History of Tidal Research Since the International Geophysical Year (IGY) 1957-58 as seen from ROB/ICET

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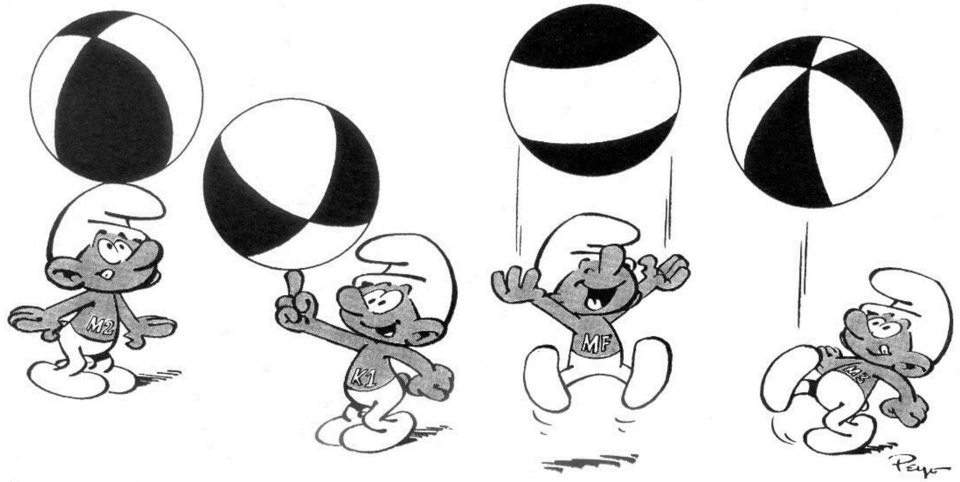
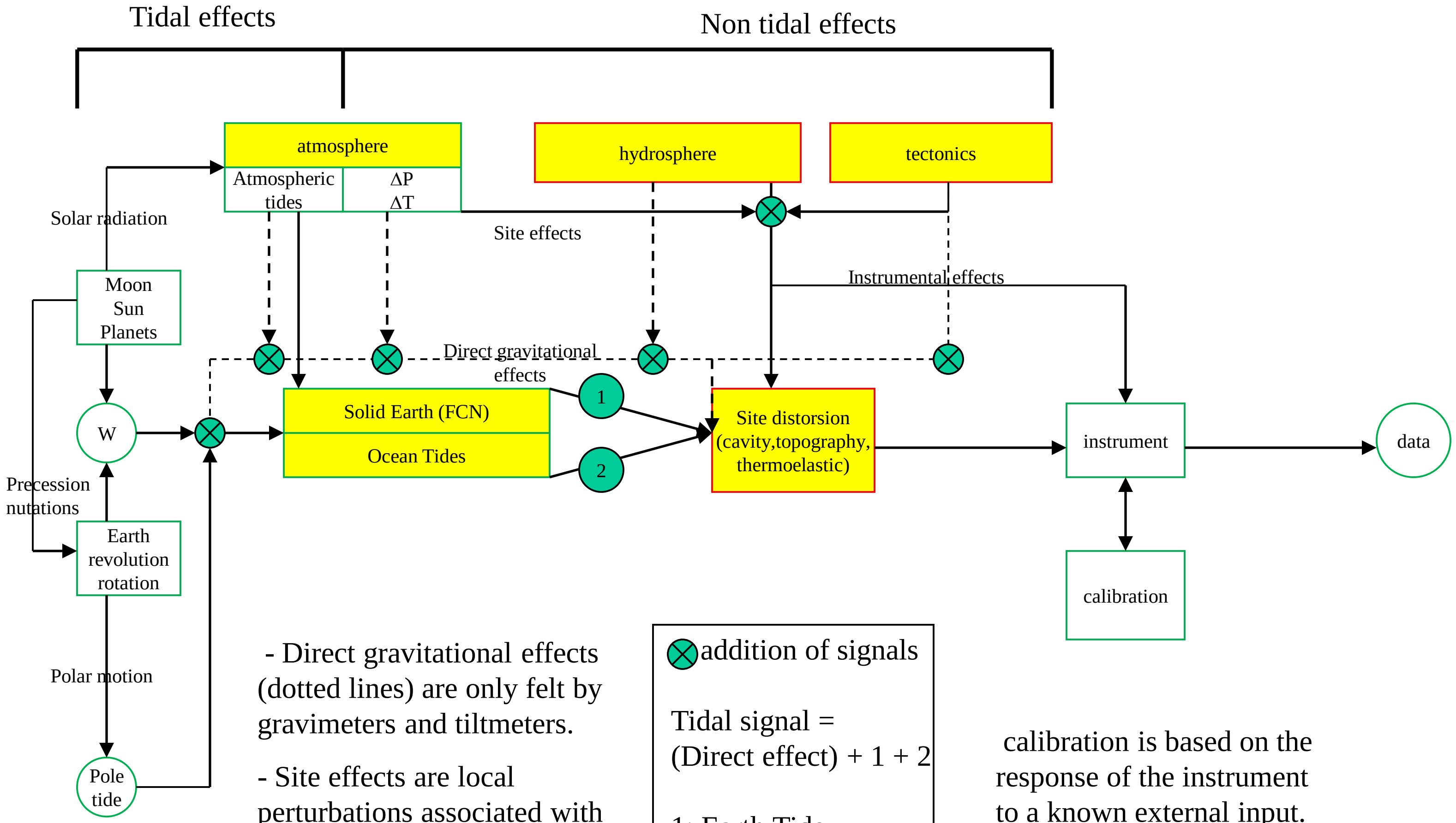


ICET

UCL
Université catholique de Louvain

Tidal registration scheme

Present situation



- Direct gravitational effects (dotted lines) are only felt by gravimeters and tiltmeters.

- Site effects are local perturbations associated with applied external forces.

- Instrumental effects are unwanted reactions of the instruments to external forces.

⊗ addition of signals

Tidal signal = (Direct effect) + 1 + 2

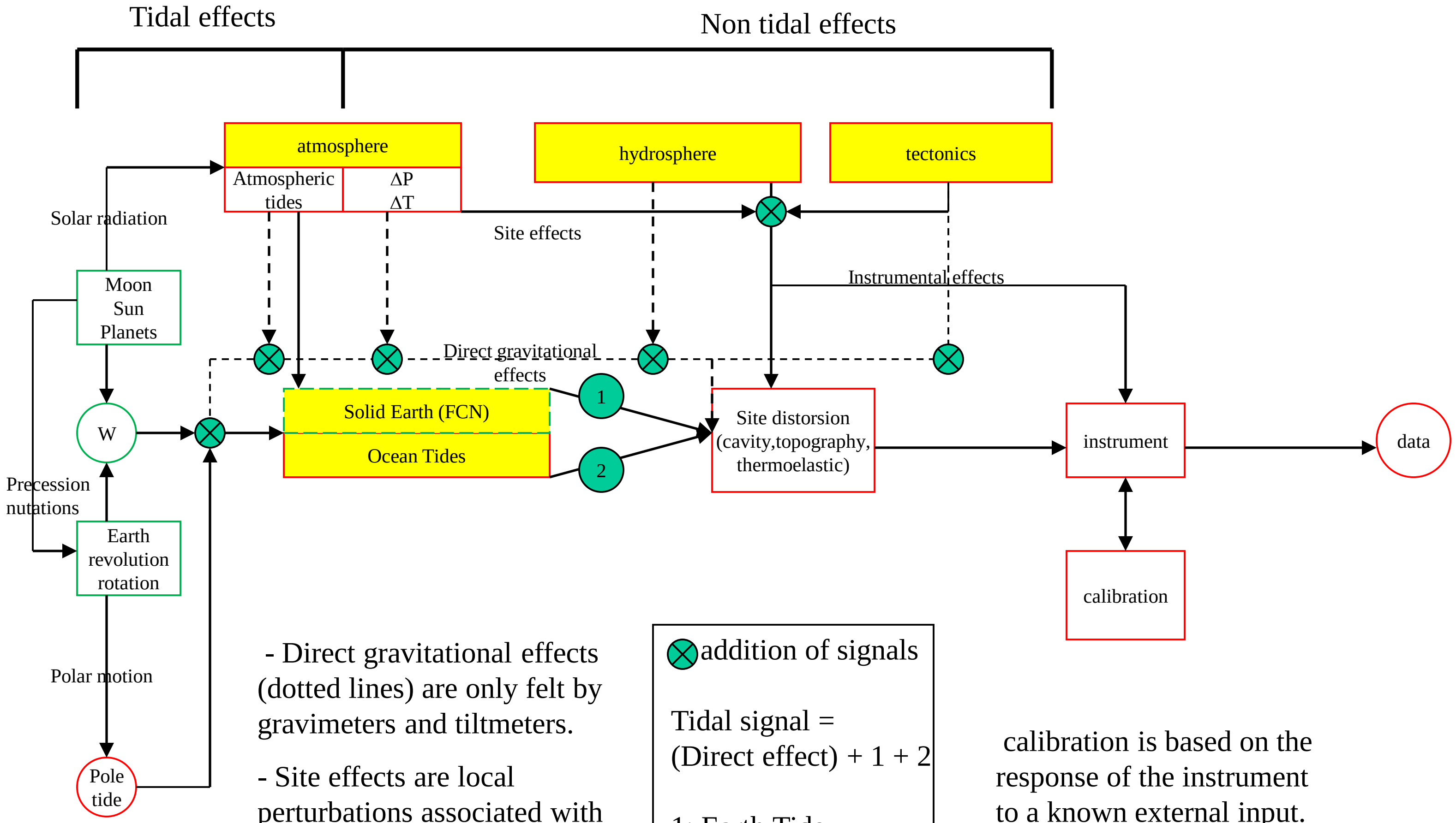
1: Earth Tide
2: Tidal loading

calibration is based on the response of the instrument to a known external input.

Green borders represent well controlled components

Tidal registration scheme

Situation in 1957



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Pierre Tardi, the IAG Secretary General, formed in 1956 a small committee to set up a program of investigations. This Committee composed by W.D. Lambert (USA), Yuri Boulanger (USSR) and P. Melchior (Belgium) proposed to the participating National Committees:

- to establish permanent observing stations
- equipped with new high sensitivity instruments
- to investigate how to correctly calibrate these instruments
- to try to measure the contribution of oceanic loading effects
- to investigate the Poincaré-Jeffreys effect, i.e. the liquid core resonance.

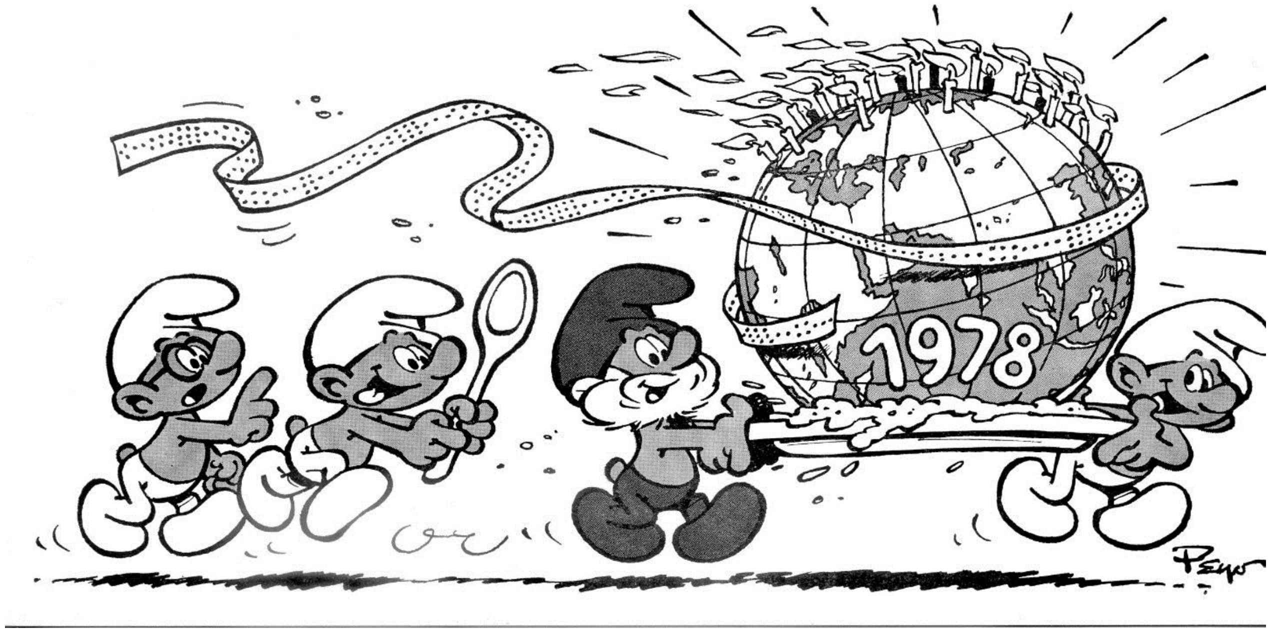
* Coordinated Earth Tides research was launched then in the framework of the "Comité Spécial pour l'Année Géophysique Internationale (CSAGI), groupe XIII (Gravimétrie), Commission pour l'étude des Marées Terrestres". This structure began to publish the "Bulletin d'Information des Marées Terrestres" (BIM) as early as 1956.

* To ensure a follow up and a real concrete activity and to help the countries to develop such researches, Pierre Tardi proposed that a Permanent Commission and an International Centre for Earth Tides (ICET) would be established to coordinate the program development and help in the data analysis.

* This structure became the International Centre for Earth Tides (ICET) in 1958 under the direction of P. Melchior and was hosted at the Royal Observatory of Belgium (ROB) until 2007. ICET developed its activities in symbiosis with the Department I of ROB.

* G. Laclavère, at that time Secretary General of the International Union of Geodesy and Geophysics, proposed to incorporate this Centre in the recently created Federation of Astronomical and Geophysical Services (FAGS) to deal with the problems raised by the IGY.

XXth anniversary



P. Melchior presented a first progress report during the XIth General Assembly of IUGG in Toronto (1957) concerning the status of the Earth tides research. He was summarizing the first results of different tidal observations based on a simple model

cE+I+S

E astronomical signal, I indirect oceanic effects, S secondary effects (atmosphere, hydrosphere, cavity…).

c is a numerical coefficient specific to each tidal phenomenon, the most common being:

gravity	$\delta = 1 + h - \frac{3}{2}k$
tilt	$\gamma = 1 + k - h$
latitude variation	$\Lambda = 1 + k - l$

cE is known as body tide i.e. astronomical tide + Earth response.

At that time, in the pre-computer era, the Doodson analysis method requested one month of records without gaps and only a few records longer than a month were available in order to obtain realistic values of tidal parameters.

- For tilt long series in the Pribram mine (CZ, 1933-1940) were reanalysed by J. Picha.
- For gravity R. Lecolazet performed observations with a North American gravimeter at Strasbourg from 1954 to 1956.
- Latitude variations were available from the International Latitude Service.
- I. Ozawa observed tidal strain with 13 extensometers installed in 3 different stations.
- P. Melchior presented the results of tides in wells observed in Belgium and in Congo.

