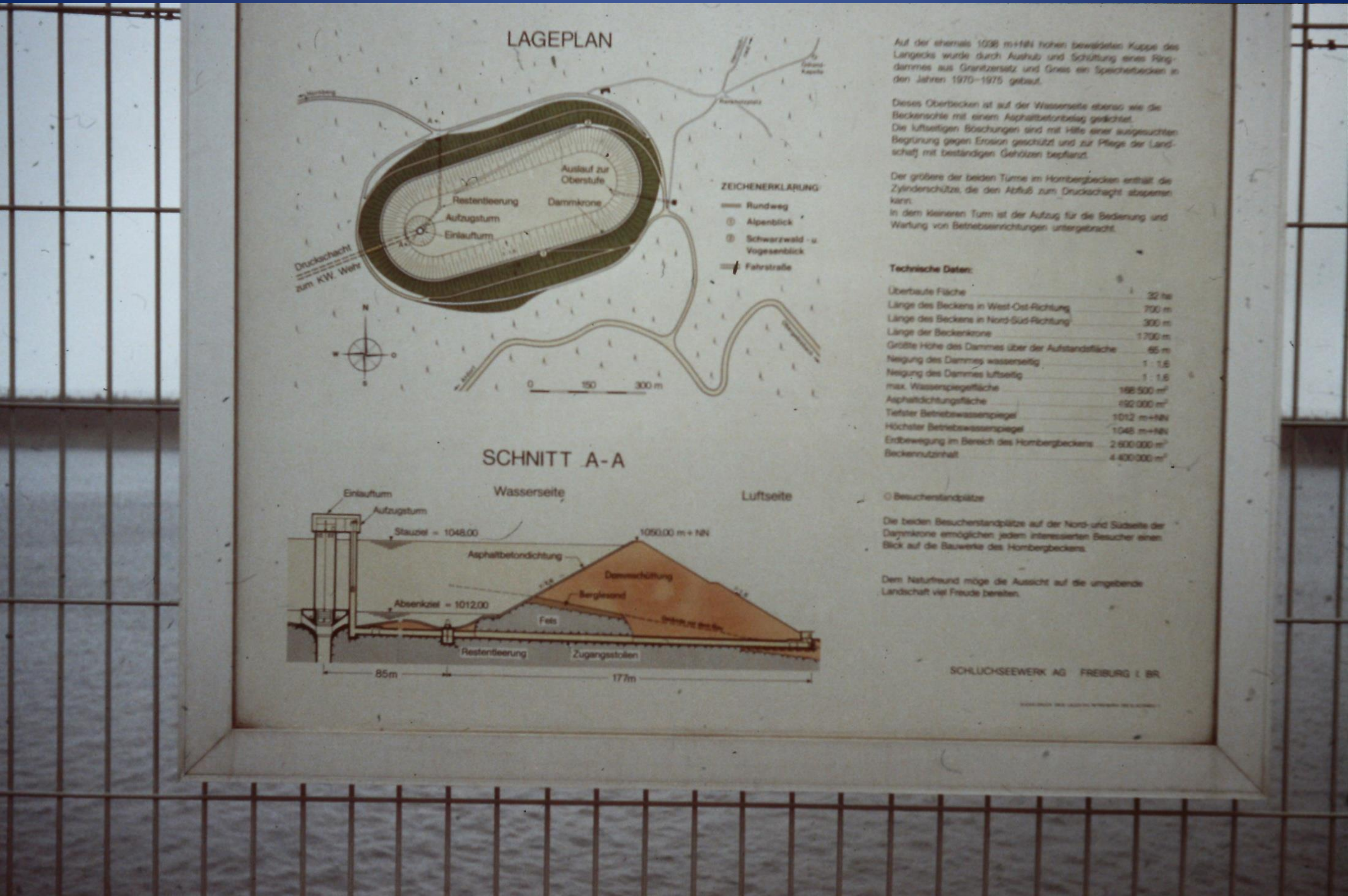
FIG. 1. Plot of $\Delta\kappa$ vs $\Delta(B/\mu)$ using the data in Table I. Ag-Fe-SO_4 refers to the reactants before and after the chemical reaction described by Eq. (7). The solid line represents the results of a least-squares fit to the data.


