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Some problems of tilt and strain measurements

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The importance of calibration methods is emphasized. It is considered that the numerical results obtained for the tidal *diurnal* tesseral waves provide a quality test for the instruments.

1. INTRODUCTION

The lecture given by G. W. Lennon reflects the main ideas and conclusions given in a paper of Vanicek & Lennon (1972; V.N.) published recently. This paper is a very interesting one and is a real contribution to solving the problem of tilt measurements. The many observations made by Vanicek & Lennon will help further improvement of these delicate instruments devised for measuring tenths of milliseconds of arc. But I cannot agree with some of their conclusions and therefore I hope that a discussion on these questionable points will help us to solve some difficulties.

The main reason for the disagreement between Vanicek & Lennon and the Brussels group (Verbaandert, Van Gils, Ducarme, Van Ruymbeke and myself) is due to the fact that we always work in *deep* underground laboratories or stations ('deep' means a minimum depth of 50 m) while they have made their observations at Bidston Observatory, at a depth of only 6 m. We think and we will try to prove that at so superficial a place, some of the advantages of our method are masked by high-level noise that practically does not exist in deep stations.

2. CALIBRATION METHOD

The calibration principle of an instrument is to apply artificially to it the phenomenon to be measured and to observe its response. In the case of horizontal pendulums we have thus to tilt the instrument artificially. The artificial tilt must be known with the highest possible precision.

With the mercury crapaudine we are able to define the artificial tilt with a precision of 0.5 % as it is derived from the wavelength of a spectral line. It is thus an absolute method. The crapaudine has *no measurable time-lag* (as suggested by V.L., p. 46).

The automatic calibration device used in our underground stations does *not* introduce a *pulse* (see V.L., p. 48) for it takes 15 min to bring about the change of pressure with a very slow departure, then a quick change followed by a very slow termination. Never, in the many hundreds of calibrations obtained in all our stations using this procedure, have we observed any asymptotic damping effect. Each calibration consists of two deflexions (up and down – separated by 3 h in time), the mean of which is taken. The maximum difference between the two deflexions may reach 9/1000 (see Bonatz, Melchior & Ducarme 1971, p. 9). In the presence of microseisms it may be impossible to measure one of the deflexions. This does not happen very often: for instance, only three in 93 times in one year at Spitsbergen (Bonatz *et al.* 1971, p. 9), despite the high noise in this island station.

The 93 calibrations of Spitsbergen are then fitted by a smoothed curve, using Vondrak's procedure, taking into account weighted third order differences. This is shown on figure 1.

For the analysis of the data two calibration tables were used: (1) considering every calibration datum (and allowing linear interpolation between each pair of data; (2) a second one considering the smoothed curve obtained by Vondrak's method.

For all the instruments we obtained essentially the same results for the amplitude factors and the mean square errors. There is perhaps a very slight improvement with the smoothed curve but I do not consider it to be significant.

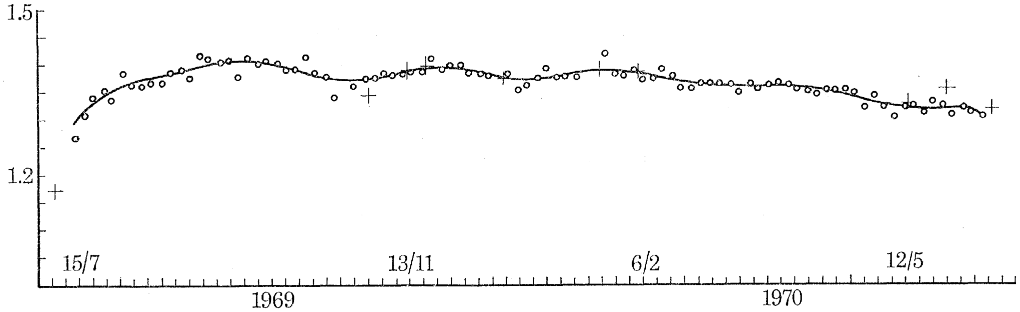

Figure 1. Sensitivity of VM quartz pendulum no. 100 installed at Spitzbergen expressed in 0.001″/mm on recording paper, ○, automatic calibration; +, calibration from period measurement.

A comparison of figure 1, showing the results obtained in the mines of Spitsbergen (depth 300 m) with the results obtained at Bidston (V.L., fig. 2), shows that the Bidston results are bad, especially as Spitsbergen stations are also very near to the sea (4 km) and should have noise comparable with Bidston. It is clear that the best laboratory for such instruments is a deep underground laboratory (constant temperature, reduced noise, no observer). One cannot expect to derive correct results in the range of 0.001″ measurements at depths of a few metres so near to the sea.

Moreover, the calibration by period measurements is not at all independent of the direct crapaudine measurements because the instrumental constant K, obtained from periodic measurements, yields the sensitivity s:

$$s = K/T^2$$

which is determined in our *surface* laboratory at Brussels, by using several crapaudines.