The main problem was the effective separation of the direct and indirect effect by means of the Corkan procedure.

Summarizing the different results P. Melchior proposes the following experimental values for the tidal parameters

$$\delta = 1.200 \pm 0.020$$
$$\gamma = 0.706 \pm 0.010$$
$$\Lambda = 1.150 \pm 0.100$$
$$l = 0.055 \pm 0.030$$

We get thus

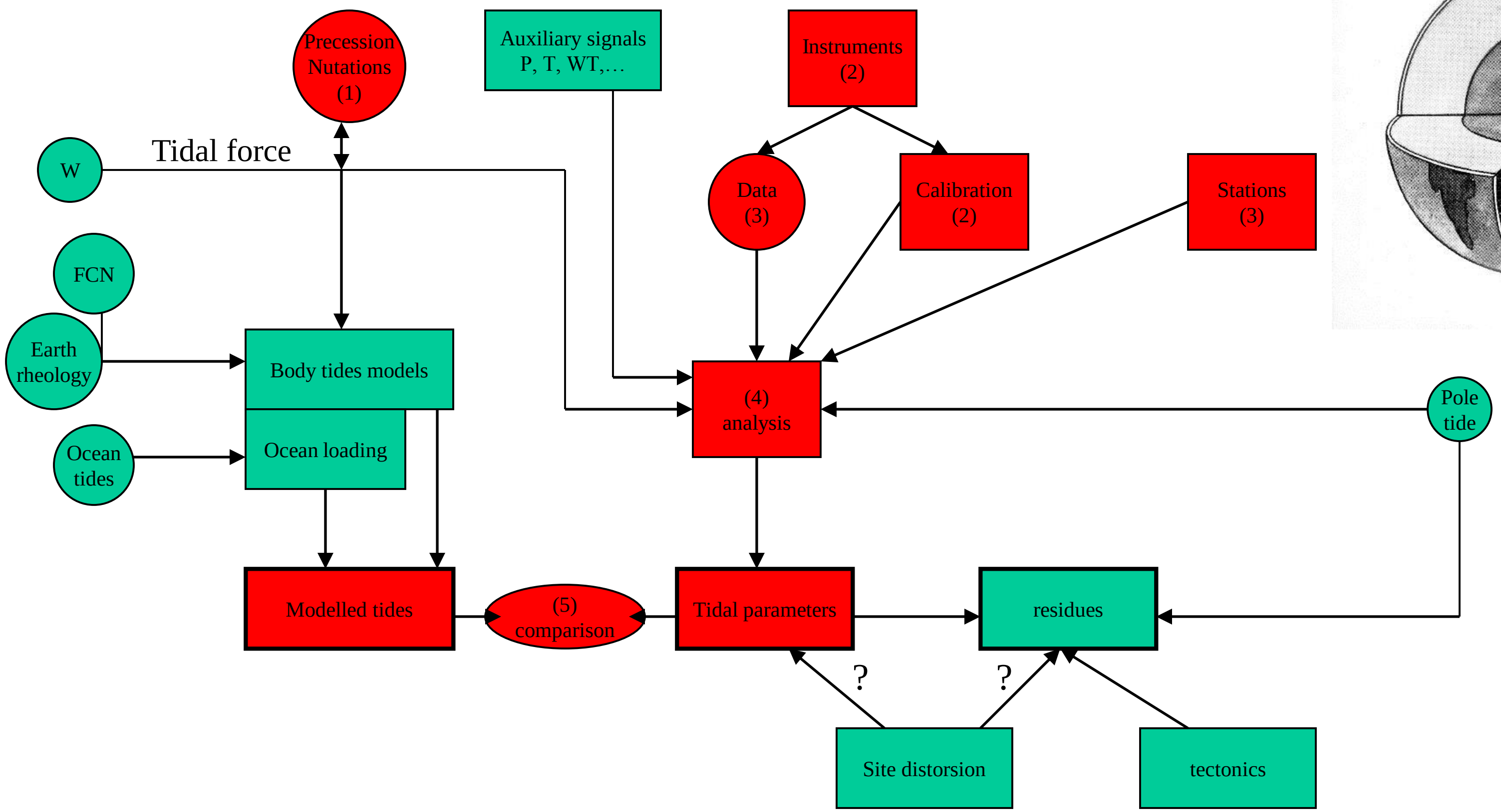
$$h = 0.482 \pm 0.07$$
$$k = 0.188 \pm 0.06$$

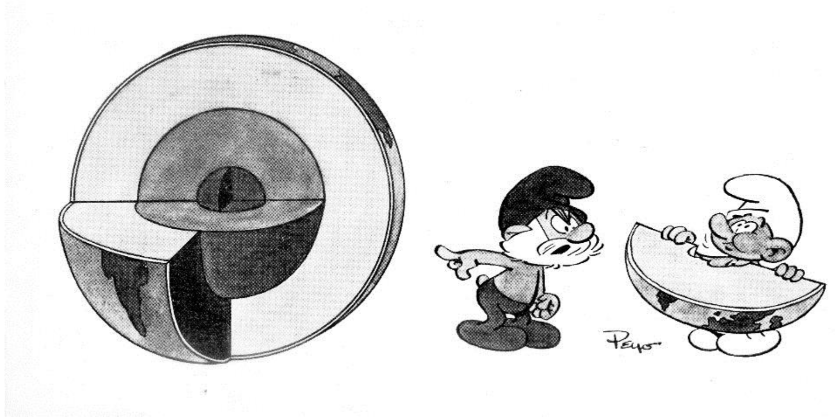
These results should be compared e.g. with Jeffreys theoretical values

	O1	K1	M2	
h	0.584	0.492	0.585	
k	0.242	0.206	0.289	
δ	1.221	1.183	1.152	
γ	0.658	0.714	0.704	

As a matter of fact the experimental value δ_{M2} =1.2 was due to the large indirect effect of the Atlantic Ocean in Western Europe.

Tidal data investigation
Main ROB/ICET contributions in red





(1)

As an astronomer P. Melchior studied the equivalence between tides and Precession nutations phenomena

(2)

ROB/ICET worked on the conception, installation and calibration of gravimeters, clinometers and extensometers

(3)

ROB/ICET developped a worldwide network of tidal stations known as TWP

(4)

ROB/ICET contributed to the development of tidal data preprocessing and analysis methods

(5)

For the comparison between observations and models ROB/ICET adopted a specific vectorial representation

Tidal analysis with computers

- P. Melchior adapted the tidal analysis methods (Doodson-Lennon, Lecolazet) on an IBM650 at the end of the fifties.
- The ROB got its own IBM1620 in 1964.
- The first harmonic analysis methods by least squares were developped independently:

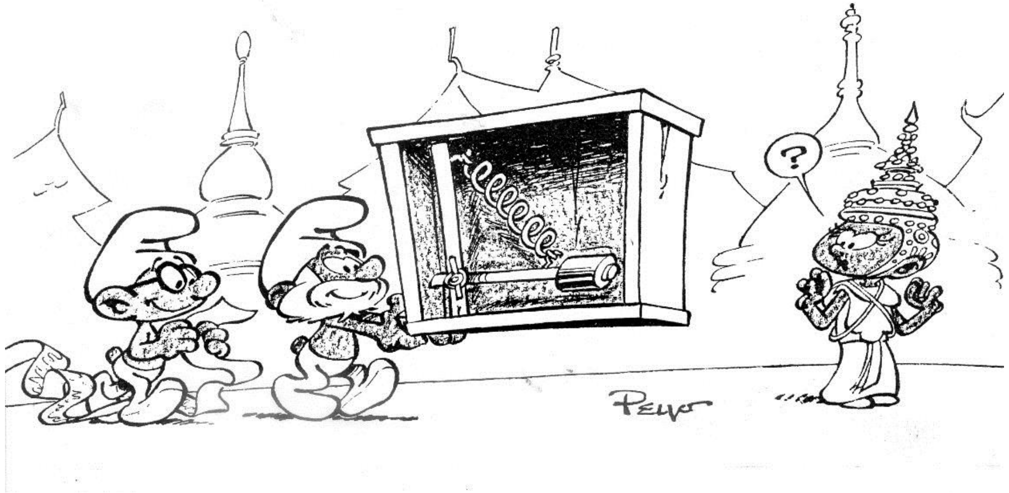
  * At ROB by A.P. Venedikov in 1966

  * At Strasbourg by T. Chojnicki 1967

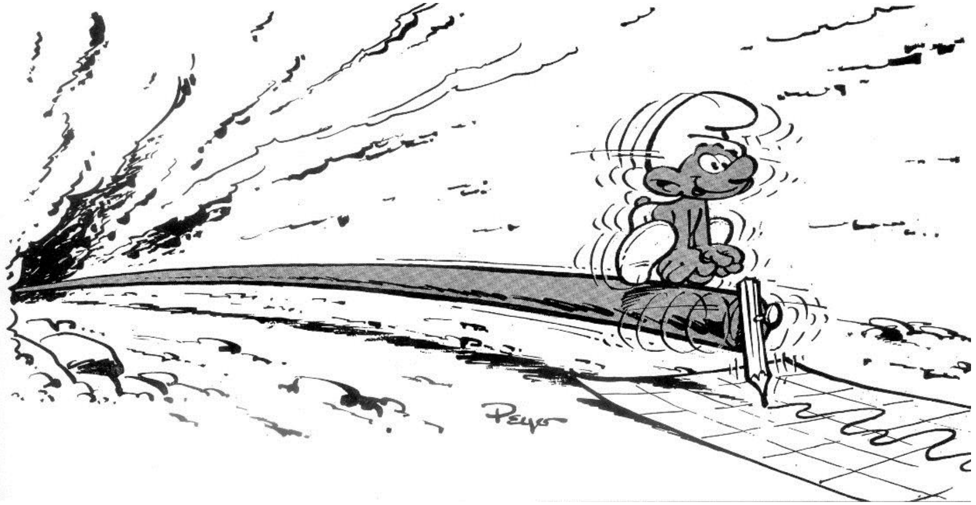
- The main differences are in the filtering methods:

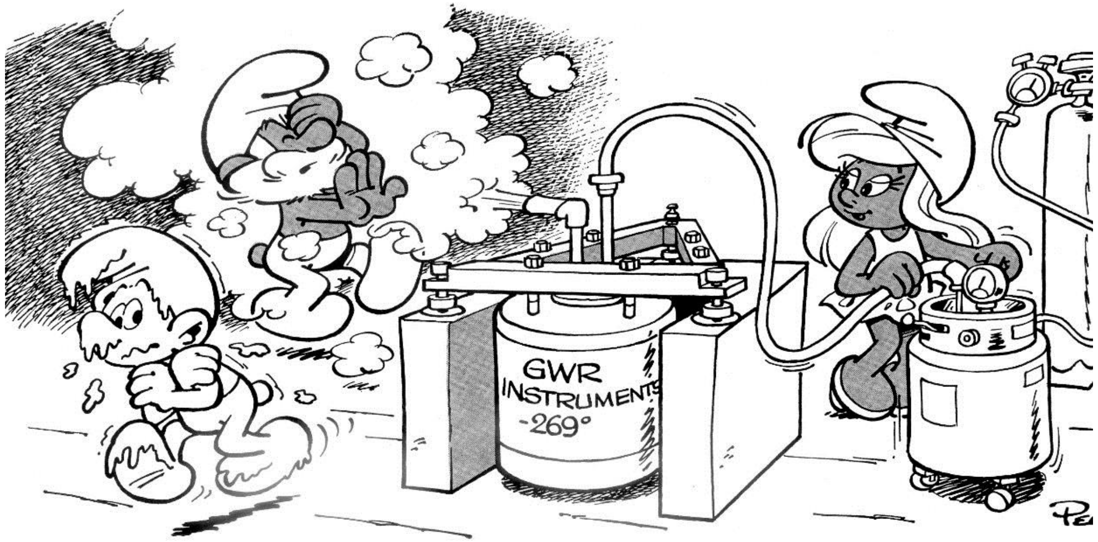
  * separation of the three families of tides with non overlapping filters for the first one,

  * separation of the complete spectrum with filters shifted step by step for the second one.
- The evolution of these methods led respectively to VAV software on one side and HYCON (K. Schueller) or ETERNA (H.G. Wenzel) software on the other.



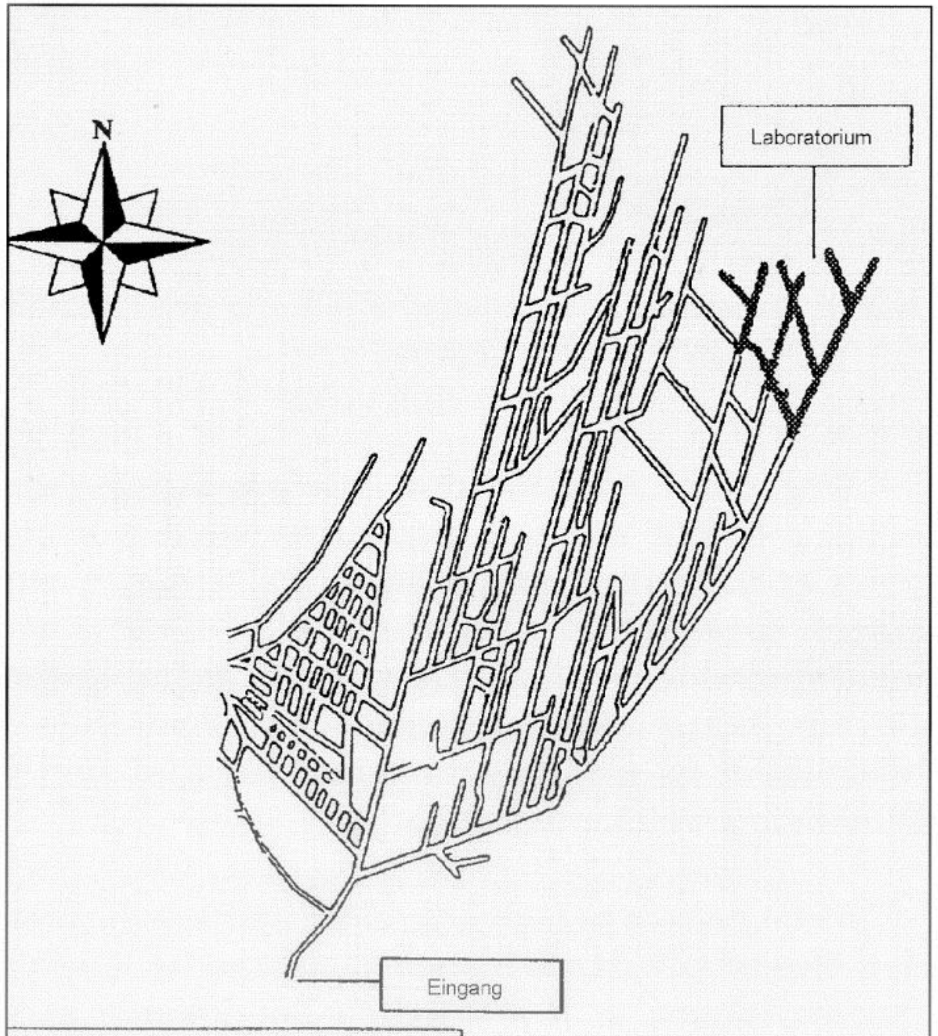
Instrumentation





The Underground Laboratory for Geodynamics of Walferdange

- Since 1968 VM pendulums have been installed in the gypsum mine of Walferdange (L) by J. Flick and P. Melchior.
- This underground laboratory was dedicated to the intercomparison of tidal instrumentation.
- ASKANIA, Geodynamics, SCINTREX and superconducting gravimeters;
- VM, VMR, Tsubokawa, NVI, ONERA clinometers;
- Chinese, Finnish and water tube tiltmeters from Luxembourg;
- Ozawa invar rod, King-Bilham wire and quartz tube strainmeters.