1.5
1.0
0.5
0
- 0.5
- 1.0
- 1.5
- 2.0
G (r) - G (o) (%)
1
10
100
1000
r (m)
Splityard
Creek
Hornberg
Laboratory
Mine (-1%, 200 m)
Ice (1.7%, 1000 m)
Ice (3.9%, 1000 m)
Tower (2.3%, 280 m)
Ice (1.7%, 10 m)
Ice (3.9%, 10 m)



I, K = tower axes

$\overline{BE} = 693.2$ m $\overline{AC} = 265.0$ m $c = 1.6\,(1050 - h)$ m


LAGEPLAN
Auslauf zur Oberstufe
Restentleerung
Dammkrone
Aufzugsturm
Einlaufturm
Druckschacht zum KW. Wehr
ZEICHENERKLÄRUNG
Rundweg
Alpenblick
Schwarzwald - u Vogesenblick
Fahrstraße
N
W
O
S
0
150
300 m
Auf der ehemals 1098 m+NN hohen bewaldeten Kuppe des Langecks wurde durch Aushub und Schüttung eines Ringdammes aus Granitzersatz und Gneis ein Speicherbecken in den Jahren 1970–1975 gebaut.
Dieses Oberbecken ist auf der Wasserseite ebenso wie die Beckensohle mit einem Asphaltbetonbelag gedichtet.
Die luftseitigen Böschungen sind mit Hilfe einer ausgesuchten Begrünung gegen Erosion geschützt und zur Pflege der Landschaft mit beständigen Gehölzen bepflanzt.
Der größere der beiden Türme im Hornbergbecken enthält die Zylinderschütze, die den Abfluß zum Druckschacht absperren kann.
In dem kleineren Turm ist der Aufzug für die Bedienung und Wartung von Betriebseinrichtungen untergebracht.
Technische Daten:
Überbaute Fläche 32 ha
Länge des Beckens in West-Ost-Richtung 700 m
Länge des Beckens in Nord-Süd-Richtung 300 m
Länge der Beckenkrone 1700 m
Größte Höhe des Dammes über der Aufstandsfläche 65 m
Neigung des Dammes wasserseitig 1 : 1,6
Neigung des Dammes luftseitig 1 : 1,6
max. Wasserspiegelfläche 198 500 m²
Asphaltdichtungsfläche 192 000 m²
Tiefster Betriebswasserspiegel 1012 m+NN
Höchster Betriebswasserspiegel 1048 m+NN
Erdbewegung im Bereich des Hornbergbeckens 2 600 000 m³
Beckennutzinhalt 4 400 000 m³
SCHNITT A-A
Wasserseite
Luftseite
Einlaufturm
Aufzugsturm
Stauziel = 1048,00
1050,00 m + NN
Asphaltbetondichtung
Dammschüttung
Berglesand
Absenkziel = 1012,00
Fels
Restentleerung
Zugangsstollen
85m
177m
○ Besucherstandplätze
Die beiden Besucherstandplätze auf der Nord- und Südseite der Dammkrone ermöglichen jedem interessierten Besucher einen Blick auf die Bauwerke des Hornbergbeckens.
Dem Naturfreund möge die Aussicht auf die umgebende Landschaft viel Freude bereiten.
SCHLUCHSEEWERK AG FREIBURG I. BR.

Data Analysis:

1, Subtract known signals from each gravimeter record to form residuals $r(t)$:

$$r_i(t) = g_i(t) - g_{N_i}(t) - t_E(t) - g_P(t)$$

$r_i(t)$ = residuals of instrument # i (i=1,6)

$g_i(t)$ = observed gravity for instrument # i

$g_{N_i}(t)$ = $g_{N_i}(x_i, y_i, z_i, s)$

  x_i, y_i, z_i - coordinates of gravimeter

  $s(t)$ - water level

computed Newtonian gravity for # i

$t_E(t)$ = model for earth tides constructed from 2 years of observations at BFO (Schiltach), ca 100 km away

$g_P(t)$ = approximation for gravity changes due to atmospheric pressure variations

= $0.42 * p(t)$ (0.42 μgals/mbar)

2, Least squares fit to residual signals of following model

$$r_i(t) = E_i \cdot g_{N_i}(t) + D_i \cdot t_E(t) + \sum_{j=0}^{K} a_j t^j$$

$$K \leq 8$$

$E_i \neq 0$	:	non-newtonian gravity	E_i = const (i)
		calibration errors	$E_i \neq$ const (i)
		both	
$D_i \neq 0$	:	calibration errors	$D_i \neq$ const (i)
		tidal model wrong	D_i = const (i)
		both	

Table 5

Results of regression analysis of residual signals

Gravimeter(s)	Amplitude of residual tides (D,%)	Amplitude of residual tides (μgal)*	Amplitude of residual water signal (E,%)	Amplitude of residual water signal (μgal)*	Variance reduction (%)	Variance reduction due to
G249	0.39	0.22	0.57	1.07	66	E
G709	0.46	0.26	0.15	0.28	19	E,D
D14	0.54**	0.30	0.03**	0.06	9	D
G79	-0.84	0.47	0.04	0.09	9	D
G156	0.28	0.16	0.25	0.54	15	E
G298	1.16	0.65	0.36	0.77	27	E,D
G249-G156	0.70	0.39	0.30	1.21	60	E
G249-G298	-0.21	0.12	0.35	1.42	53	E
G709-G156	0.35	0.19	0.09	0.36	10	E
G709-G298	-0.53	0.30	0.14	0.57	14	E

