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DISCUSSION ON THE RESULTS OF ANALYSES OF YEARLY OBSERVATIONS (2003) OF PLUMB LINE VARIATIONS FROM HORIZONTAL PENDULUMS AND LONG WATER-TUBE TILTMETERS

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ABSTRACT

In the paper we present the results of analyses of plumb line variations measurements from long water-tube tiltmeter during the first year of its work (2003). At the same time we made analysis of the yearly series of plumb line variations from horizontal pendulums. The results of the observations analyze from the long water-tube and horizontal pendulums enabled us to compare both instruments. We found significant discrepancies between phases of main tidal waves obtained on the basis of the long water-tube observations, as well as quartz horizontal pendulums. In our opinion, the reasons of the phases discrepancies are systematic errors of azimuth determination of pendulums measurements. We also compared mean square errors of the adjustment of data from both instruments. The ratio of mean square errors is close to 0.8. This result is unexpected on account of large difference between precisions of both instruments measurements. Possibilities of registration of the Earth's free oscillations phenomenon with help of the long water-tube tiltmeter were noticed during very strong earthquake (8.6 magnitude), which took place on 25 September 2003 near Japanese coast. The instrument registered two hours long anomaly of plumb line variations of the order of milliseconds of arc, caused by long surface waves which periods were at interval from one to tens of minutes. These plumb line variations were produced by phenomenon of the Earth's free oscillations originated by the earthquake. Because of the resonance effect most of the standard instruments, such as seismographs, gravimeters, and tiltmeters are not able to register phenomena associated with the Earth's free oscillations. Introduction to the hydrodynamic system of the long water-tube elements which suppress water waving caused that the resonance effect was not present.

KEYWORDS: Geodynamics, the Earth tides, earthquake, the Earth's free oscillations, tidal deformations, tilt effect, tiltmeters, horizontal pendulums, long water-tube

1. THE RESULTS OF THE ADJUSTMENT OF THE YEARLY SERIES OF PLUMB LINE VARIATIONS FROM QUARTZ HORIZONTAL PENDULUMS H-74 AND H-75 AND LONG WATER-TUBE TILTMETERS

The first tiltmeters working since thirty years in Low Silesian Geophysical Observatory are horizontal pendulums (Chojnicki - Weiss, 2003). We applied one pair of quartz horizontal pendulums, named H-74 and H-75. In the year 2003 mean azimuths of observations were –175 degrees for H-74 pendulum and –65 degrees for H-75 pendulum. Changes of azimuth reach ±5 degrees during the year. Tidal adjustments of observations of plumb line variations were made in azimuth NS and EW. While the projection of observations on directions NS and EW we considered the variability of measurements azimuths of both pendulums. To adjust observations of plumb line variations the algorithm basing on the least-squares method (Chojnicki, 1977) was applied. We estimated the accuracy of tidal waves parameters from Fourier analysis of residuum (Chojnicki, 1978). Because of variations of sensitivities of pendulums all observations were calibrated before adjustment. Momentum values of pendulums sensitivities were determined basing on measurements of the pendulums periods.

Between the moments of periods measurements we assumed linear variation of sensitivities. Results of final adjustment of data series from horizontal pendulums have been shown in Tables 1 and 2.

Simultaneously to the pendulums measurements, since two years we carry out observations of plumb line variations with help of the long water-tube tiltmeter (Kaczorowski, 2004a and 2004b). The questions joined with processing of data from water-tube tiltmeter are essentially different than questions of the horizontal pendulums observations processing.

In the case of the long water-tube we have constant and well known azimuth of observations. Because of constant sensitivity of instrument the repetition of the long water-tube calibration procedure is not necessary.

The sensitivity of measurements of new tiltmeter is very stable (Bower, 1970 and 1973). Accordingly to the technical data stability of the He-Ne laser light length is close to 632.8 ± 0.1 nanometers (Kaczorowski, 1999a and 1999b).

Table 1 The results of adjustment of plumb line variations data from H-74 and H-75 pendulums, projected on NS azimuth. In table there have been shown main waves groups.