Lage des Laboratoriums in der Gipsmine

Similar laboratories are existing in Germany (BFO Schiltach, W. Zürn) and China (Huangshi, Cai W.X.)

EVOLUTION OF TECHNICS

End of fifties

- Small electromotive forces are produced by induction coils (seismometers) of photoelectric cells (Askania gravimeters).
- Galvanometers are used to measure these electromotive forces.
- Rotation is transformed in displacements by reflexion of a spot on a mirror and recorded on a photographic paper.

End of sixties

With the development of capacitive transducers it became possible to use chart strip recorders and digital voltmeters.

TILTMETERS

- P. Melchior and J. Verbaandert developped at ROB a new horizontal pendulum with its calibration device and photographic recording system.
- This kind of instrument was installed in underground stations not only in Europe from South of Italy to Spitsbergen (Astro-Geo Project Spitsbergen, 1969-70, M. Bonatz), but also in Canada, Argentina and even Australia.
- It was equipped with capacitive transducers by M. van Ruymbeke in 1976.
- Other quartz horizontal pendulums have been developped e.g. the Blum-Jobert instrument in a sealed capsule.

VERBAANDERT-MELCHIOR QUARTZ HORIZONTAL PENDULUM

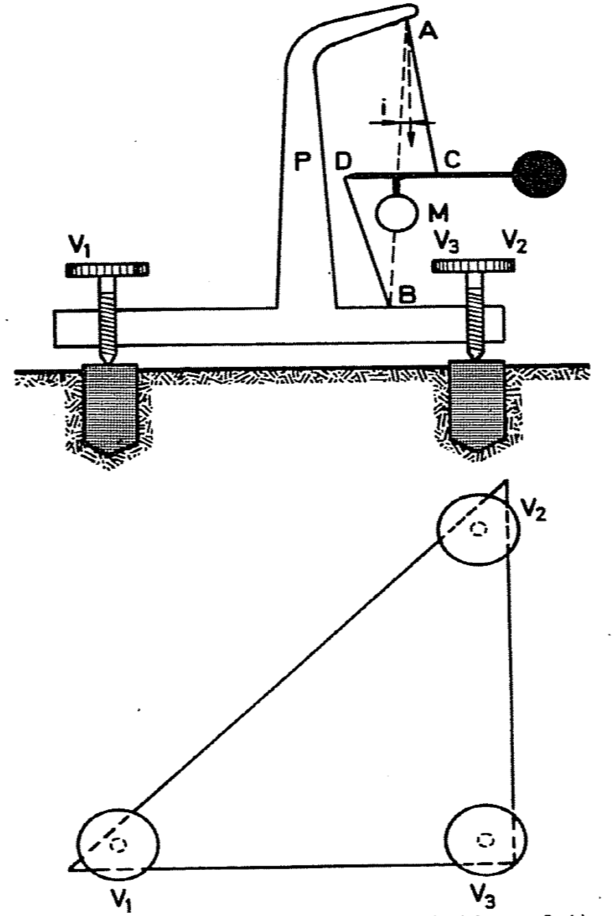
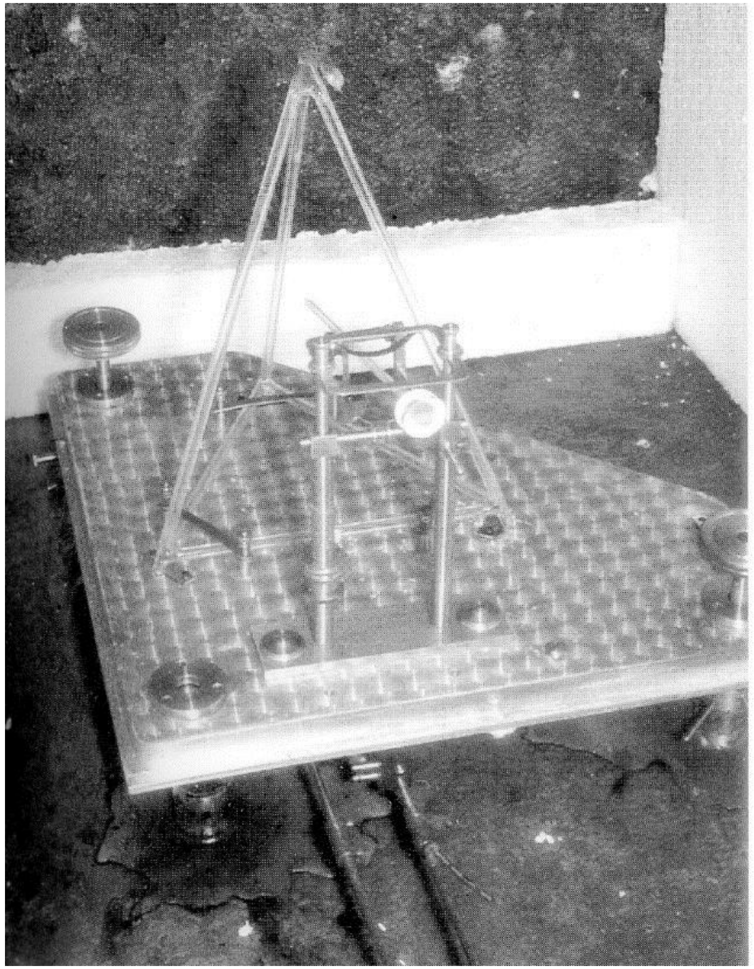


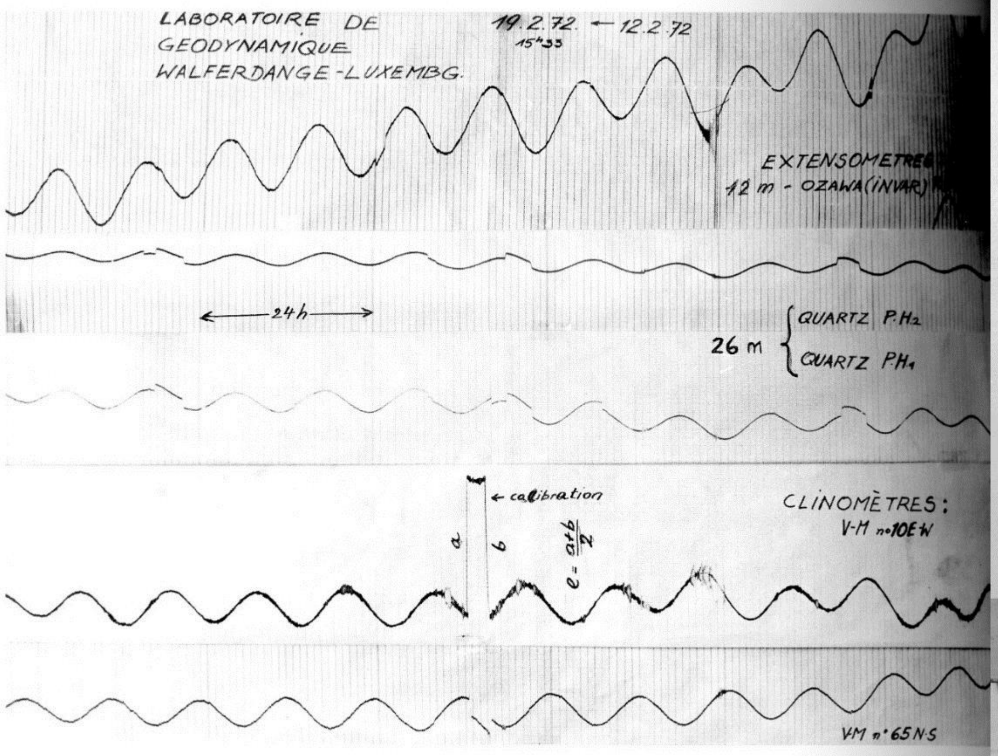
Fig. 8.3. Schematic representation of the Zöllner suspension.



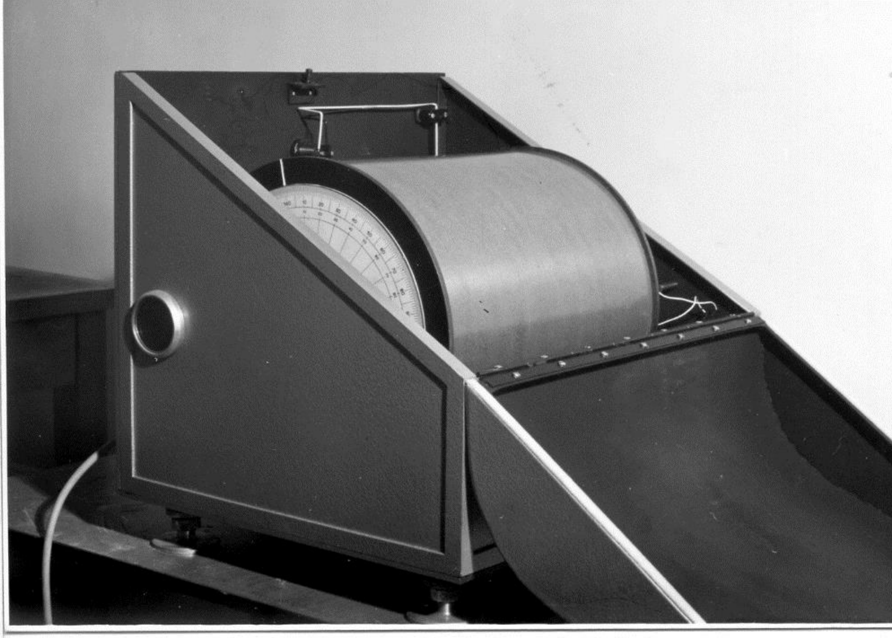
Working period 80s

Advantages of VM pendulum

- Fused quartz suspension wires are directly soldered on the frame so that the axis of rotation remains stable and large working periods become possible.
- The tetrahedric structure of the frame is undeformable.
- The two tilting directions (drift and period) are completely decoupled thanks of the square triangle design of the supporting plate.



Février 1972: une semaine d'enregistrement de 3 d'instruments en parallèle

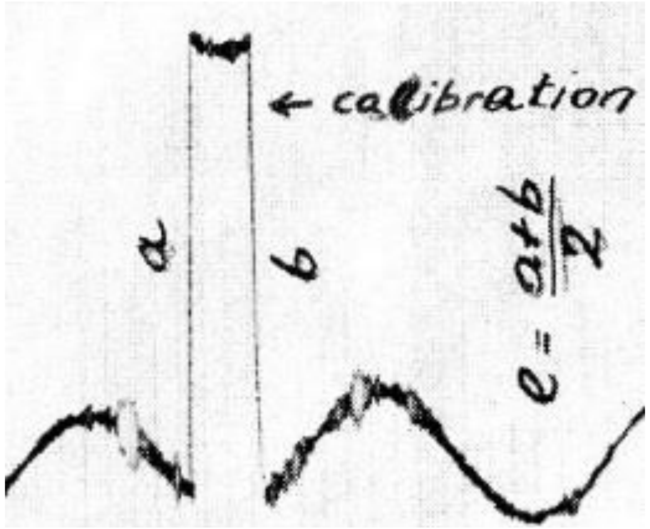


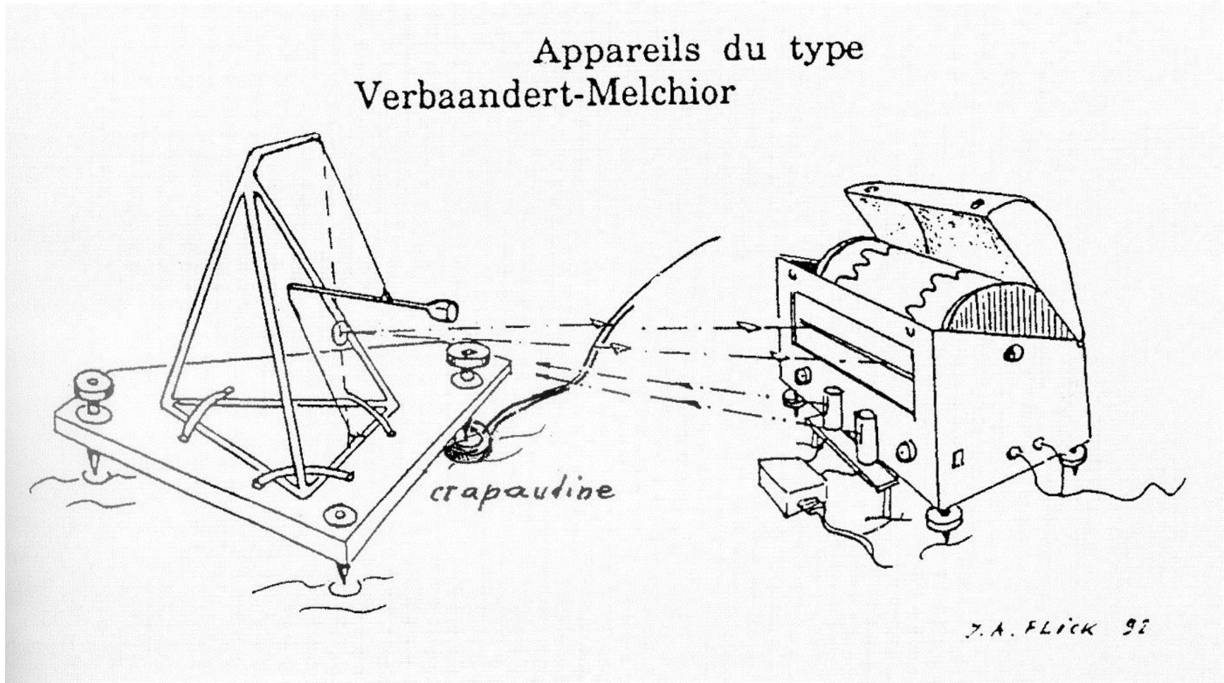
Sensitivity on photographic paper 1mas/mm
Reading precision ±0.1mm, signal to noise ratio ≤500