* Standard deviation

** Average (see Fig. 13)

$E_{BOTTOM} = (0.25 \pm 0.4)\%$ $\bar{r} = 68$ m

$E_{TOP} = (0.21 \pm 0.4)\%$ $\bar{r} = 39$ m

Correlation between tide and water signal small k = .38

Hornberg II (1988) - Results

Residual water signals

Gravimeter LCR #	Amplitude %	Variance reduction %	Site
G 709	0.15	10	
G 249	0.57	41	below water
D 014	0.03	6	
G 156	0.25	8	
G 298	0.36	14	above water
G 079	0.04	5	

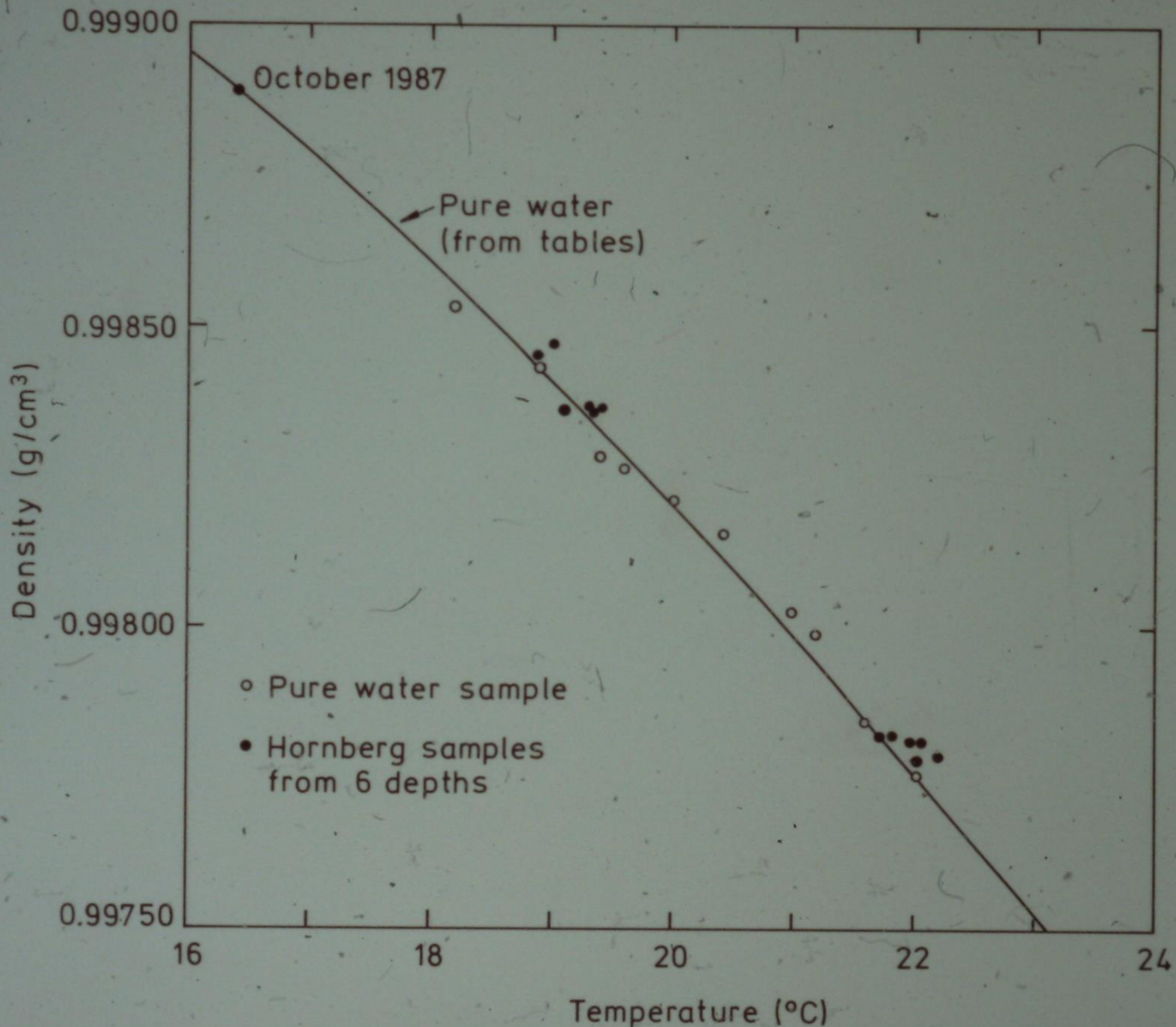
Detection limit of gravimeters determined by calibration uncertainties

- relative errors ca. 0.3 %
- absolute error from Hannover vertical line ca. 0.1 %