This method also allows the quality of the instrument to be checked ($6.0 \leqslant K \leqslant 6.3$). We indeed observed in four cases out of some 100 that, *after transportation*, the constant K might have changed. Unfortunately we could not find any explanation for it. Only in one case (Helsinki), was one crapaudine (old type) definitely a bad one.

Thus, as there is *no difference in principle* between the calibration made in our laboratory (20 measurements) and the large set of calibrations obtained in far better conditions in a deep underground station, the latter determinations evidently must be adopted for the calculations. It is quite obvious that checking the results by period measurements is interesting, but what is really important is to detect coherent changes of sensitivity, as those given by Vanicek & Lennon (1972, fig. 2). Nevertheless, the excellent fit of Spitsbergen results for VM 100 is far more satisfactory. We also had a systematic discrepancy (5 %) like that stated at Bidston for one of the eight pendulums installed at Spitsbergen (Bonatz *et al.* 1971). For our calculations we adopted the calibrations made *in situ* and the numerical results for the γ factor were then in good agreement with the other instruments.

The possibility of the constant K changing during transportation (shocks?) as well as with time (viscosity of suspension?), unavoidable with instruments, shows that the basic measurements made in the laboratory cannot be extrapolated but that they must be repeated frequently inside the station.

I must add that we are not at all convinced that period measurements could be more precise than crapaudine displacements as we have operated both methods more than a thousand times since 1960.

With metallic pendulums there is a strong dependence of the free period on the amplitude of oscillations, mainly for band suspensions. For quartz pendulums, with good soldering this dependence is usually not observable (Melchior 1964). But in any case, oscillations of very small amplitude (5 cm or so) must be measured and as the spot is moving then so slowly it is difficult to measure periods with a precision greater than 0.1 Hz. Moreover, this should be done with the observer in a remote position as his presence disturbs the instrument. It must be recalled that very sophisticated methods cannot be applied either in mines (owing to the humidity) or in all stations (owing to the very expensive components used).

To be independent, the 'period method' in no way should make use of a basic crapaudine determination of the constant K.

3. PRECISION OF INSTRUMENTS

So far, VM quartz pendulums are installed in fourteen different countries which already have published results. We also have published sixteen volumes with complete detailed measurements, including a great number of calibration tables (Observatoire Royal de Belgique). These tables seem not to have been considered in Vanicek & Lennon's paper. Contrariwise to Bidston, (V.L., fig. 2, p. 47), the sensitivity changes are very small or very regular and can be fitted very well by polynomial methods.

Personally I think that the best criterion for the quality of an instrument is to check and compare the obtained results. One has to consider separately the different species of tidal waves, mainly the tesseral diurnal ones, the sectorial semi-diurnal and the sectorial ter-diurnal ones.

(*a*) *Tesseral diurnal waves*

These waves are observable only in east-west component for stations situated at mid-latitudes (all but the one at Spitzbergen) as the north–south component has its amplitude vanishing at the latitudes 45°.

The results, as shown in table 1, are in excellent agreement with the models of the Earth. This indicates evidently that the calibration principle is correct.

So far only quartz pendulums enable us to derive correctly the diurnal waves upon which the temperature effects are very troublesome.

(*b*) *Sectorial semi-diurnal waves*

These waves are strongly disturbed by indirect oceanic effects. It is true that the north–south component results are erratic in Europe and so far no explanation has been found. However, in the east–west component, the results show clearly a regional repetition (table 2). This may become better understandable when a more regular network of stations is installed.

(*c*) *Sectorial ter-diurnal waves*

The main wave of this type M_3 has a theoretical amplitude of about 0.0001″ in the two directions at a latitude of only 50°. We have results from quartz pendulums which are given in table 3 and are in excellent agreement with the theoretical models. This again speaks for the quality of these instruments as well as for their calibration.

TABLE 1

	period 23 h 56 min	$A_{\max} = 0.009''$
K_1 wave	γ_2	n
Belgium	0.7535 ± 0.0061	2332
	0.7269 ± 0.0153	544
	0.7794 ± 0.0082	1326
	0.7545 ± 0.0032	2556
	0.7554 ± 0.0031	2336
	0.7250 ± 0.0160	488
Luxembourg	0.7531 ± 0.0052	768
	0.7469 ± 0.0097	400
Czechoslovakia	0.7321 ± 0.0084	846
Germany	0.7554 ± 0.0082	312
Austria	0.7359 ± 0.0123	598
Hungary	0.7599 ± 0.0261	42
Finland	0.7163 ± 0.0085	780
Sweden	0.7326 ± 0.0046	2380
w. mean	0.749 ± 0.005	—
Molodensky model 1	0.734	