FINAL ADJUSTMENT WITH 18 GROUPS OF WAVES, CHOJNICKI METHOD
STATION 0906 KSIAZ, POLAND
HORIZONTAL PENDULUM, BLUM NO H-74, H-75
TOTAL NUMBER OF DAYS 364, 3273 READINGS

WAVE GROUP			ESTIM. AMPL		AMPLITUDE FACTOR		PHASE DIFFERENCE		RESIDUALS	
ARGUMENT	N	SYMBOL	VALUE [mas]	R.M.S. [mas]	VALUE	R.M.S.	VALUE [deg]	R.M.S. [deg]	AMPL [mas]	PHASE [deg]
143.-149.	26	O1	0.86	0.05	0.59489	0.03375	18.496	3.261	0.33	123.3
161.-163.	10	P1	0.54	0.05	0.9455	0.08099	33.336	4.919	0.3	80.1
165.-168.	20	K1	1.53	0.05	0.79514	0.02552	13.217	1.841	0.36	77.1
243.-248.	24	N2	1.02	0.03	0.64907	0.01888	-8.256	1.662	0.16	-115.3
252.-258.	26	M2	5.06	0.03	0.66854	0.00367	-7.996	0.315	0.73	-104.7
271.-274.	9	S2	2.48	0.03	0.71688	0.00765	1.179	0.614	0.12	25.9
275.-2X5.	38	K2	0.66	0.03	0.61851	0.024	-5.806	2.221	0.1	-138.6

R.M.S.ERROR M-ZERO 0.6696 mas
R.M.S.ERROR FOR BANDS D 1.8779 SD 1.1067 TD 0.5246 QD 0.4374
O1/K1 0.7482 1-O1/1-K1 1.9775 M2/O1 1.1238

Table 2 The results of adjustment of plumb line variations data from H-74 and H-75 pendulums, projected on the EW azimuth. In table there have been shown main tidal waves groups only.

FINAL ADJUSTMENT WITH 18 GROUPS OF WAVES, CHOJNICKI METHOD
STATION 0906 KSIAZ, POLAND
HORIZONTAL PENDULUM, BLUM NO H-74, H-75
TOTAL NUMBER OF DAYS 364, 3273 READINGS

WAVE GROUP			ESTIM.AMPL.		AMPLITUDE FACTOR		PHASE DIFFERENCE		RESIDUALS	
ARGUMENT	N	SYMBOL	VALUE [mas]	R.M.S. [mas]	VALUE	R.M.S.	VALUE [deg]	R.M.S. [deg]	AMPL [mas]	PHASE [deg]
143.-149.	26	O1	3.95	0.06	0.69999	0.01122	-21.632	0.915	1.47	-98.2
161.-163.	10	P1	1.94	0.06	0.87093	0.02707	-17.161	1.773	0.64	-62.7
165.-168.	20	K1	5.67	0.06	0.75897	0.00852	-18.269	0.643	1.78	-92.8
243.-248.	24	N2	1.66	0.06	0.83246	0.0314	-10.264	2.166	0.4	-48.2
252.-258.	26	M2	8.1	0.06	0.83115	0.00606	-10.274	0.417	1.93	-48.4
271.-274.	9	S2	3.59	0.06	0.8029	0.01267	-9.733	0.901	0.77	-52.3
275.-2X5.	38	K2	0.96	0.05	0.69462	0.03956	-12.361	3.265	0.21	-93

R.M.S.ERROR M-ZERO 0.7889 mas
R.M.S.ERROR FOR BANDS D 2.4294 SD 2.3513 TD 0.6635 QD 0.5369
O1/K1 0.9223 1-O1/1-K1 1.2447 M2/O1 1.1874

These are two others problems connected with the long-water tube measurements :

- Form of the single observation and its capability. The average capacity of one image is 16 KB of memory per one file. We must store on disk about 36 000 files per one day. The analysis of the yearly series of observations requires processing of 12 millions images.
- Occurrence of the cycle-slip effects at the moments of rapid variations of the water level.

To obtain smooth function of the water level variations we had to choose optimal frequency of measurements (frequency of images registration). High frequency of measurements is desirable to decrease the probability of cycle-slip effects occurrence. Otherwise, we cannot unlimitedly increase

Table 3 The results of adjustment of plumb line variations data from long water-tube tiltmeter for NS azimuth . In table there have been shown only main waves groups.