Residual tides

- orthogonal to mdel used
- do not correlate much with water signal

No clear evidence for Non-Newtonian gravity



0.99900
0.99850
0.99800
0.99750
Density (g/cm³)
October 1987
Pure water
(from tables)
Pure water sample
Hornberg samples
from 6 depths
16
18
20
22
24
Temperature (°C)

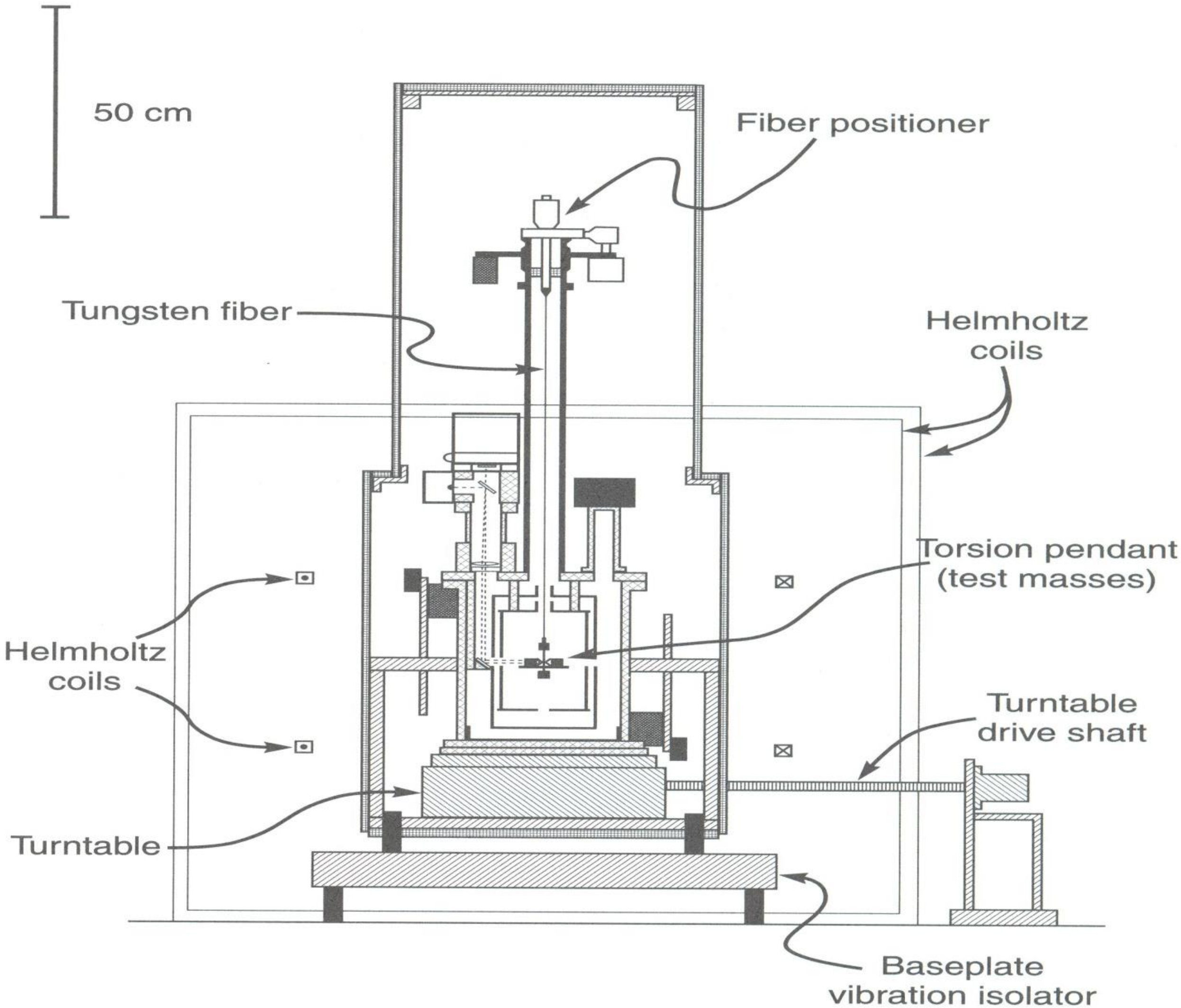


Figure 4.9: Diagram of the Eöt-Wash torsion balance of Adelberger et al. adapted from [ADELBERGER, 1990]. The experimental site is the Nuclear Physics Laboratory, located on a hillside at the University of Washington in Seattle.