	period 24 h 04 min	$A_{\max} = 0.003''$
P_1 wave	γ_2	n
Belgium	0.697 ± 0.019	2332
	0.654 ± 0.049	544
	0.756 ± 0.026	1326
	0.724 ± 0.010	2526
	0.726 ± 0.010	2336
	0.679 ± 0.053	488
Luxembourg	0.714 ± 0.017	768
	0.697 ± 0.032	400
Czechoslovakia	0.622 ± 0.028	846
Germany	0.687 ± 0.027	312
Austria	0.826 ± 0.040	598
Finland	0.616 ± 0.029	780
Sweden	0.678 ± 0.015	2380
w. mean	0.717 ± 0.018	
Molodensky Model 1	0.699	

	period 25 h 49 min	$A_{\max} = 0.006''$
O_1 wave	γ_2	n
Belgium	0.6839 ± 0.0085	2332
	0.6883 ± 0.0203	544
	0.6915 ± 0.0112	1326
	0.6645 ± 0.0044	2526
	0.6670 ± 0.0042	2336
	0.6958 ± 0.0206	488
Luxembourg	0.6762 ± 0.0070	768
	0.6329 ± 0.0130	400
Czechoslovakia	0.6917 ± 0.0112	846
Germany	0.6787 ± 0.0111	312
Austria	0.6476 ± 0.0166	598
Hungary	0.7006 ± 0.0369	42
Finland	0.6983 ± 0.0112	780
Sweden	0.7108 ± 0.0063	2380
w. mean	0.674 ± 0.005	
Molodensky model 1	0.688	

$\gamma_2 = 1 + k_2 - h_2$.

n, number of days of observations analysed.

TABLE 2. A COMPARISON OF CLINOMETRIC RESULTS IN WESTERN EUROPE

	E–W component γ_2	M_2 wave α
1. Sclaigneaux 1, 2, 3	0.851	10 16
2. Kanne	0.916	3 45
3. Dourbes 1, 2	0.836	5 90
4. Warmifontaine 1, 2	0.805	−6 54
5. Luxembourg	0.871	−4 75
6. Walferdange 1, 2	0.886	−5 87
7. Villiers Adam	0.770	−5 6
8. Savonnieres	0.881	−14 9
9. Sainte Marie	0.887	3 4
10. Bussang	0.825	−11 8
11. Erpel	0.944	3 21
12. Tiefer Koningst.	0.732	−5 30
13. Bad Grund	0.792	−11 97
14. Tiefenort	0.843	−9 27
15. Berchtesgaden	0.821	−12 50
16. Pribram	0.849	−10 21
17. Roburent	0.821	−8 17
18. Costozza	0.804	−5 16
19. Graz	0.679	0 11
20. Sopron	0.741	0 24
21. Dannemora	0.644	4 20
22. Lohja	0.641	0 62

γ_2, amplitude factor $= 1+k_2-h_2$; α, phase, $(-)$ represents a lag.

TABLE 3

	period 8 h 18 min E–W		$A_{45°} = 0.0001''$ N–S	
M_3 wave	γ_3	n	γ_3	n
Belgium	0.805 ± 0.117	1084	0.861 ± 0.113	1088
	0.742 ± 0.091	1160	0.789 ± 0.148	824
	0.834 ± 0.028	2390	0.811 ± 0.023	2560
	0.784 ± 0.029	2326	0.784 ± 0.037	2448
	0.819 ± 0.056	1556	0.769 ± 0.123	1304
Luxembourg	0.799 ± 0.078	868	0.743 ± 0.093	426
Czechoslovakia	0.741 ± 0.090	796	0.827 ± 0.081	838

		γ_3
Models	Molodensky	0.802
	Takeuchi	0.809
	Longman	0.803

$\gamma_3 = 1+k_3-h_3$; n, numbers of days of observations analysed.

4. SOME REMARKS

(a) *Azimuth effects*

Vanicek & Lennon criticize (p. 44) the use of a triplet of recording lamps. I must say that the lateral lamps are not used for correcting deviations from the initial azimuth but only when an exceptional drift (hydrological effects, earthquakes) occurs.

(b) *Atmospheric pressure effect*

Atmospheric pressure variations correspond to some 5 kPa (4 cmHg). It is thus necessary to maintain the upper reservoir of mercury open in order to equilibrate the atmospheric pressure acting on the crapaudine plate. If such a precaution is not respected the crapaudine will react as an aneroid capsule.

5. Strain measurements

Strain measurements are now undertaken in the underground laboratory of Geodynamics at Walferdange–Luxembourg. Instruments and methods are described in Flick, Melchior, Van Gils & Ducarme (1973).

References (Melchior)

Bonatz, M., Melchior, P. & Ducarme, B. 1971 *Obs. Roy. Belgique – Bull. Obs. Marées Terrestres* **4**, 1.
Melchior, P. 1964 *B.I.M.* **35**, 1180–1182.
Observatoire Royal de Belgique 1972 *Bulletin d'Observations des Marées Terrestres.* (16 volumes until 1972).
Vanicek, P. & Lennon, G. W. 1972 *Studia geophys. geod.* **16**, 30–50.