Speed of rotation 6mm/hr
Autonomy one week

Photographic Recording

CALIBRATION





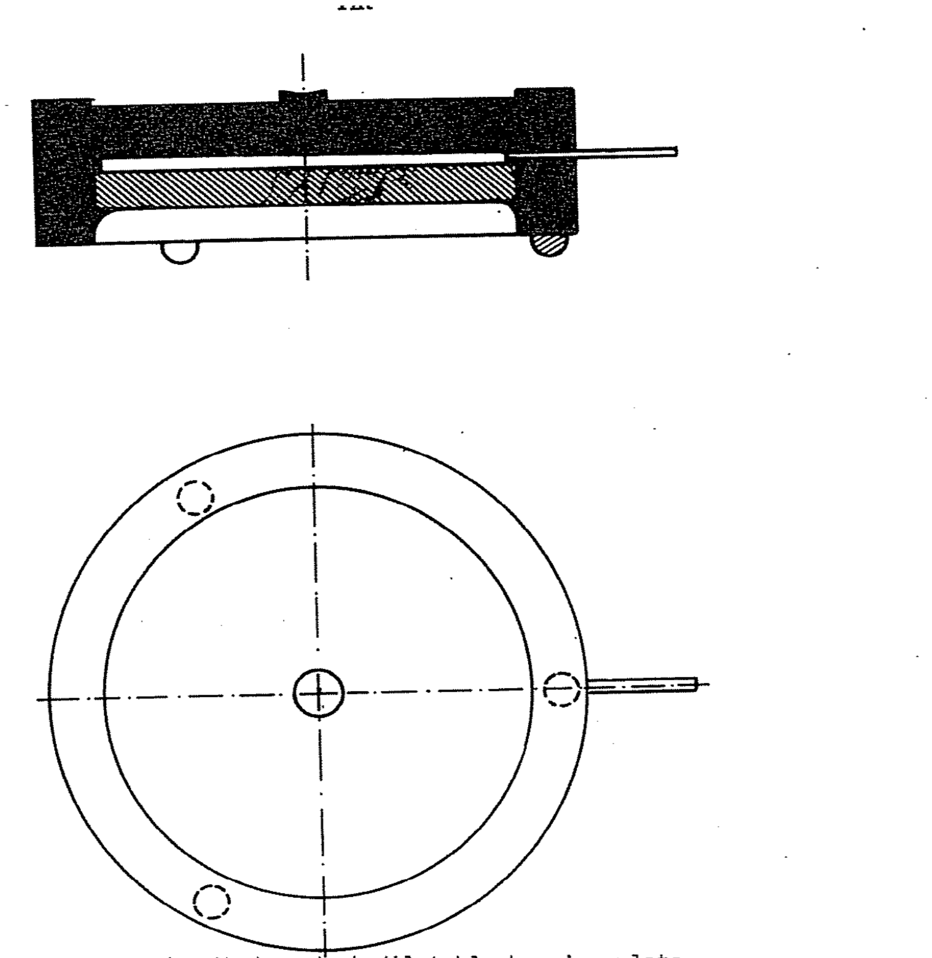
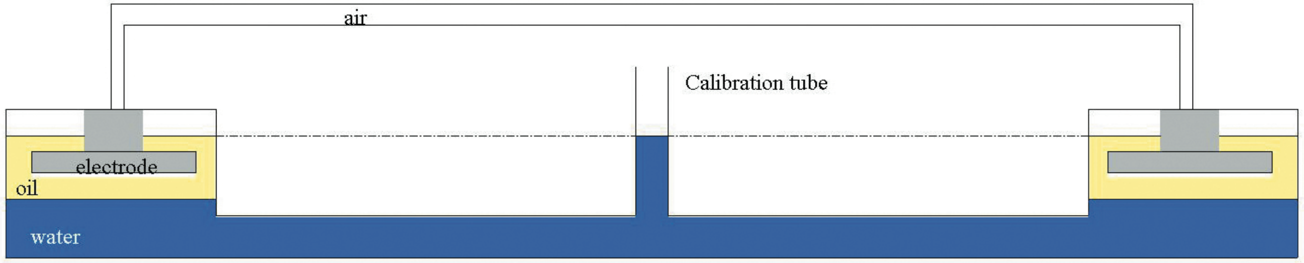
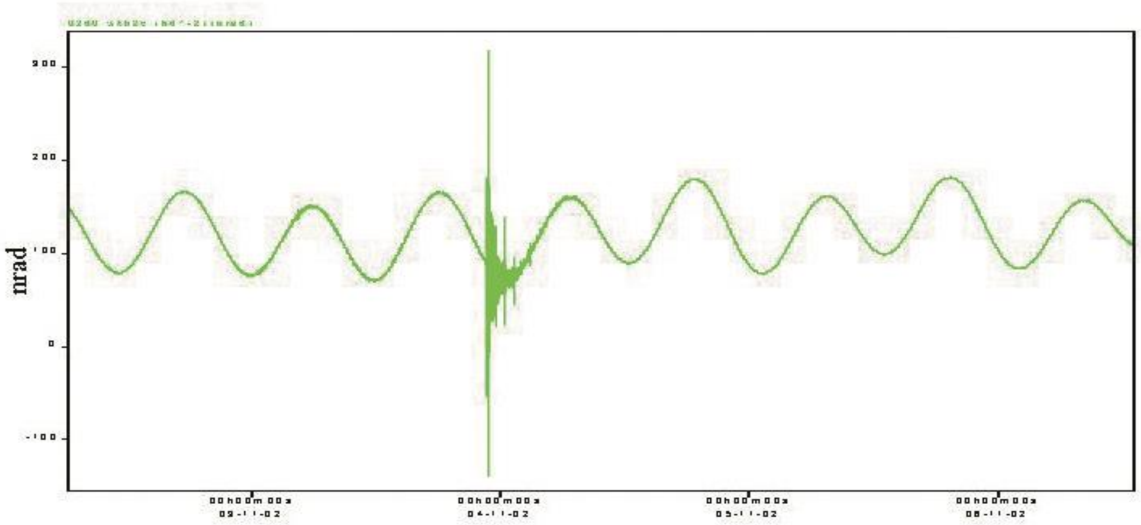


Fig. 8.10. Verbaandert dilatable bearing plate.
(crapaudine)

Interferometrically calibrated against the mercury spectral line (λ=0,546µm).
Accuracy better than 1%

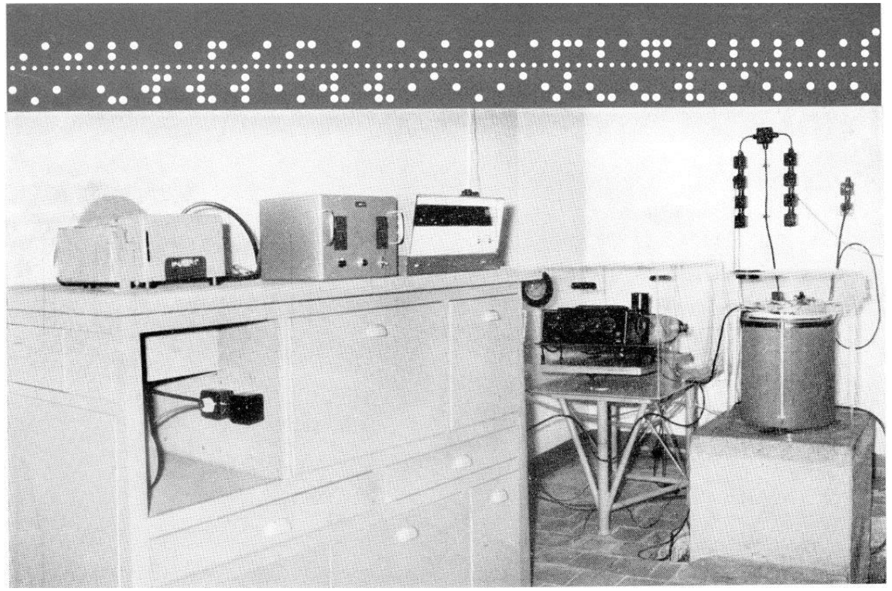
Up to date instrumentation





Water tube tiltmeter at the Underground Laboratory of Geodynamics (N. d'Oreye)
Resolution 0.001mas

GRAVIMETERS



P. Melchior started tidal gravity recording with ASKANIA gravimeters at ROB in 1958.

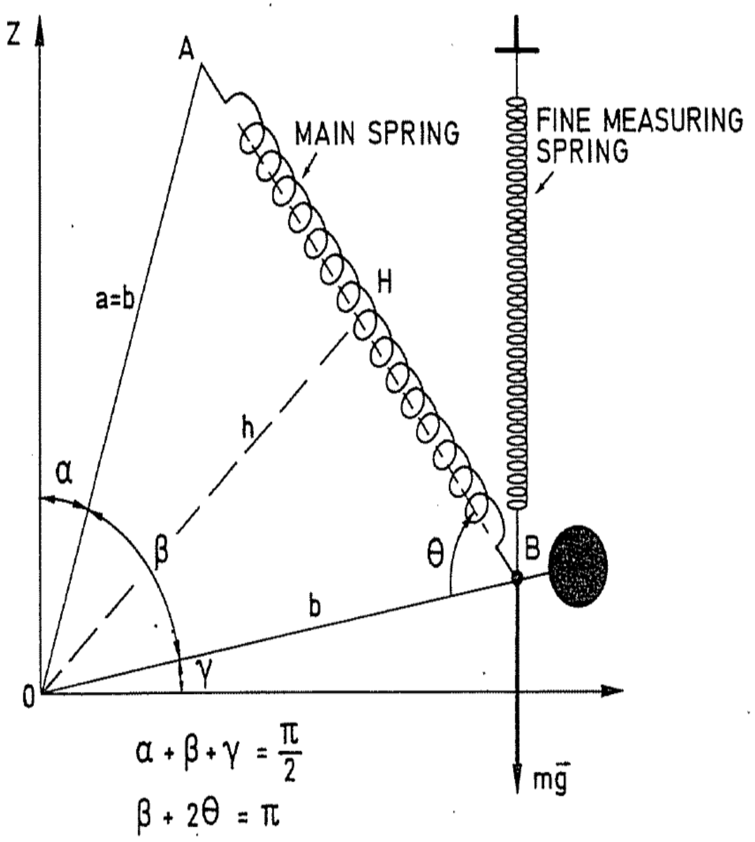
J. T. Kuo brougth the first Geodynamics (modified North American) instruments to ROB in 1970.

LaCoste & Romberg (LCR) gravimeters were used since 1973

LCR meters were equipped of feedback system by M. van Ruymbeke since 1985

The superconducting gravimeter was installed at ROB in 1982

Gravimeters with horizontal beam



The equilibrium of the gravimeter is defined by two torques: M1 associated with gravity and M2 due to the restoring force of the spring.

M_1 (g, α,β) = M_2 (C, β)

Let us consider a small displacement around the equilibrium position

$\partial M_1/\partial g \, dg + \partial M_1/\partial \alpha \, d\alpha + \partial M_1/\partial \beta \, d\beta = \partial M_2/\partial \beta \, d\beta + \partial M_2/\partial C \, dC$

It becomes

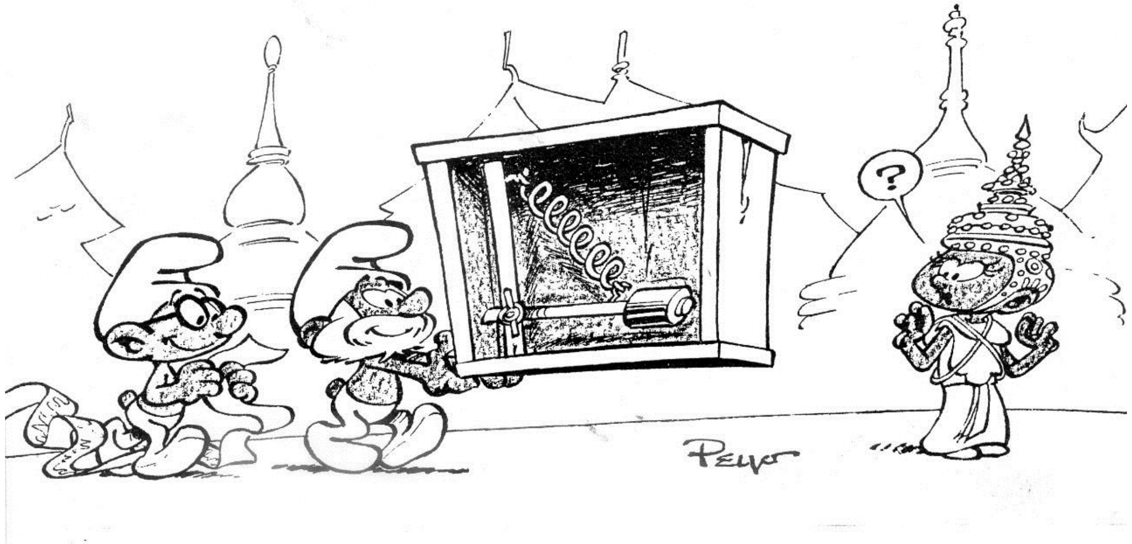
$$d\beta = \frac{\frac{\partial M_1}{\partial g} dg - \frac{\partial M_2}{\partial C} dC + \frac{\partial M_1}{\partial \alpha} d\alpha}{\left(\frac{\partial M_2}{\partial \beta} - \frac{\partial M_1}{\partial \beta}\right)}$$

Or

(1) (2) (3)

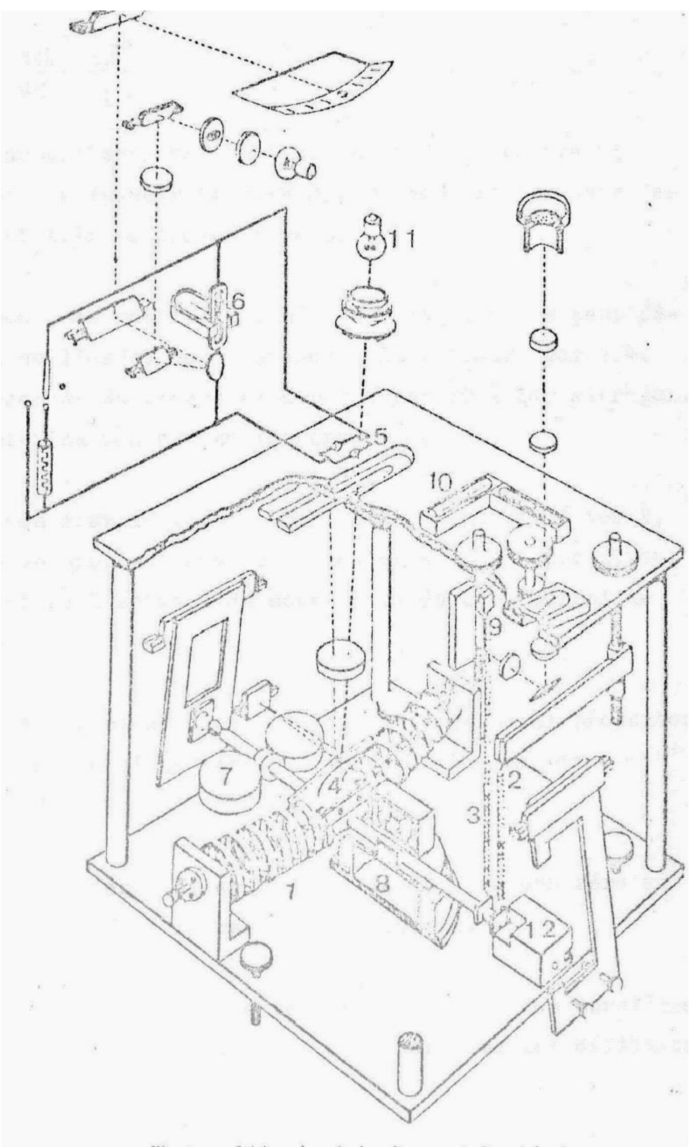
$d\beta = A\, dg/g - A\, dC/C + A\cot g(\alpha + \beta)\, d\alpha$