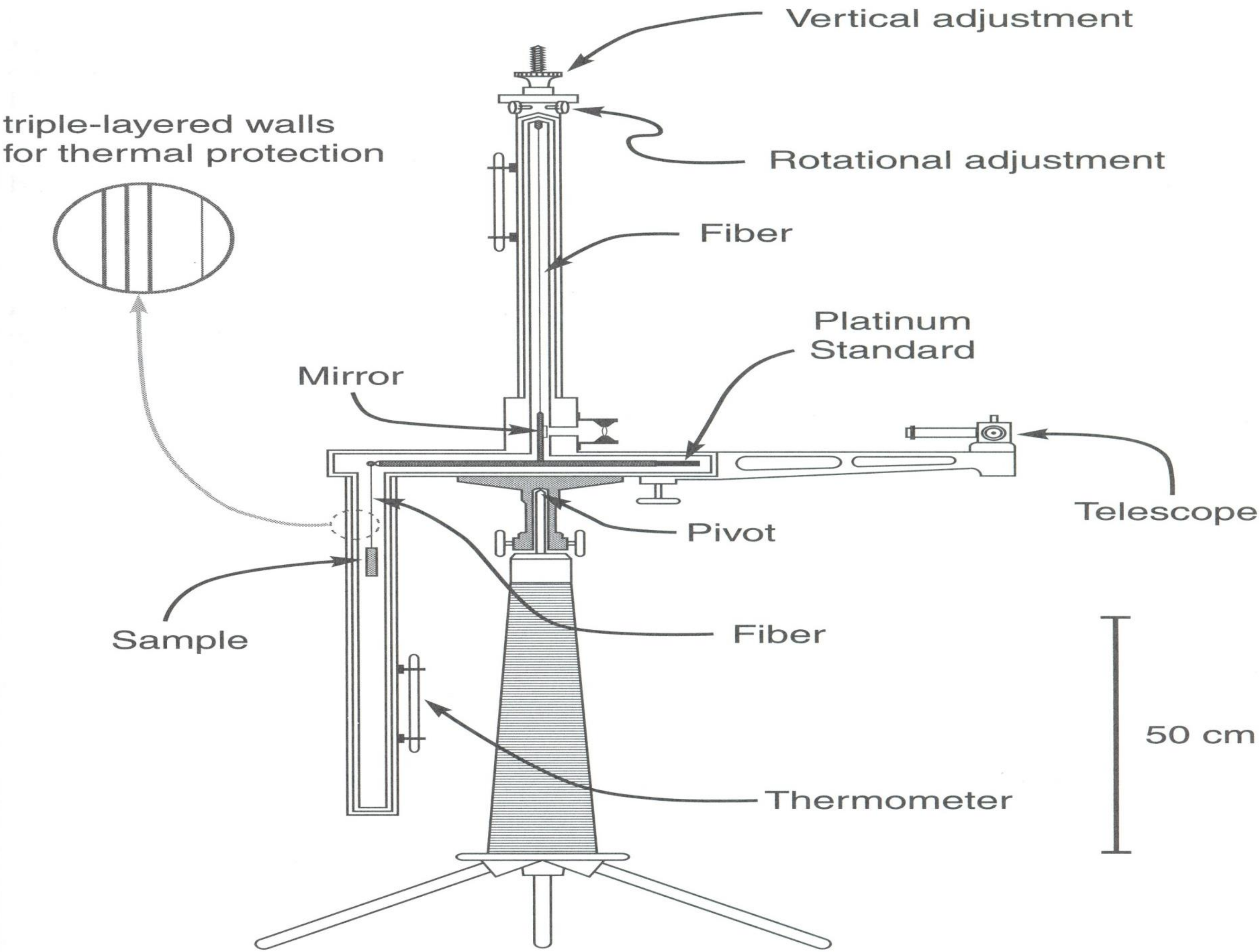


Figure 4.6: Single-arm torsion balance used by Eötvös, Pekár, and Fekete.