FINAL ADJUSTMENT WITH 18 GROUPS OF WAVES, CHOJNICKI METHOD
STATION 0906 KSIAZ, POLAND
LONG WATER TUBE TILTMETER
CALIBRATION ABSOLUTE
TOTAL NUMBER OF DAYS 369, 6165 READINGS

WAVE GROUP			ESTIM.AMPL.		AMPLITUDE FACTOR		PHASE DIFFERENCE		RESIDUALS	
ARGUMENT	N	SYMBOL	VALUE[mas	R.M.S. [mas]	VALUE	R.M.S.	VALUE [deg]	R.M.S. [deg]	AMPL [mas]	PHASE [deg]
143.-149.	26	O1	3.39	0.04	0.69549	0.00899	-5.669	0.741	0.34	-86.6
161.-163.	10	P1	1.39	0.08	0.7227	0.04187	-11.254	3.322	0.27	-86.3
165.-168.	20	K1	4.96	0.08	0.76815	0.01278	-8.725	0.947	0.77	-77.1
243.-248.	24	N2	1.43	0.04	0.76458	0.01878	-11.004	1.407	0.3	-66.3
252.-258.	26	M2	6.68	0.03	0.72496	0.00355	-13.256	0.281	1.54	-83.4
271.-274.	9	S2	2.73	0.03	0.64707	0.00742	-12.511	0.657	0.64	-111.3
275.-2X5.	38	K2	0.88	0.03	0.67258	0.02294	-9.332	1.955	0.15	-101.8

R.M.S.ERROR M-ZERO 0.5300 mas
R.M.S.ERROR FOR BANDS D 1.6018 SD 1.1979 TD 0.4819 QD 0.3302
O1/K1 .9054 1-O1/1-K1 1.3134 M2/O1 1.0424

Table 4 The results of adjustment of plumb line variations data from long water-tube tiltmeter for EW component. In table there have been shown main waves groups only.

FINAL ADJUSTMENT WITH 18 GROUPS OF WAVES, CHOJNICKI METHOD
STATION 0906 KSIAZ, POLAND
LONG WATER TUBE TILTMETER
CALIBRATION ABSOLUTE
TOTAL NUMBER OF DAYS 369, 6165 READINGS

WAVE GROUP			ESTIM.AMPL.		AMPLITUDE FACTOR		PHASE DIFFERENCE		RESIDUALS	
ARGUMENT	N	SYMBO	VALUE [mas]	R.M.S. [mas]	VALUE	R.M.S.	VALUE [deg]	R.M.S. [deg]	AMPL [mas]	PHASE [deg]
143.-149.	26	O1	2.4	0.06	0.75034	0.01887	-9.134	1.439	0.42	-66.1
161.-163.	10	P1	1.37	0.12	1.08424	0.09205	-5.762	4.888	0.5	-16
165.-168.	20	K1	3.15	0.12	0.74573	0.02837	-14.329	2.158	0.78	-93.1
243.-248.	24	N2	1.34	0.03	0.78388	0.01989	-17.94	1.455	0.43	-76.2
252.-258.	26	M2	6.39	0.03	0.77829	0.00377	-16.448	0.277	1.88	-74.8
271.-274.	9	S2	2.83	0.03	0.75144	0.00781	-19.15	0.595	0.93	-84.6
275.-2X5.	38	K2	0.89	0.03	0.76519	0.02397	-16.194	1.793	0.25	-77.2

R.M.S.ERROR M-ZERO 0.5642 mas
R.M.S.ERROR FOR BANDS D 2.2521 SD 1.1595 TD 0.7075 QD 0.4323
O1/K1 1.0062 1-O1/1-K1 0.9819 M2/O1 1.0373

frequency of water level testing because of increase capability of data. The optimal frequency of testing results from experiences is - one photo per ten seconds. This compromise is determined by potential of computation of present machines. In the case when variations of water level are generated by tidal effects only, chosen frequency is fully sufficient. Problems appear when the reasons of water level variations are seismic, meteorological or local origin. The rapid variations of the water level produced by these phenomena cause indetermination of progressive phase. Problem of cycle-slip appeared during phenomenon of the Earth's free oscillations in September 2003. Before data adjustment from long water-tube some drawbacks like jumps or discontinuities were eliminated from observations. After preliminary elaborations, the observations were processed with help of algorithm applied for horizontal pendulums data. The results of adjustment in main azimuths EW and NS have been shown in Tables 3 and 4.

Table 5 The comparison of mean square errors (R.M.S.) in milliseconds of arc obtained from tidal adjustment of the observations from horizontal pendulums and long water-tube tiltmeters.