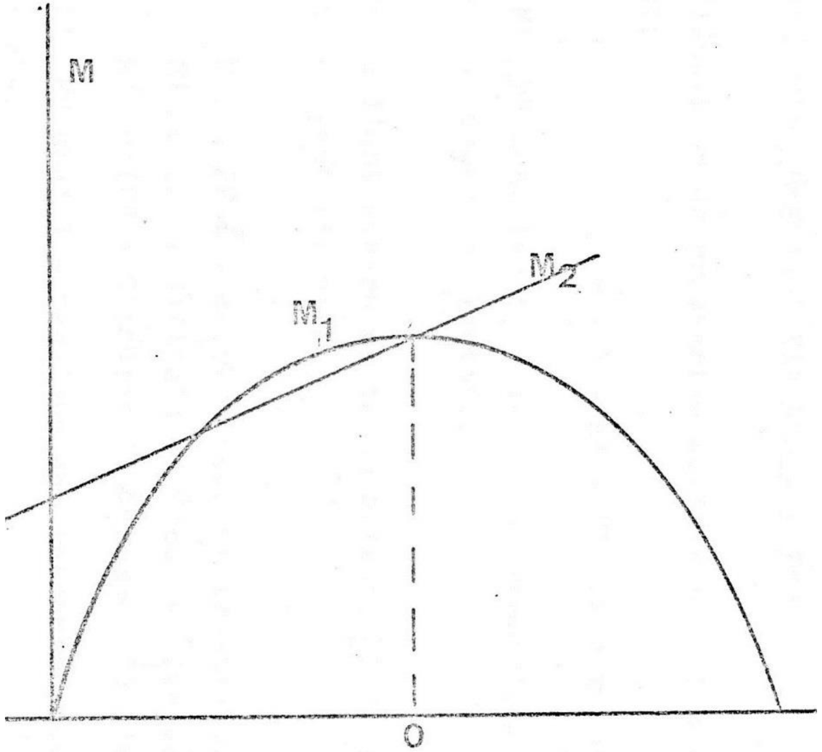
$$A = \frac{M_1}{\frac{\partial M_2}{\partial B} - \frac{\partial M_1}{\partial \beta}} \quad coefficient \quad d'amplification$$



ASKANIA GRAVIMETER

Linear torque M2 ⇒ static gravimeter

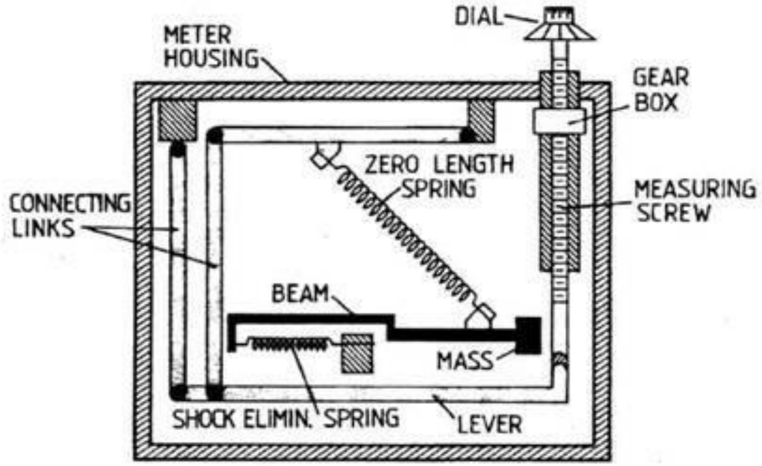


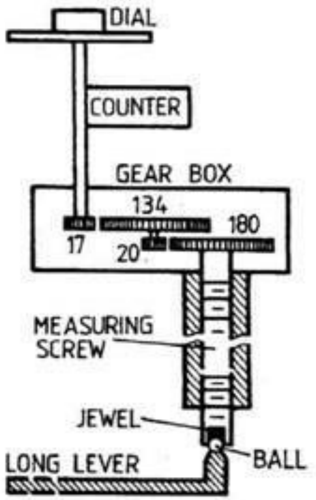


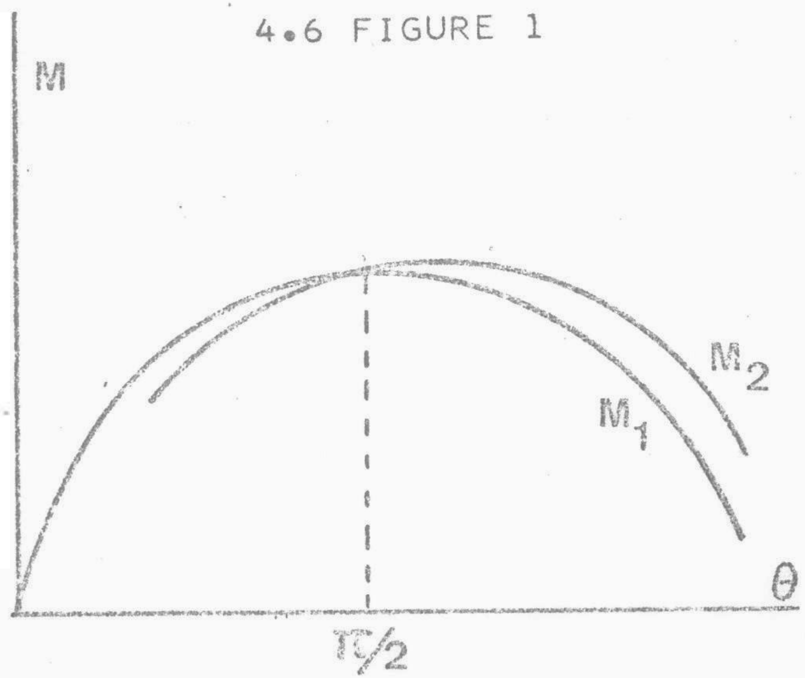
Period < 1s

non linear torque M2 $\Rightarrow$ astaticized gravimeter

LCR gravimeter







Period ≥ 20s

$F = C|AB| = C(H_0+H)$

1/ For a zero length spring ($H_0=0$) $F=H$

If OA = OB = l, we get

$M_1 = mgl \sin(\alpha + \beta)$

$M_2 = CHl \sin\theta = Cl^2 \sin\beta$

As in triangle OAB we have $H/\sin\beta = l/\sin\theta$

The equilibrium equation is thus

$$mgl \sin(\alpha + \beta) = Cl^2 \sin\beta$$

2/ Let us consider the amplification coefficient

$$A = \frac{M}{\left(\frac{\partial M_2}{\partial \beta} - \frac{\partial M_1}{\partial \beta}\right)}$$

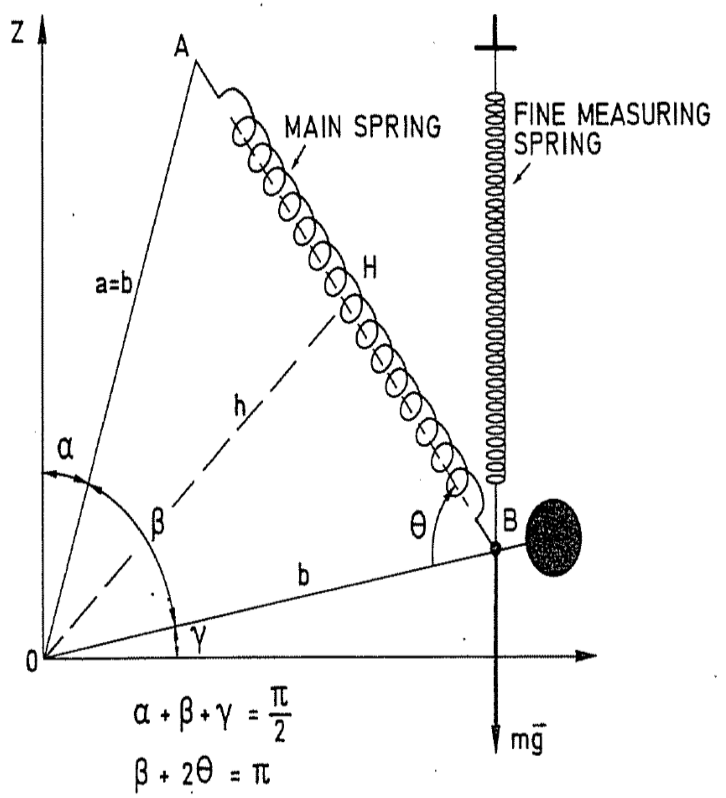
$\partial M_2/\partial b = M_2 \,\mathrm{ctg}\,\beta$, $\partial M_1/\partial\beta = M_1 \,\mathrm{ctg}\,(\alpha + \beta)$

$$A = M \sin\alpha/\sin\beta \sin(\alpha + \beta)$$

If the beam is horizontal ($\gamma = 0$), $(\alpha + \beta) = \pi/2$

$$A = \sin\beta/\sin\alpha$$

and A becomes infinite if $\alpha = 0$.



Sensitivity Adjustment

- The sensitivity can be adjusted by changing the reading line which is equivalent to change the value of β.
- To get $\gamma = 0$ it is necessary to find the position of the longitudinal level insensitive to tilting (summit of a parabola).
- As we have then $(\alpha + \beta) = \pi/2$,

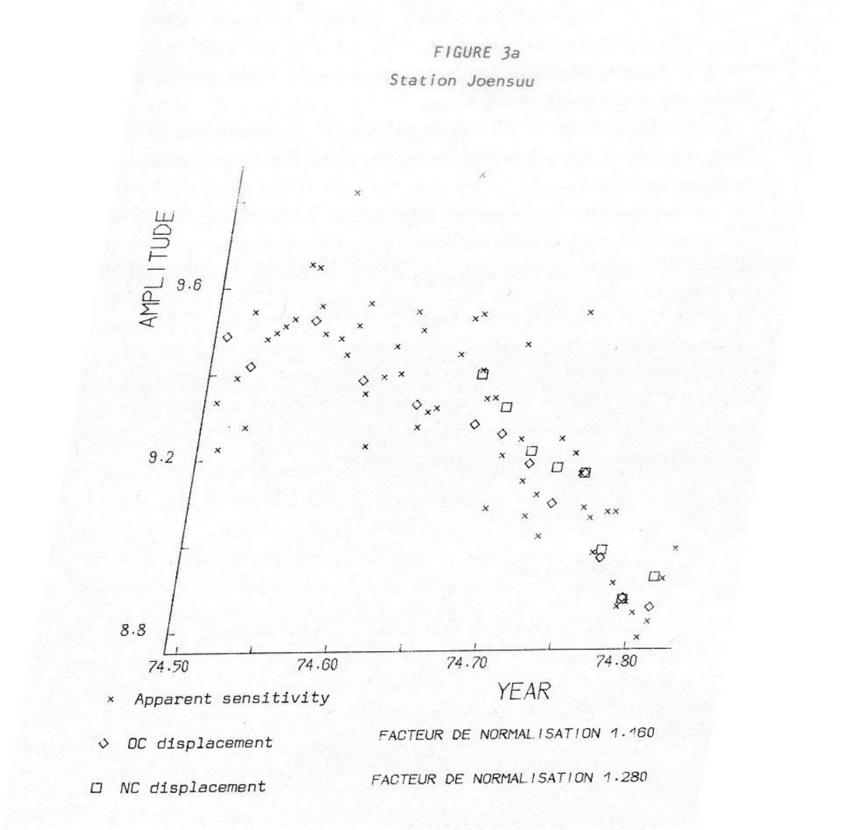
changing β is equivalent to change α.

Advantages

- Very large amplification ($\cong$ 1000) allows to reach free periods close to 20s.
- The displacements of the beam can be observed with a microscope.
- The signal to noise ratio in gravity tides recording is improved.

Disadvantages

- The sensitivity depends strongly from tilting along longitudinal level.
- The transfer function of the instrument becomes complex



Variation of sensitivity of an astaticized gravimeter

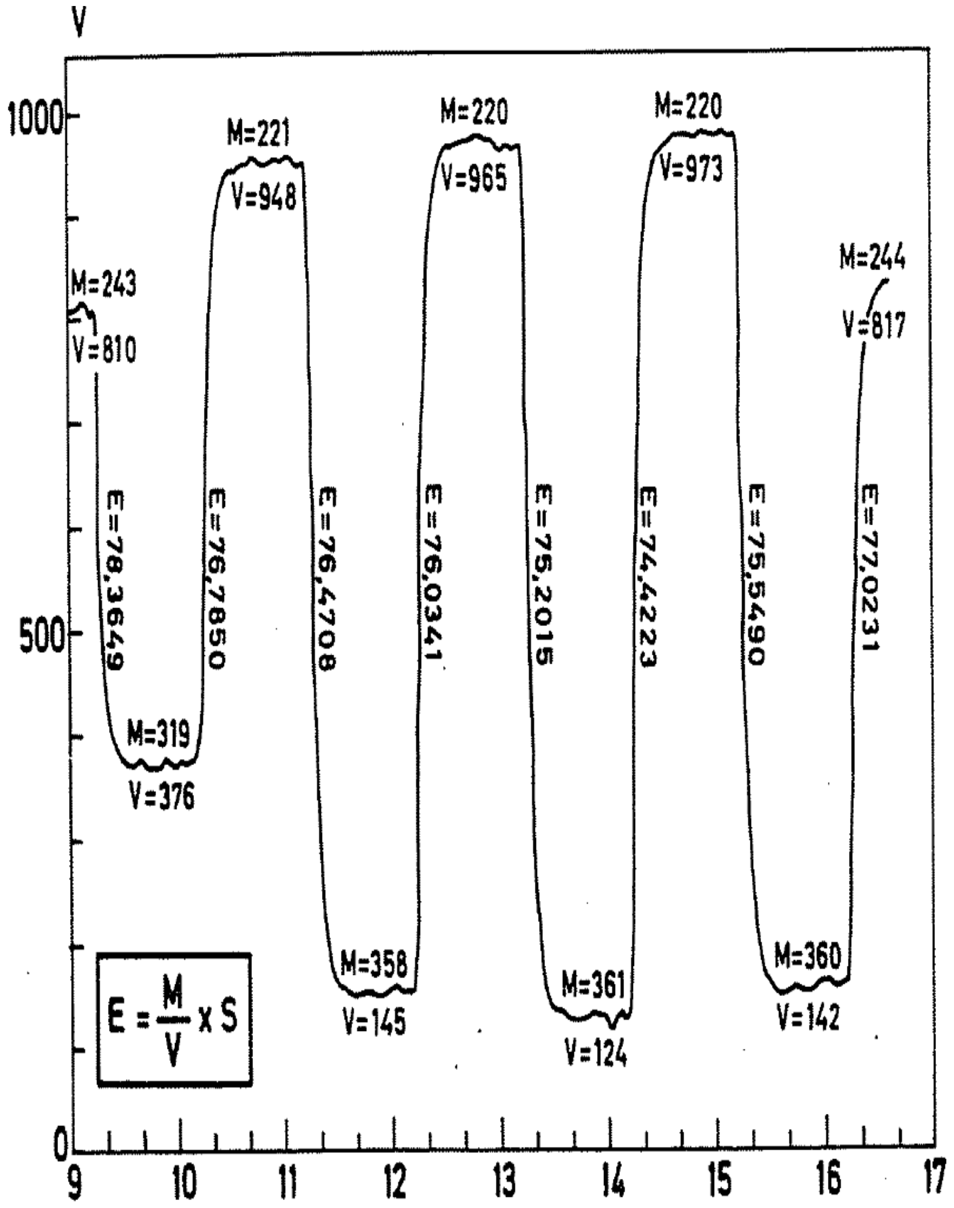
CALIBRATION

Determination of the transfer function in amplitude and phase

AMPLITUDE

- Spring gravimeters are equipped with a micrometric screw calibrated against a known difference of gravity.
- The sensitivity on the records is determined by successive displacements of the micrometer.