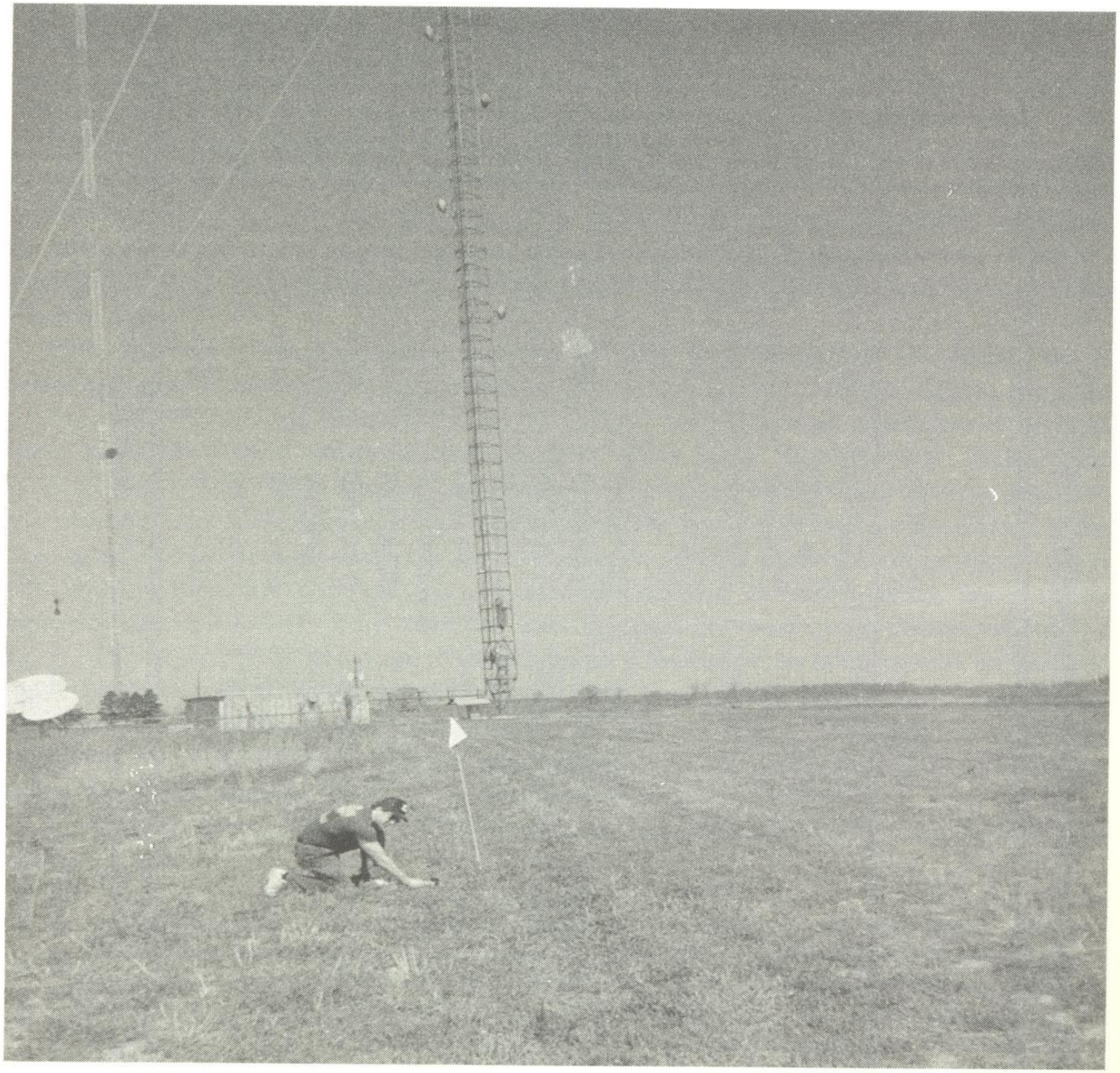


FIGURE 43. Carrick Talmadge positioning an antenna for the Global Positioning Satellite as part of a current tower gravity experiment, which also includes Eckhardt and Fischbach. Note the flatness of the terrain. Courtesy of Ephraim Fischbach.