Component NS		Component EW	
R.M.S. Pendulums	R.M.S. Long Water-Tube	R.M.S. Pendulums	R.M.S. Long Water-Tube
0.6696 msec.	**0.5300 msec.**	**0.7889 msec.**	**0.5642 msec.**

Table 6 The comparison between the phases of main tidal waves obtained from adjustment of data from the long water-tube and horizontal pendulums tiltmeters.

COMPONENT			NS				EW			
TILTMETER			PENDULUM		LONG WATER-TUBE		PENDULUM		LONG WATER-TUBE	
WAVE GROUP			PHASE DIFFERENCE		PHASE DIFFERENCE		PHASE DIFFERENCE		PHASE DIFFERENCE	
ARG.	N	SYMB.	VALUE [deg]	R.M.S. [deg]	VALUE [deg]	R.M.S. [deg]	VALUE [deg]	R.M.S [deg]	VALUE [deg]	R.M.S [deg]
143.-149.	26	**O1**	**18.496**	3.261	**-9.134**	1.439	**-21.632**	0.915	**-5.669**	0.741
161.-163.	10	**P1**	**33.336**	4.919	**-5.762**	4.888	**-17.161**	1.773	**-11.254**	3.322
165.-168.	20	**K1**	**13.217**	1.841	**-14.329**	2.158	**-18.269**	0.643	**-8.725**	0.947
243.-248.	24	**N2**	**-8.256**	1.662	**-17.94**	1.455	**-10.264**	2.166	**-11.004**	1.407
252.-258.	26	**M2**	**-7.996**	0.315	**-16.448**	0.277	**-10.274**	0.417	**-13.256**	0.281
271.-274.	9	**S2**	**1.179**	0.614	**-19.15**	0.595	**-9.733**	0.901	**-12.511**	0.657

2. PRELIMINARY COMPARATIVE-RESEARCH OF THE TWO TILTMETERS

Applying two types of tiltmeters opens for us a good opportunity for new researches.

We expect that differences of the principles of work of pendulums and water-tubes tiltmeters help us to answer some questions:

- How do thermal waves and pressure variations in underground effect on both instruments?
- What is the influence of the local effects such as topographical and cavity on measurements of plumb line variations?
- What is real instrumental phase lag caused by viscosity and mechanical inertia?

To answer these questions we must first gather several years long series of observations, which enable to make comparative analysis of data from both instruments.

Now, we are able to make comparison of mean square errors obtained from adjustment of one year long series of plumb line observations.

The results presented in Table 5 are striking on account of large difference of the tiltmeters sensitivities (0.01 and 1 millisecond of arc, Moulton, 1919). The ratio of mean square errors (R.M.S.) of both instruments is close to 0.75 while the ratio of sensitivities is close to 0.01. The relatively large values of the R.M.S. errors of long water-tube observations result, neither from limitation of the sensitivity, neither from failings of applied algorithms of data processing. In our opinion, large values of the R.M.S. are associated with the local disturbances of the free water surface, as well as with large-scale tilt phenomena of the non-tidal origin. Local disturbances are mostly joined with gradient of the air pressure variations along the tubes. Changes of the air pressure of the order 10^{-6} of Hp in surrounding of the measurements platform cause 10 nanometers variation of water level.

This value of water level variations is well determined by the measurements system. The effect of the gradient of air pressure variations is generated by the process of the pressure compensation between underground and outside. The effects of the air pressure variations occur during meteorological phenomena of rapid variations of atmospheric pressure. Other reasons of big R.M.S. are large-scale effects producing non-tidal tilts like: non-tidal ocean loading and Newtonian effect, as well as atmospheric loading effects and the Earth's free oscillations. On the basis of yearly observations we are able to estimate the level of local and large-scale non-tidal tilt effects to 0.5 millisecond of arc. Because of frequency differentiation of the local and large scale non-tidal tilt effects, we expect that separation of both classes of phenomena will be possible.

The successive compared elements are differences between the phases of the main tidal waves obtained from adjustment of the both instruments observations. We obtained large discrepancy between phases mainly in NS component (Tab. 6). For long water-tube all phases are retarded (negative) in relation to theoretical tides and vary less than 5 degrees between diurnal and semi-diurnal groups.