A high precision calibration line has been installed in a building in Hannover with a reduced gravity difference for the calibration of tidal gravimeters



Auxiliary calibration devices have been used:

- For ASKANIA gravimeters balls of known mass could be lifted down on the beam.

DRAWBACK: strong perturbation of the instrument which had to be tilted upside down to lift the ball.

- For GEODYNAMICS instruments a DC Voltage could be applied on the plates of the capacitors to attract the mass

DRAWBACK: - Attraction is depending of the position of the mass between the capacitor plates

- Voltage source located outside the gravimeter was sensitive to temperature changes.

- For LCR meters the vertical gradient of gravity can be used by lifting the instrument slowly up and down on a platform.

DRAWBACK: - Low precision of the gradient determination (0.5%)

- Tilt of the instrument during lifting procedure

CALIBRATION

Determination of the transfer function in amplitude and phase

PHASE

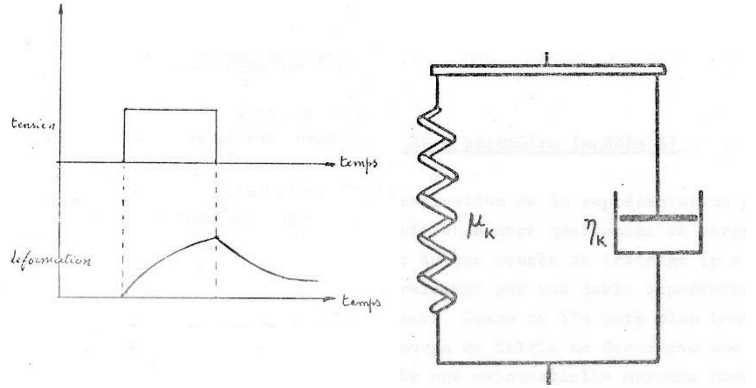
a) RECORDING DEVICES

At tidal frequencies :

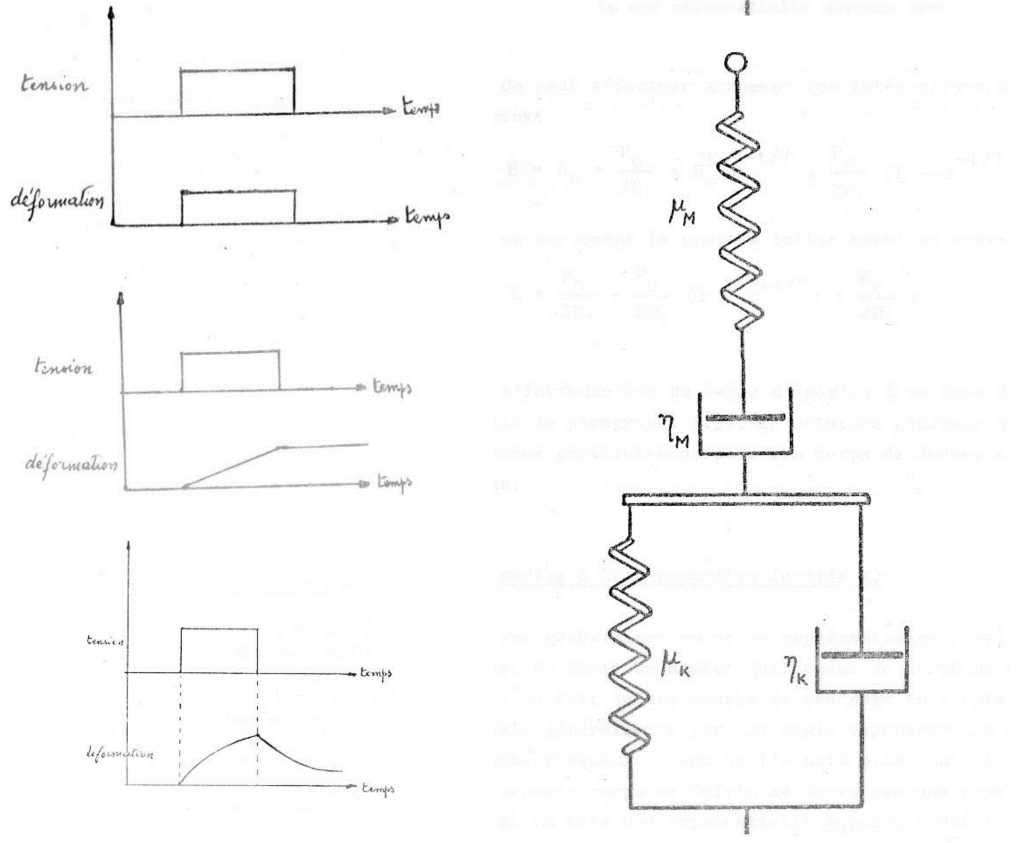
- the phase lag introduced by the galvanometers for old ASKANIA are easily modelled.
- RC filters can be approximated by a simple time lag producing phase differences proportional to frequency.

b) GRAVIMETER

Static gravimeters ⇒ Kelvin body
Short period instruments ⇒ time lags of a few seconds



Astaticized gravimeters ⇒ Burgers body
Superposition of direct and delayed response
Long period instruments ⇒ time lags larger than 60 minutes



The general equation of motion being

$$K\ddot{x} + P\dot{x} + Dx = 0$$

1/ Let us consider the response of the system Hooke body plus Kelvin bodies to a step function A_0

$$x(t) - x(0) = A\left[1 + \varepsilon\ (1 - e^{-t/\theta}\ )\right]$$

It is the sum of the step response of the Hooke body

$A = A_0/D_0$

and the decay of the Kelvin body with a retardation time θ

$$\varepsilon A = (1 - e^{-\frac{t}{\theta}})$$

With $\varepsilon = D0/D$, $\theta = P/D$

2/ If we consider now the tidal forcing by a tidal wave of pulsation n: $P = A_0 \sin(nt)$

As n is very small compared to n_0 and n_1, we get if $\alpha = \theta n$

$$\tan\Delta\varphi = -\varepsilon \frac{\alpha}{1 + \varepsilon + \alpha^2}$$

$$F = \frac{A(T)}{A(\infty)} = \sqrt{\frac{(1+\varepsilon)^2 + \alpha^2}{1 + \alpha^2}} \Big/ (1+\varepsilon) = \sqrt{\frac{1 + \frac{\alpha^2}{(1+\varepsilon)^2}}{1 + \alpha^2}}$$

* The attenuation F and the phase lag φ of a tidal wave of pulsation n is completely determined if we know the retardation time θ and the relative contribution ε of the Kelvin body. It can be determined through a step function experiment. This modelling was first developped at Strasbourg by L. Steinmetz (1960).

* Inversely if we know the phase lag of two tidal waves O1 and M2 we can build the rheological model.

If $\alpha = \theta n$

$$f = \frac{\tan \Delta\varphi_{O1}}{\tan \Delta\varphi_{M2}} = \frac{\alpha_{O1}(1+\alpha_{M2}^2)}{\alpha_{M2}(1+\alpha_{O1}^2)} \qquad R = \frac{T_{O1}}{T_{M2}} = 2.07875$$

We get

$$\alpha_{O1}^2 = \frac{Rf - 1}{R^2 - Rf} \qquad \varepsilon = -\frac{\tan \Delta\varphi_{O1}(1+\alpha_{O1}^2)}{\tan \Delta\varphi_{O1} + \alpha_{O1}}$$

Rheological model for NA138 in Strasbourg

	θ (min)	ε	α_{O1}	$\Delta\varphi_{O1}$	$\Delta\varphi_{M2}$
Phases adjusted on C026	210	0.029	0.853	0.8*	0.7*
Ducarme B., 1973•	229*	0.033*	0.929	0.95	0.77

* Fixed to compute other parameters

• recomputation of θ and ε from original data (mémoire de J.Vitry)

It was decided

- to normalize the astaticized gravimeters on the results of ASKANIA gravimeters in Brussels

$\delta(O1) = 1.161$

$\varphi(O1) = -0.2°$, $\varphi(M2) = 2.7°$

This normalisation was called « Brussels Fundamental Station »

- to determine the corresponding rheological model for each instrument

The feedback solution

- The only way to cope with the rheological properties of astaticized gravimeters is the transformation in « zero method instruments ».
- A mechanical feedback first and an electrostatic one later was proposed very early by LaCoste with its ET meters
- LCR model G and D have been equipped with a feedback by M. van Ruymbeke since 1985.
- It was not possible to modify GEOGYNAMICS instruments.

Tidal Gravity Profiles

- A tidal gravity profile is a set of tidal gravity stations occupied for a period of 6 months minimum, for the separation of P1,S1K1 and S2, K2.
- The first initiative was the US transect launched by J.T.Kuo prior to 1970.
- The main profiles based on Brussels Fundamental Station were

  * Trans European Profile (TEP) 1970-1973, J.T. Kuo

  * Fennoscandinavian Profile 1971-1977, J. Kääriäinen

  * Trans World Tidal Gravity Profile (TWP) 1973-1993

  P. Melchior, B. Ducarme, M. van Ruymbeke, C. Poitevin

  * Iberian Profile 1976-1986, R. Vieira

- The Tidal Institute (Liverpool, UK) performed independantly a lot of observations with its ET meters (T. F. Baker).
- Let us mention also the « Blue Road Geotraverse, 1981 »(G. Jentzsch)

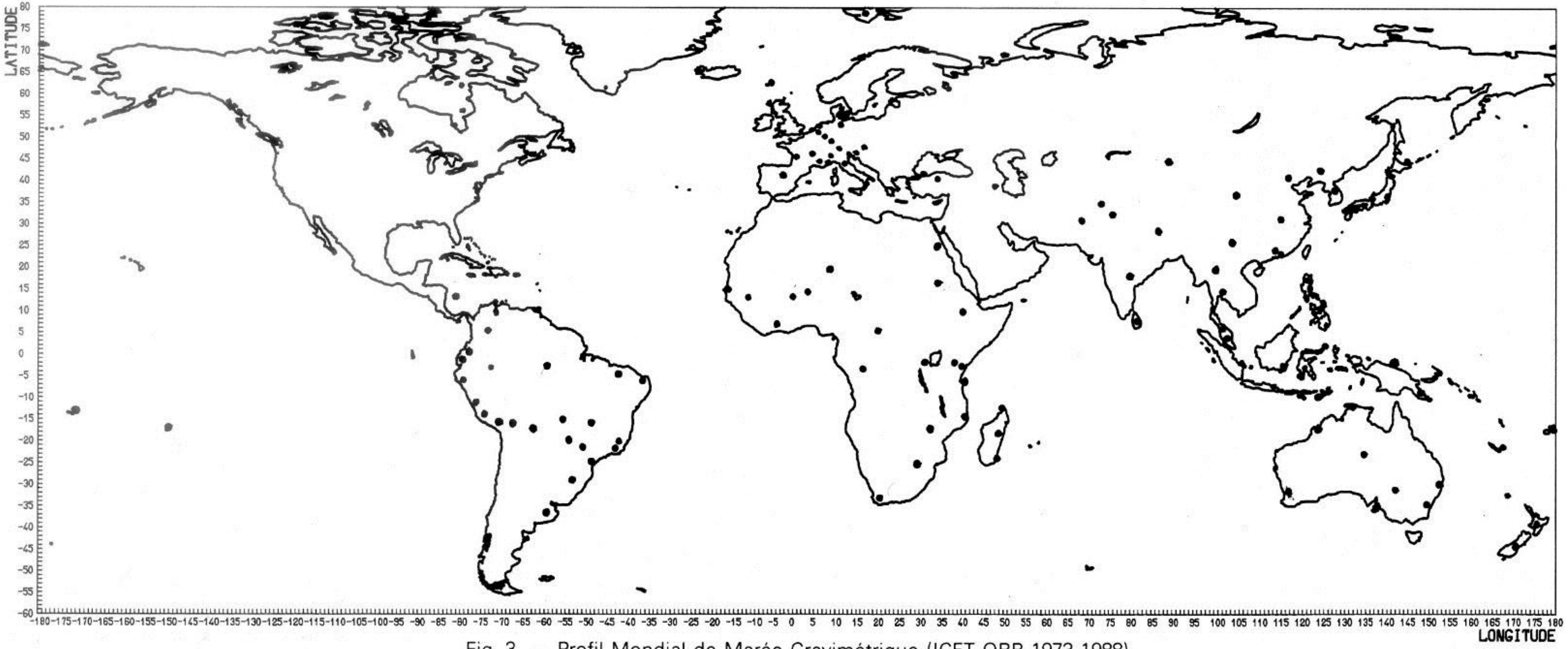


Fig. 3. — Profil Mondial de Marée Gravimétrique (ICET-ORB 1973-1988).

Trans World Tidal Gravity Profile (ICET-ORB 1973-1988).