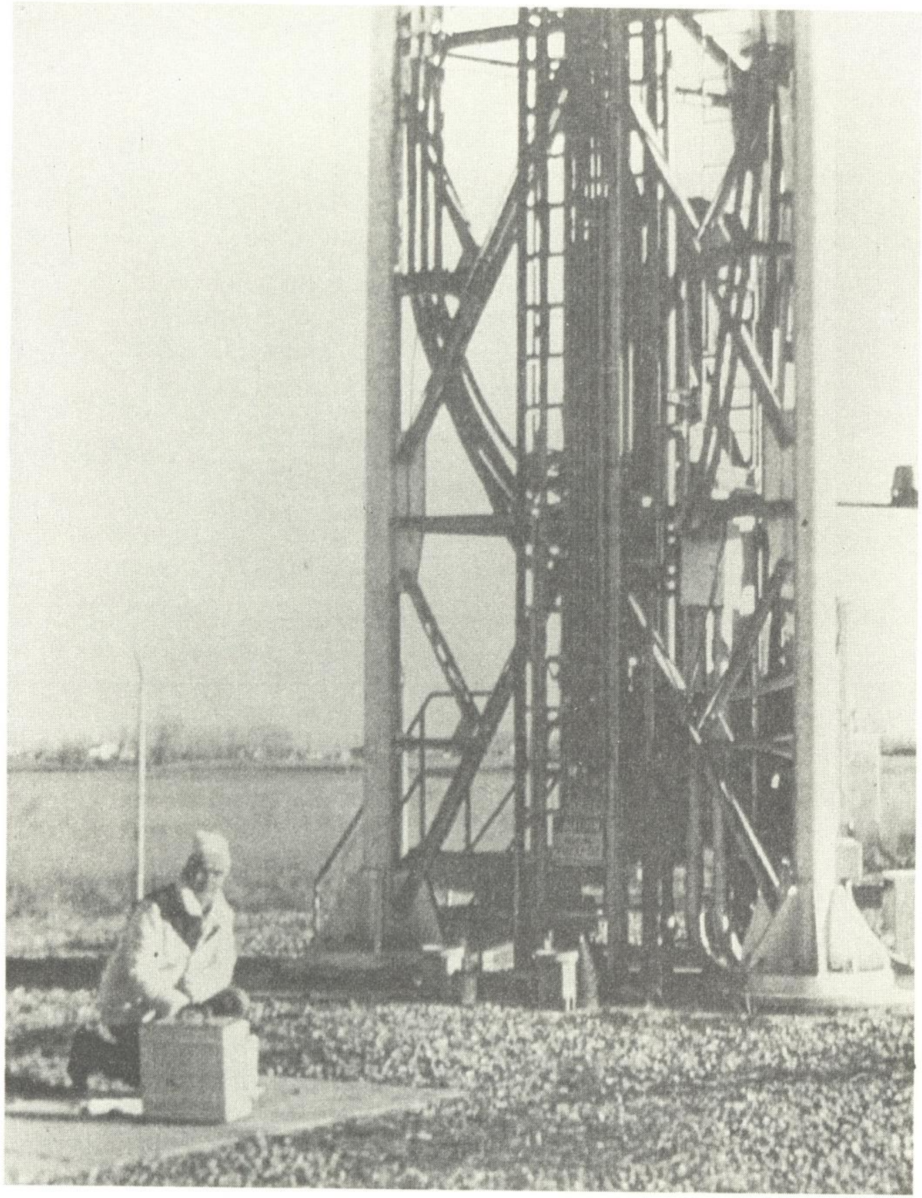


FIGURE 42. Clive Speake and a LaCoste-Romberg gravimeter at the base of the Erie tower. Courtesy of Jim Faller.