The phases obtained from adjustment of horizontal pendulums data precede theoretical tides (are positive) for NS component and are retarded too much for EW component. In both cases phases disagree with theory of tides. The phases presented in Tab. 6 are very close to the phases obtained during many years from horizontal pendulums observations (Chojnicki - Weiss, 1988). These results indicate on systematic errors in the horizontal pendulums measurement process. In the past we tried to explain the discrepancies between the phases and the theory of tides by the influence of cavity and topographical effects. The cavity and topographical effects affect the horizontal pendulums, as well as long water tube in similar manner but we obtained correct phases in relation to theoretical tides for the long water-tube. The phases shifts from horizontal pendulums in relation to theoretical tides are too large (25 degrees) to be explained by local effects. Therefore, the hypothesis that the discrepancies between the phases and theoretical tides are produced by cavity and topographical effects is false. The problem of the large discrepancies between the phases of tidal waves and theoretical tides results from the incorrect determination of the measurements azimuth of pendulums. The error of the determination of measurements azimuth equal 0.3^0 causes the error of the determination of tidal waves phases, close to 1^0.

This relationship results from the mechanism of the pendulums, as well as from the system of the optic magnification applied in the photographical registration. Adjustments of plumb lines variations to theoretical tidal function ought to be made in the azimuth of observations. Any discrepancy between the azimuth of observations and the azimuth of adjustment causes incorrectness of determination of tidal waves phases. The reason of incorrect values of tidal waves phases is error in determination of angle λ (Fig. 1). Angle λ describes the divergence between the azimuth of equilibrium surface of the pendulum and the direction of the optic axis of the mirror. It is a serious problem to determine angle λ with sufficient accuracy. Quartz horizontal pendulums have a few centimeters dimensions. The mechanism of the pendulum – a bar with a mirror supported by a bifilar suspension is closed hermetically inside a glass vessel. To solve this problem we are going to construct a special platform for pendulums calibration, as well as for determination of angle λ.

3. EARTH FREE OSCILLATIONS REGISTERED BY THE LONG WATER-TUBE TILTMETER IN KSIAZ GEOPHYSICAL STATION

An important problem was adaptation of the hydrodynamic system of the tiltmeter for registration of phenomenon of free Earth oscillations. It was necessary to introduce low-pass, strongly-dumping filters into the hydrodynamic system. These filters reduce contribution of short-period phenomena (less than a few minutes) from plumb line variations registration. Simultaneously, applied filters do not generate phases retardations in registered phenomena which periods are longer than few minutes. The hydrodynamic system was verified during a very strong earthquake (8.6 magnitude) which took place on 25th September 2003 near Hokkaido island. Improvements of the hydrodynamic system caused that the process of accommodation of water surface to equipotential surface became quasi-equilibrium (null phase shift) for geodynamic effects of five-minute or longer periods. The earthquake generated phenomenon of Earth free oscillations, as well as associated effects of long periods surface waves (Benioff, 1954, and Alterman et al., 1959**).** The effects of surface waves were registered by the tiltmeter as series of anomalous plumb line variations.

The time of dumping of free oscillations of the Earth globe was about two hours. We observed an effect of passing of thousands-kilometer long surface waves.These waves produced several milliseconds of arc amplitude of plumb line variations. The high effectiveness of the dumping system of short-period water level variations was confirmed. The water tube was weakly affected by strong, but short-period tilt signals associated with seismic waves P and S. The water system was not introduced in a state of resonance. This circumstance enabled us to register plumb line variations produced by phenomenon of Earth free oscillations (Fig. 2) (Pekeris et al., 1958).

4. CONCLUSIONS

The first year of common observations of plumb lines variations carried out with the help of two tiltmeters of different classes provided us with new information about presently applied methodology of measurements, as well as with the interpretation of obtained results.

By means of long water-tube measurements we significantly approach to a solution of the problem of incorrect phases-shifts from horizontal pendulums measurements. We are going to build special platforms for installation of pendulums. These platforms will help us to determine angles of measurement azimuth of pendulums and introduce angular corrections to measurements. Thanks to the measurements from horizontal pendulums we obtained information of level of local noises, affecting long water-tube measurements (comparable values of

R.M.S.). These disturbances produced signal close to 0.5 millisecond of arc. In our opinion, the phenomenon of air pressure compensation in the underground plays main role in the water free surface disturbances. To diminish this effect we are planning to improve hermetic sealing of the underground to slow down the process of air pressure compensation. The results of measurements from the long water-tube confirm particular properties of the new instrument such as high sensitivity, lack of instrumental drift, as well as effectiveness of dumping system which was adopted to registration of long-period geodynamic phenomena. Differential method of data elaboration helps us to appreciate the level of errors of instrumental origin. In the case of geodynamic phenomena producing rapid variations of water level the cycle-slip effects occurred. It turned out that 10 second sampling period is too seldom which results in generating cycle-slip effects during post-seismic registrations.