The LCR model G and D gravimeters have been equipped with a feedback after 1985. The definition of a rheological model was then no more necessary

Results and Interpretaion

- Tidal signal was recorded with chart strip recorders (speed 6cm/h) and digitized with a semi-automatic readind device.
- The rate of sampling was one reading per hour.
- The resolution was 0.1mm corresponding to

  0.01% of tidal range and 6s in time.
- Calibration was performed twice a week with Geodynamics and at least every fortnight for LCR.
- Timing was controlled by a quartz clock.
- The data were preprocessed and analyzed with the VAV66 least squares analysis procedure

The interpretation was based on the diagram of the tidal vectors introduced by T.F. Baker

- The tidal gravity observation vector **A**$(\delta A_{th},\alpha)$ can be compared with the body tides models **R**$(A_{th}.\delta_{th}, 0)$, if we subtract the tidal loading effects **L**(L,λ) to get the so called "corrected tidal parameters": amplitude factor δ_c and phase difference α_c.

$$\mathbf{A_c}(\delta_c A_{th}, \alpha_c) = \mathbf{A} - \mathbf{L}$$

- It is possible to compute "modelled tidal factors"

$$\mathbf{A_m}(\delta_m A_{th}, \alpha_m) = \mathbf{R} + \mathbf{L}$$

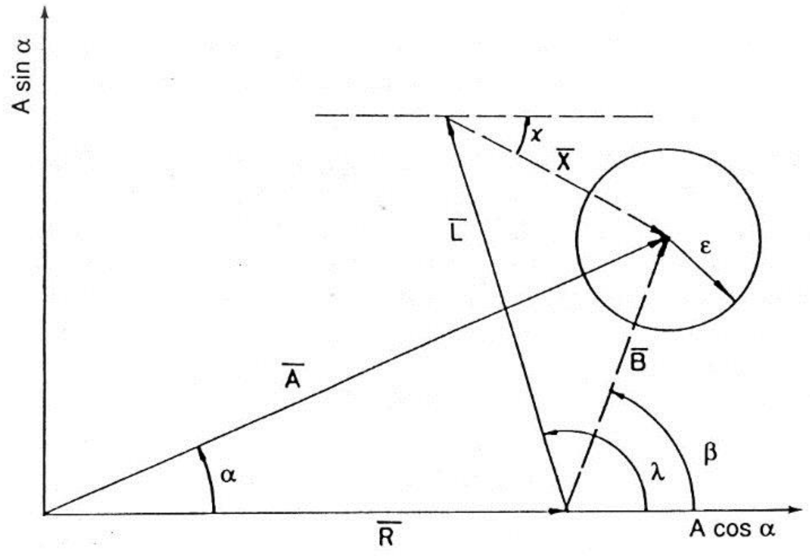


Fig. 4. — Diagramme vectoriel pour une onde de marée : **A** vecteur observé (A : amplitude, α : déphasage). **R** vecteur théorique (R : amplitude, pas de déphasage). **B** = **A**-**R** vecteur résidu (B : amplitude, β : déphasage). **L** vecteur décrivant les effets d'attraction et de surcharge des marées océaniques (L : amplitude, λ : déphasage). **X** = **B**-**L** vecteur résidu final après modélisation des effets de océaniques (X : amplitude, χ : déphasage). ε erreur d'observation. Les différences de phase sont mesurées par rapport à la marée astronomique. Pour l'onde M_2 l'échelle de la figure serait : A de 40 μgal (Europe) à 80 μgal (région équatoriale). α compris entre $+5^0$ et -5^0 ; L ≈ B de 2 à 10 μgal ; ε de 0,5 μgal (Europe) à 1 μgal (région équatoriale).

Vectorial diagram for a tidal wave : **A** *observed vector (A : amplitude, α : phase difference).* **R** *theoretical vector for an elastic oceanless Earth with a liquid core (R : amplitude, no phase difference).* **B** = **A**-**R** *residual vector (B : amplitude, β : phase difference).* **L** *vector discribing the attraction and loading effects of the oceanic tides (L : amplitude, λ : phase difference).* **X** = **B**-**L** *final residue after modelisation of the oceanic effects (X : amplitude, χ : phase difference). ε observational error. Phase differences are given with respect to the astronomical tide. For M_2 realistic values should be : A from 40 μgal (Europe) to 80 μgal (Equator). α comprised between $+5^0$ and -5^0 ; L ≈ B from 2 to 10 μgal ; ε from 0.5 μgal (Europe) to 1 μgal (Equator).*

TWP results, wave M2

P. Melchior, B. Ducarme, 1989. L’étude des phénomènes de marée gravimétrique. Géodynamique, 4 (1), 3-14

- Correlation between **B** and **L** (Schwiderski map)

  0.848 (in phase), 0.929 (out of phase)
- **X** vector represents the unmodelled part of the tidal signal.
- Larger dispersion for the in phase component

  Number of residues lower than :

  0.5µgal: 32% (in phase), 60% (out of phase)

  1.0µgal: 53% (in phase)

Why?

as α is $\leq 5°$

- The in phase component is mainly influenced by the calibration on **A**, the body tides **R** and the load vector **L**.
- The out of phase component is mainly influenced by the timing error and by **L**

109 stations

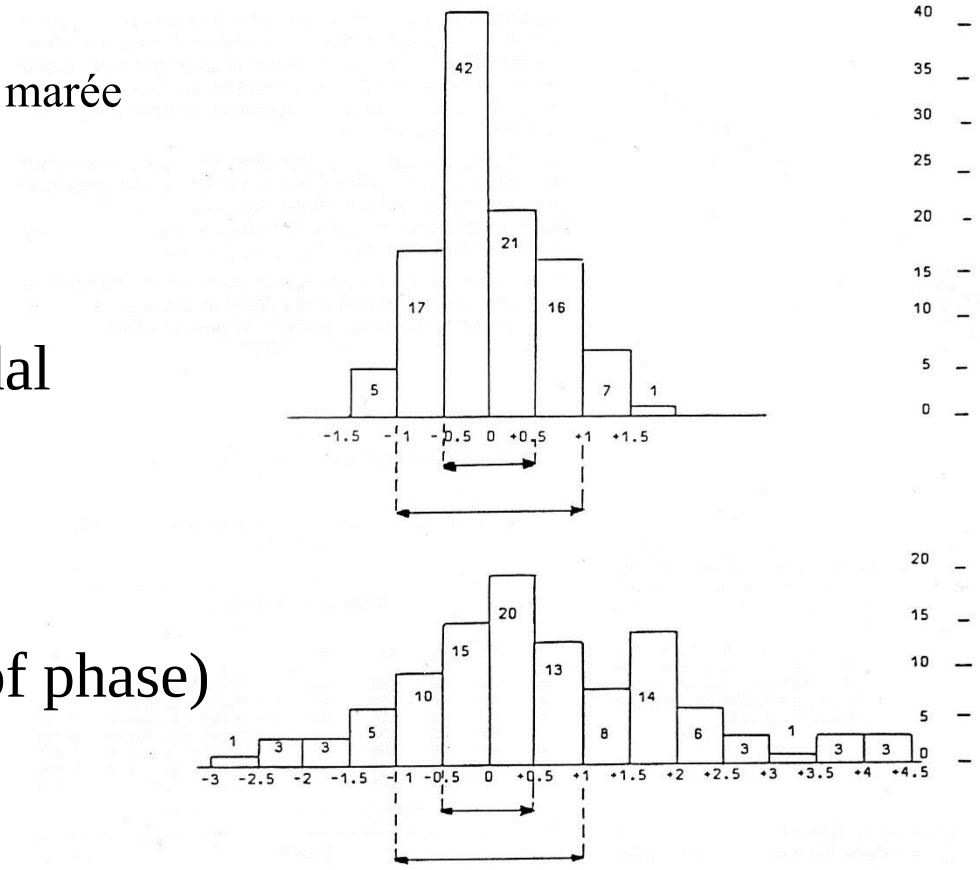


Fig. 5. — Histogramme donnant la répartition des résidus de marées pour l'onde semi-diurne M_2 (109 stations non européennes). Diagramme supérieur X sin χ ; diagramme inférieur X cos χ.

Histogram showing the repartition of the final residues for the semidiurnal wave M_2 (109 stations outside Europe). Upper diagram X sin χ ; lower diagram X cos χ.

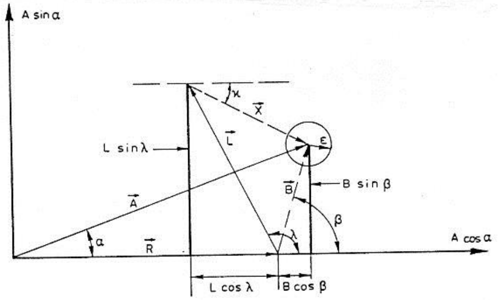


Fig. 1. Comparison of observed and calculated ocean–continent tidal interactions. For the semi-diurnal M_2 wave, the correct scale of this figure should be: $R \simeq A \simeq 40$ (Europe)–90 (Equator) µgal; $\alpha \simeq 0-\pm 5°$; $L \simeq B \simeq 2$ (Europe)–10 (South Pacific) µgal; $X \simeq 0.5-5$ µgal; $\epsilon \simeq 0.5$ (Europe)–1 (Equatorial zone) µgal (**B**=**A**−**R**, **B**−**L**=**X**).

TWP results, wave M2

P. Melchior, B. Ducarme, 1989. L'étude des phénomènes de marée gravimétrique. Géodynamique, 4 (1), 3-14

Errors on load vector L

The Schwiderski map had a low precision and a coarse grid of 1°x1°

BUT

- A recent recomputation by O. Francis with recent ocean tides models did not reduce the dispersion on **X**.
- The effect should be the same for the in phase and out of phase components.

Timing errors

- Timing errors affect mainly the out of phase component
- Less than 5s (0.05° for M2) should not induce error larger than 0.1% on the out of phase component.
- The standard deviation close to 0.5µgal reflects essentially the errors on loading computation

Errors of calibration

- As the phase difference α is small the error on $|A|$ will affect mainly the in phase component.
- It corresponds to a scattering of the normalisation of the different instruments at Brussels.
- The claimed accuracy was 1% corresponding to residues around ±0.6µgal
- Combining the loading error (0.5µgal) and calibration error (0.6µgal) we get 0.8µgal
- The dispersion is larger than 1.0µgal. There is perhaps another contribution.

TWP results, wave M2

P. Melchior, B. Ducarme, 1989. L'étude des phénomènes de marée gravimétrique. Géodynamique, 4 (1), 3-14

Is there another factor hidden in the anomalous dispersion of the in phase component?

- This factor could affect directly the **R** vector.
- It should come from the Earth interior.
- In continental areas « Heat Flow » depends on the age of the lithosphere.
- We found a correlation between y = Xcosχ
  and the reduced heat flow H*= H - 62.3mW/m^2.
- The coefficient of correlation k is close to 0.7

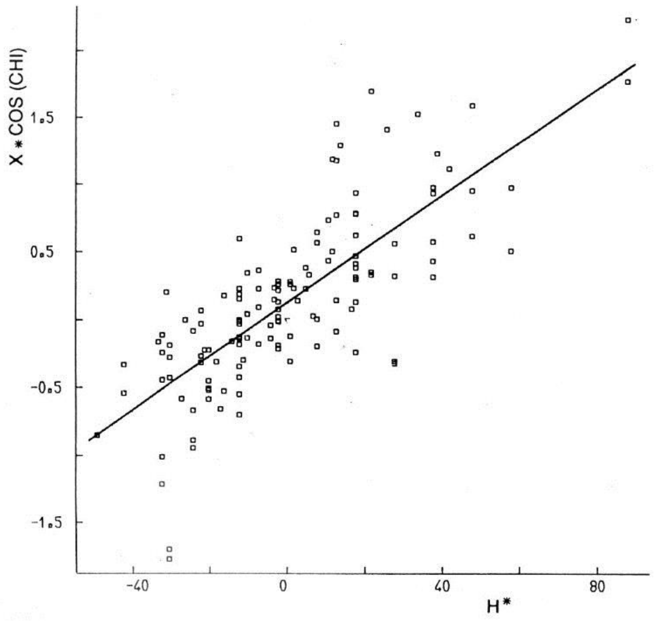


Fig. 6. — Régression linéaire entre la composante du résidu final **X** en phase avec la marée théorique et la valeur réduite du flux de chaleur H* = H − 62,3 mWm^{-2}. Calcul pour 63 stations, valeur des résidus réduite à 45°. X cos χ = 0,163 µgal + 0,0208 H* ; écart type 0,4 µgal ; coefficient de corrélation k = 0,733.

Linear regression between the component of the final residue **X** *in phase with the theoretical tide and the reduced heat flow H* = H − 62.3 mWm^{-2}. Computation for 63 stations, values of residues reduced to 45°. X cos χ = 0.163 µgal + 0.0208 H* ; standart deviation 0.4 µgal ; correlation coefficient k = 0.733.*

Correlation between tidal residues and heat flow
Wave M2

Monde (sans l'Europe)

Øo	Ø1	Ho	H1	n		k
0	30	20	150	29	y = 0.130 + 0.0217 H*	0.786
0	40	20	150	49	y = 0.136 + 0.0206 H*	0.730
0	50	20	150	62	y = 0.168 + 0.0210 H*	0.735
0	65	20	150	63	y = 0.163 + 0.0208 H*	0.733
20	65	30	150	42	y = 0.185 + 0.0199 H*	0.677
30	65	30	150	34	y = 0.198 + 0.0196 H*	0.670
40	65	30	110	14	y = 0.266 + 0.0232 H*	0.802

The vector **X** is normalised on the amplitude of M2 at 45°

TWP results, wave M2

P. Melchior, B. Ducarme, 1989. L'étude des phénomènes de marée gravimétrique. Géodynamique, 4 (1), 3-14

- Similar results are found in Europe

Europe

$Ø_0$	$Ø_1$	H_0	H_1	n		k
35	50	40	120	42	$y = 0.108 + 0.0131\ H^*$	0.704
35	60	35	120	62	$y = 0.149 + 0.0145\ H^*$	0.644
35	65	30	120	70	$y = 0.111 + 0.0170\ H^*$	0.665

- And globally

Monde Entier

$Ø_0$	$Ø_1$	H_0	H_1	n		k
0	50	20	150	104	$y = 0.129 + 0.0186\ H^*$	0.712
0	65	20	150	133	$y = 0.137 + 0.0193\ H^*$	0.708
0	70	20	150	139	$y = 0.127 + 0.0198\ H^*$	0.725

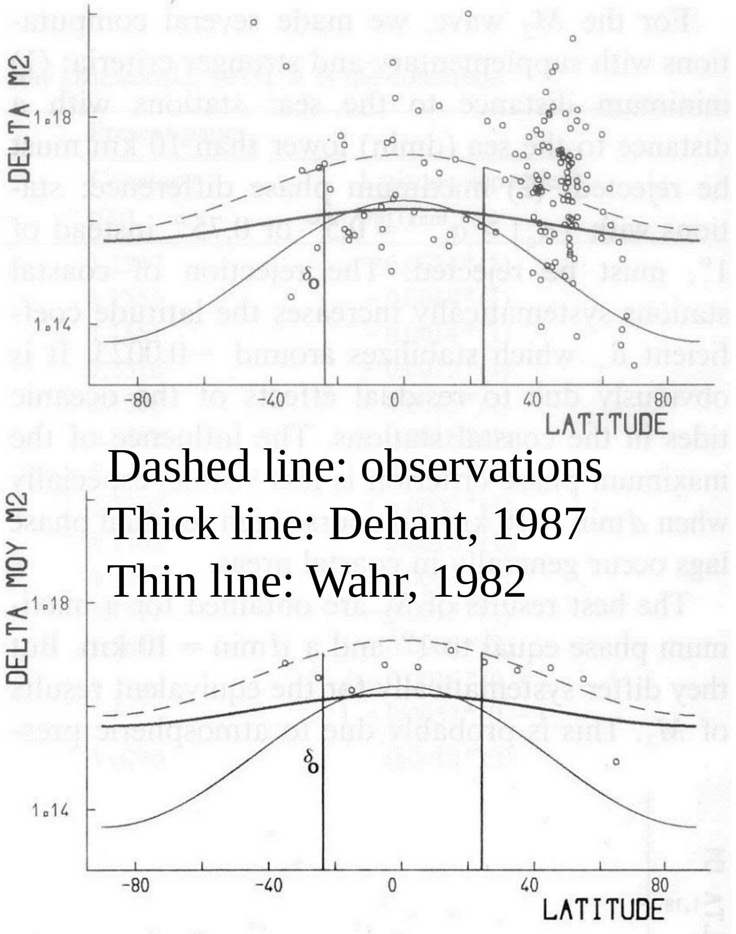
ATTENTION: The slope of the regression for O1 is only 0.01!