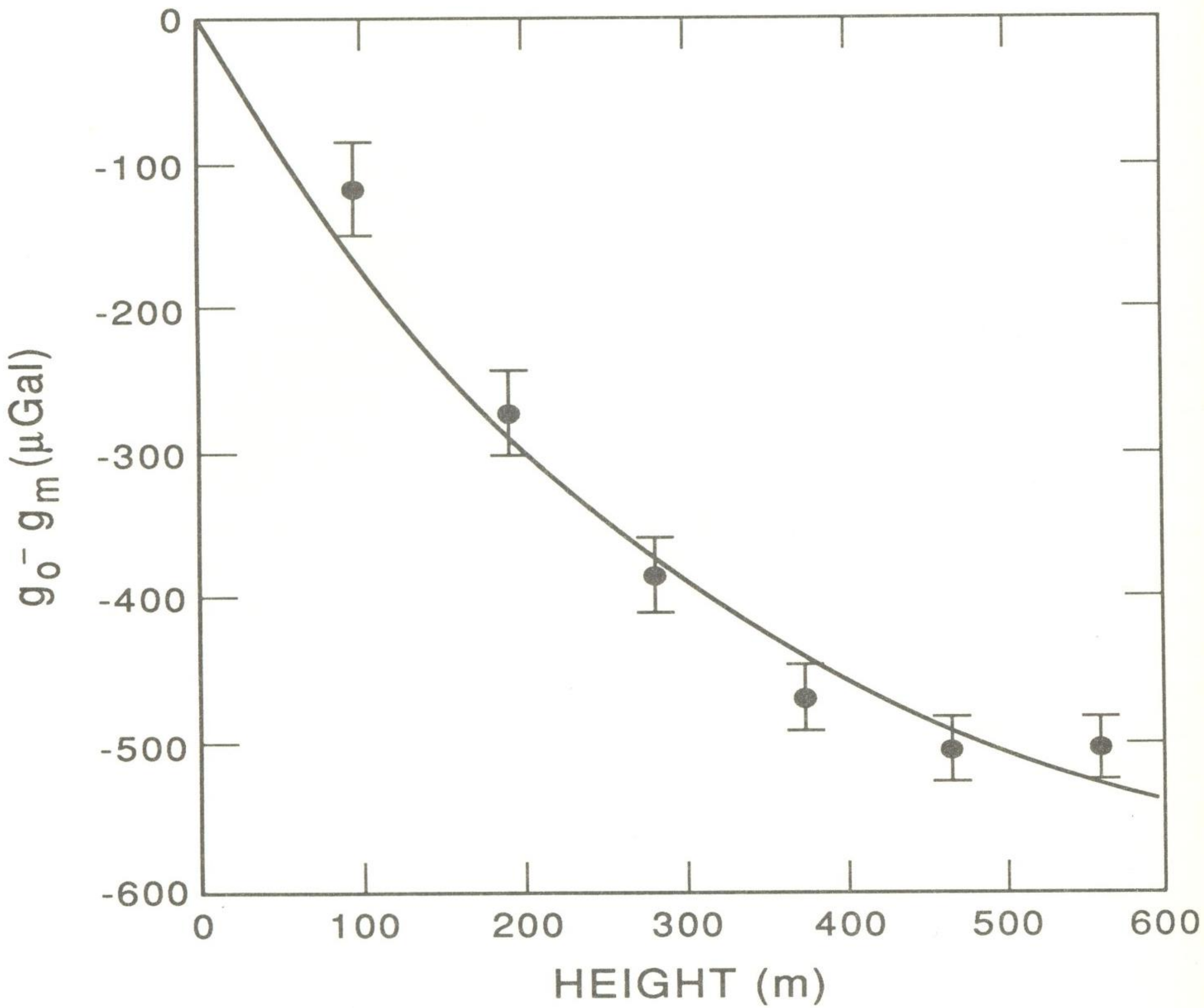


FIGURE 32. Eckhardt's experimental results fitted to a scalar Yukawa model. From Fairbank [1988].

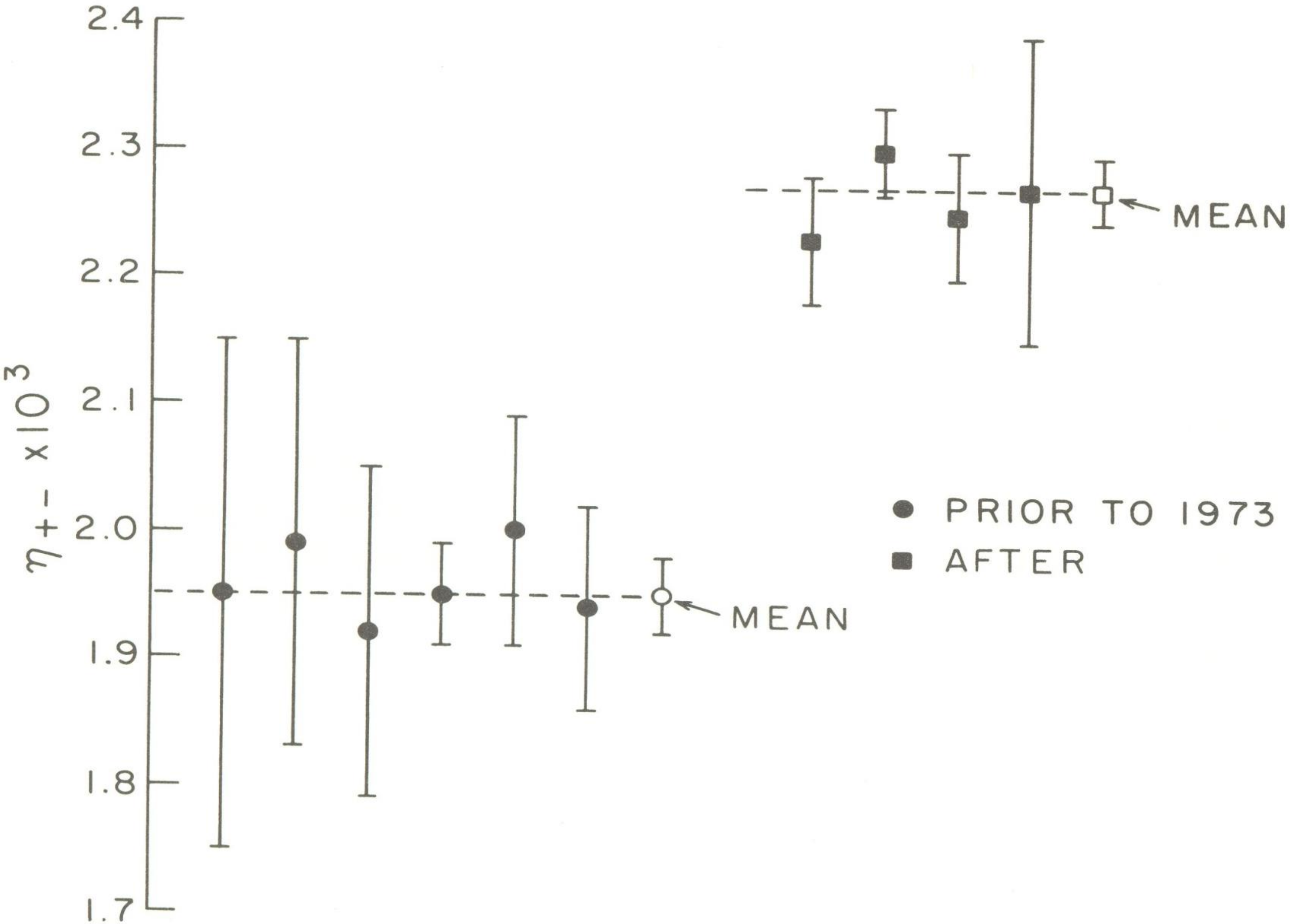


FIGURE 44. Measurements of $|\eta_{+-}|$ in the order of their publication.