Over two hours after a very strong earthquake (8.6 magnitude), the instrument observed anomalous plumb line variations associated with Earth free oscillations. In the preliminary, high dynamic stage of phenomena we obtained a plot of plumb line variations with a great number of cycle-slip effects. After the first hour of phenomena the number of cycle-slip errors diminishes to zero. To solve the problem of cycle-slip effects we are planning to decrease the period of sampling to one second.

Nevertheless, the possibilities of registration of Earth free oscillations with the help of the long water-tube were confirmed. The hydrodynamic system of low-pass filters dumped effects of high frequency seismic waves and prevented resonance of the water-tube system.

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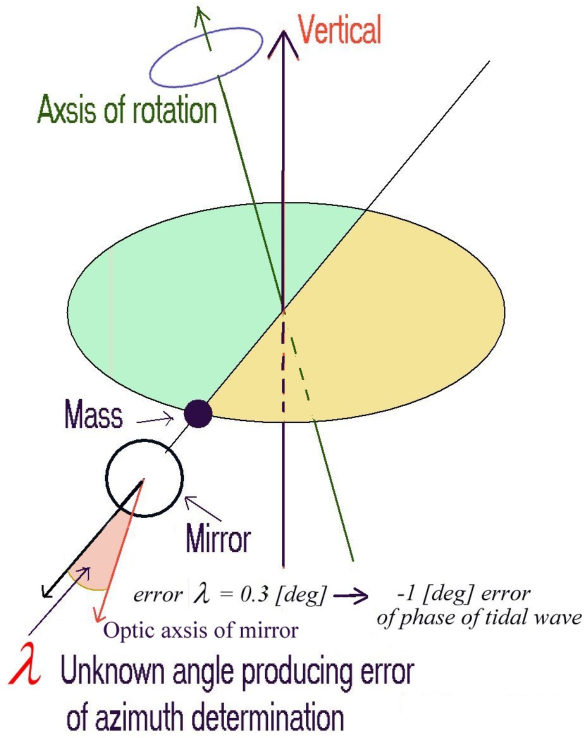

Fig. 1 The problem of determination of measurements azimuth of the horizontal pendulums.

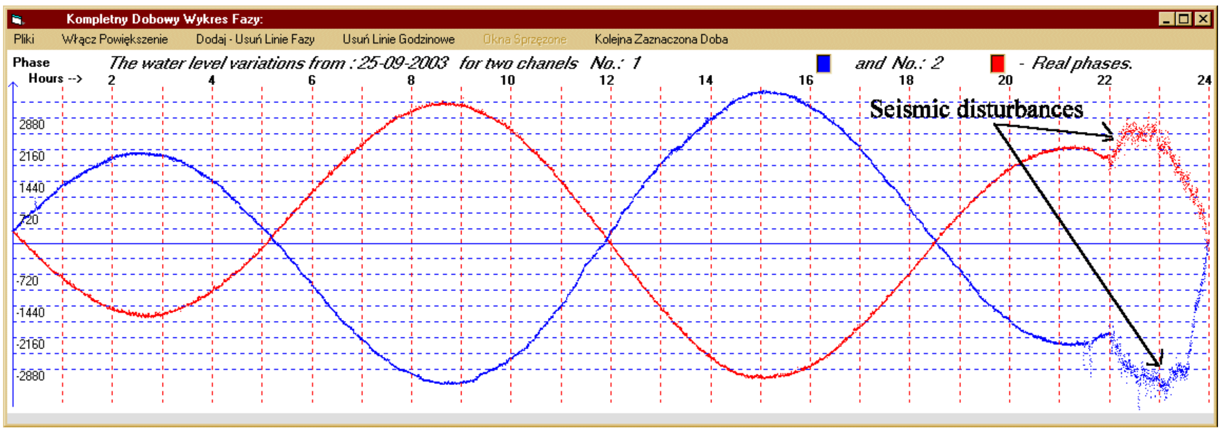

Fig. 2 The plots of water level variations at the opposite ends of the water-tube tiltmeter on 25 September 2003. The azimuth of the tube is $-121^0.4$ NW.