TWP results, wave M2

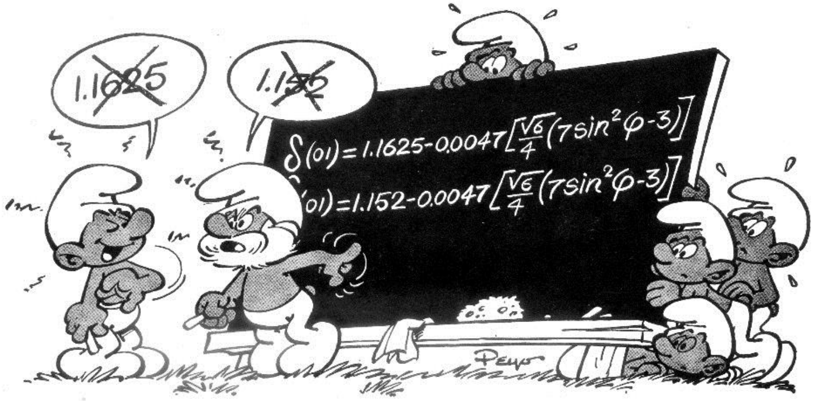
V. Dehant, B. Ducarme, 1987.
Comparison between the theoretical and observed tidal gravimetric factors
Phys. Earth Planet. Int., 49, 192)212

- In 1987 V. Dehant presented a new model of the response of the Earth to the Tidal Potential (« Earth tides » senso stricto).
- The latitude dependance in her model was much less important than in the previous J.M. Wahr model.
- The δ_c values of TWP were in better agreement with the Dehant, 1987 model.
- However a systematic calibration error close to 1% was obvious
- Results presented at the 10th International Symposium on Earth Tides (Madrid, 1985) had already shown that the calibration of the Brussel's Fundamental station based on old Akania gravimeters should be modified:

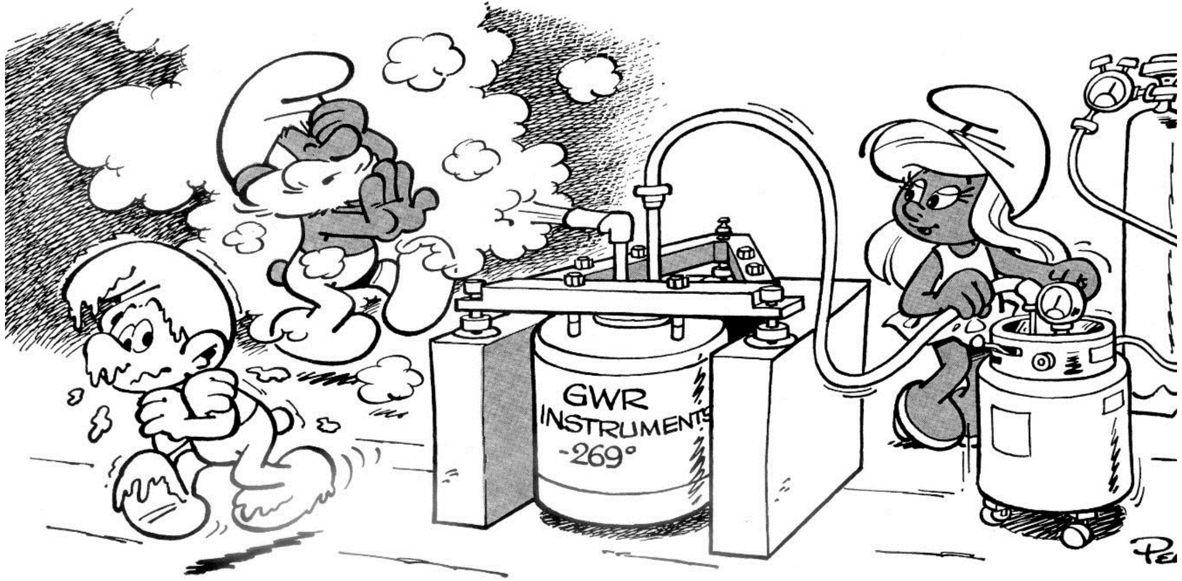
  * Improving the accuracy of tidal gravity measurements (Edge R.J., Baker T.F., Jeffries G.),
  * Calibration of LaCoste-Romberg gravimeters by inertial acceleration (M. van Ruymbeke).



Dashed line: observations
Thick line: Dehant, 1987
Thin line: Wahr, 1982



Evolution since 1990



- Spring gravimeters are equipped with feedback.
- New gravimeters appeared SCINTREX, ZLS
- Digital sampling at one minute interval is generalized.
- The global network of superconducting gravimeters (GGP) was launched in 1997.
- More precise calibration became possible by
  * Inertial acceleration using sinusoidal waves
    B. Richter, superconducting gravimeters
    M. van Ruymbeke, LCR gravimeters
  * Comparison with absolute gravimeters JILAG or FG5 (J. Makinen, O. Francis)
- Precise determination of the transfer functions (H.G. Wenzel, M. Van Camp)
- More precise ocean tides models allow better ocean loading computation
- Finite elements models are used to compute cavity and topographic effects
- Global atmospheric models improve correction of atmospheric effects.
- Non tidal phenomena are investigated
  * Slichter triplet around 4h period
  * local and regional hydrological effects

Period (seconds)	calibr. factor (10^{-8} ms^{-2}/Volt)
600	58.899
900	59.133
1200	58.443
2400	59.425
mean	58.975 ± 0.414

2007status

- A comparison of spring and superconducting gravimeters in Europe showed agreement at the level of 0.05% for the mean values.
- Individual instruments could be offset of 0.2%
- For O1 the mean ratios between the observed and theoretical amplitude factors are: DDW/H 1.00051, MAT01/NH 0.99948, DDW/NH 0.99923.
- For M2 the mean ratios are: DDW/H 1.00137, MAT01/NH 1.00040, DDW/NH 1.00013.
- The models are in agreement within 0.1%; MAT01/NH is closer to the results

From:

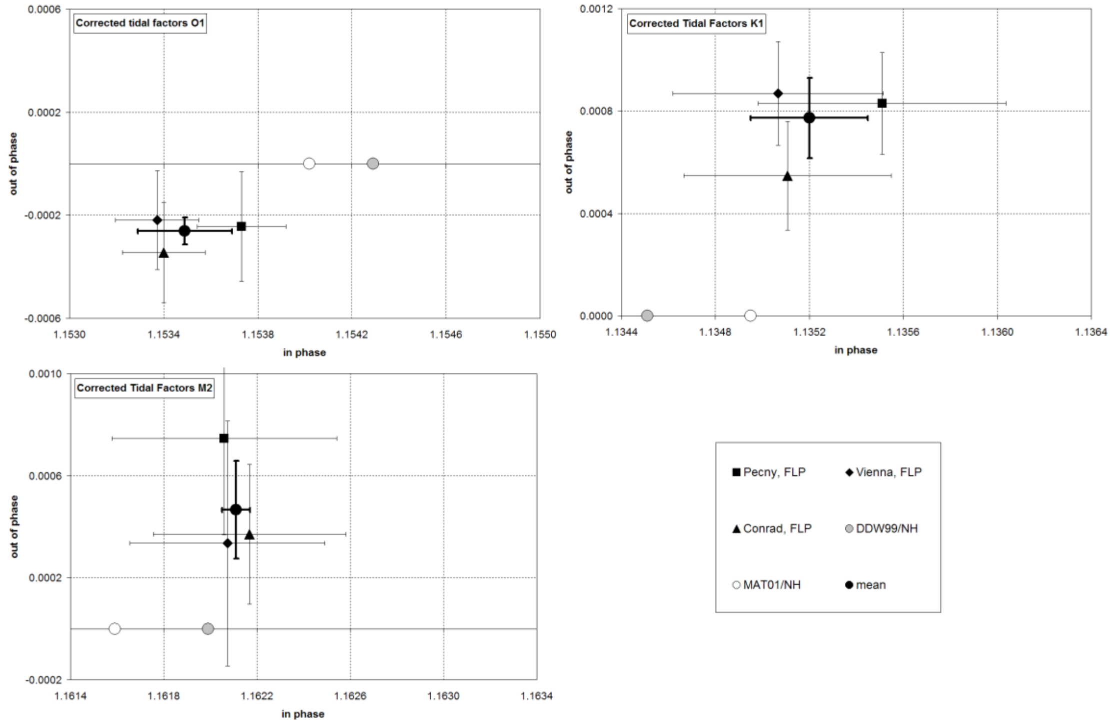
European tidal gravity observations: Comparison with Earth Tides models and estimation of the Free Core Nutation (FCN) parameters.

Ducarme B., Rosat S., Vandercoilden L., Xu J.Q., Sun H.P., 2009. Proceedings of the 2007 IAG General Assembly, Perugia, Italy, July 2 - 13, 2007, Observing our Changing Earth, M.G. Sideris (ed.), Springer Verlag, International. Association of Geodesy Symposia 133, 523-532*(DOI10.1007/978-3-540-85426-5)*.

wave		O1		M2		M2/O1
		Corrected Factors		Corrected Factors		
		δ_c	α_c	δ_c	α_c	δ_c(M2)/ δ_c(O1)
GGP profile						
0243	Membach	1.15359	0.018	•1.16142	*0.119	*1.00679
0306	Strasbourg	1.15366	0.010	1.16232	0.045	1.00751
0734	B. Homburg	1.15450	0.021	1.16287	0.074	1.00725
0770	Moxa	1.15315	0.029	1.16159	0.063	1.00732
0506	Medicina	1.15334	0.010	1.16237	0.011	1.00783
0731	Wettzell	1.15237	0.032	1.16116	0.048	1.00763
0698	Vienna	1.15224	0.031	1.16092	0.029	1.00753
mean		1.15326	0.022	1.16187	0.046	1.00747
STD		0.00078	0.009	0.00072	0.023	0.00021
Additional stations						
0200	Brussels	1.15405	-.028	•1.16077	*0.093	*1.0058
0257	Walferdange	1.15506	-.013	1.16294	-.037	1.00682
0765	Potsdam	1.15413	0.018	1.16324	0.034	1.00789
0930	Pecny	1.15443	0.021	1.16342	0.026	1.00779
0716	Schiltach	1.15293	0.011	1.16180	0.043	1.00769
0705	Karlruhe	1.15339	0.046	1.16198	0.048	1.00745
0709	Hanover	1.15350	0.053	1.16240	0.040	1.00775
0615	Zürich	1.15226	-.006	1.16147	-.001	1.00799
0610	Chur	1.15173	0.002	1.16110	0.006	1.00814
mean		1.15350	0.012	1.16229	0.020	1.00762
STD		0.00106	0.026	0.00085	0.029	0.00041
Global						
mean		1.15340	0.016	1.16211	0.031	1.00755
STD		0.00092	0.021	0.00081	0.029	0.00034
RMS		0.00023	.0005	.00020	0.007	0.00008

2014 status

- Comparison of 3 GGP stations located in Central Europe: Pecny, Vienna and Conrad
- Agreement of the calibrations within 0.03%
- Agreement with Strasbourg results 0.05%
- The hydrostatic models are not convenient.
- MAT01/NH is the closest model for O1 (discrepancy 0.05%) and K1 (discrepancy 0.025%). DDW99/NH is the closest model for M2 (discrepancy 0.01%)
- Agreement of phases within 0.02°



FROM:

Ducarme B.,Pálinkáš V., Meurers B., Cui Xiaoming, Vaľko M. 2014. **On the comparison of tidal gravity parameters with tidal models in central Europe.** Proc. 17th Int. Symp. On Earth Tides, Warsaw, 15-19 April 2013. S. Pagiatakis ed., J. Geodynamics, 80, 12-19. DOI: 10.1016/j.jog.2014.02.011

2014 status

- Comparison of two superconducting gravimeters at Wuhan.
- the calibrations agree within 0.4‰ in amplitude and 0.03° in phase.

Wave group	iGrav-007		SG-065		Difference (iGrav- SG)	
	δ & RMS error	Δφ(°) & RMS error	δ	Δφ(°)	Δδ(x1000)	ΔΔφ(°)
O_1	1.17436 ±0.00012	-0.5009 ±0.0059	1.17416 ±0.00033	-0.5016 ±0.0162	+0.20	+0.0007
K_1	1.14842 ±0.00010	-0.5626 ±0.0052	1.14802 ±0.00040	-0.5529 ±0.0202	+0.40	-0.0097
M_2	1.17094 ±0.00004	-0.4724 ±0.0017	1.17092 ±0.00006	-0.4456 ±0.0027	+0.02	-0.0268
S_2	1.16509 ±0.00012	-0.6857 ±0.0077	1.16487 ±0.00020	-0.6549 ±0.0126	+0.22	-0.0308

FROM:

Comparison of noise levels of the new *i*Grav-007 superconducting gravimeter and the SG-065 superconducting gravimeter in Wuhan (China).

Zhang Miaomiao, Xu Jianqiao, Sun Heping, Shen Wenbin, Chen Xiaodong, 2014

Bull. Inf. Marées Terrestres, 148, 11987-12000

CONCLUSIONS

The challenge proposed in 1957 was:

- to establish permanent observing stations
- equipped with new high sensitivity instruments
- to investigate how to correctly calibrate these instruments
- to try to measure the contribution of oceanic loading effects
- to investigate the Poincaré-Jeffreys effect, i.e. the liquid core resonance.

- Tidal observations have been performed over the whole Earth, including the permanent network of GGP stations.
- Superconducting gravimeters have a resolution of 0.1nm/s^2 , water tube tiltmeters 0.001mas.
- Calibration are performed to better than 0.1%.
- Very precise ocean tides models and tidal loading computation software (Free Loading Provider; M. Bos, H. G. Scherneck) are in use.
- The FCN is modelled with a precision of 0.1% (J. Wahr, V. Dehant, P. Defraigne, P.M. Mathews) and observations agree within the same error bounds