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Recordings with the Askania Borehole Tiltmeter (Vertical Pendulum) in the Frequency Range of Earth's Free Oscillations

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Abstract. The Askania borehole tiltmeter (vertical pendulum) has been only used for recording earth tides so far. But because of its wideband instrumental characteristic and low noise installation in a borehole it is very suitable for recording the earth's free oscillations as well. The applicability of the instrument as a tiltmeter and an accelerometer makes it possible to record both spheroidal and torsional oscillations of the earth.
The experimental equipment of the tiltmeter is described and the preliminary analysis of a signal is given.

Key words: Free Oscillations — Borehole Tiltmeter — Vertical Pendulum.

1. Introduction

In the last years more and more importance has been attached to the observations of free oscillations of the earth excited by larger earthquakes and detected by tiltmeters, gravity meters and strain gauges. A large number of frequencies of free oscillations can be estimated and they provide rather precise information on the density and the elastic moduli within the earth.

At the station Zellerfeld-Mühlenhöhe (51.82 °N, 10.34 °E), where the Askania borehole tiltmeter based on the vertical pendulum principle is in operation with success in the range of tides and longer periods since several years, we also record since March 1973 in the frequency range of earth's free oscillations. Full details about this tiltmeter are given by Jacoby (1966), and Rosenbach and Jacoby (1969).

To our knowledge, at other places this instrument is used so far as a tiltmeter in the frequency range of earth tides only. In this case however, the applicability of the tiltmeter is not fully utilized. By the construction principle of the instrument, the advantageous installation in 30 m deep boreholes applied at Zellerfeld-Mühlenhöhe from the beginning (Flach and Rosenbach, 1971), and by the electronic stage of progress we were encouraged to do recordings in the frequency range of the earth's free oscillations as well, especially as in this range the normal microseismic noise is extremely low.

The signals of free oscillations which can only be observed after larger earthquakes are very small. Therefore, a band-pass filter was built with a band width in the range of free oscillations (1 cph to 60 cph) and with a 110-fold amplification. By this the sensitivity of recording was decisively improved, and we succeeded in indentifying free oscillations quite clearly. These arrangements however were only possible because of the advantageous signal-to-noise ratio, the instrument being installed in a 30 m deep borehole.

In the following paragraph the filter is described more precisely.

2. *Filter*

For the development and construction of the band-pass filter the following characteristics were important for us, and according to them we chose the properties of the filter:

upper and lower cutoff frequency,
gain in the filter pass band,
attenuation rate beyond the cutoff frequencies,
type of filter (Butterworth, Bessel, Tschebyscheff),
step response.

The characteristic properties of the used filter can be taken from Fig. 1.

The lower cutoff frequency is determined by the lowest frequency of free oscillations, the spheroidal first harmonic or so-called football-mode which has a period of about 54 min. Furthermore, it is nécessary to attenuate the gain above this period to such an extent that earth tides are suppressed. By this, any difficulties with the harmonic analysis of the free oscillations are avoided. This attenuation was achieved by a three-pole Butterworth high-pass with a cutoff frequency $f_l = 3 \times 10^{-4}$ Hz (period 55 min). As the gain decreases beyond the cutoff frequency by f^3, the attenuation of the amplitude of the semidiurual principle tidal wave M_2 is —66dB e.g. being sufficient in our opinion.

Above the lower cutoff frequency f_l the signal is amplified. The gain of 41 dB is fixed in such a way that on the one hand a high sensitivity is achieved but on the other hand the noise of the band-pass and of the tiltmeter was not increased too much, see also paragraph 4.

Because of the use of a four-pole low-pass the gain above he upper cutoff frequency $f_u = 0.015$ Hz (period 66 sec) is decreased by f^4. By this, the oceanic microseism in the frequency range of 0.15 Hz, where usually the largest amplitudes occur, is attenuated so much that it normally does not disturb the recordings.

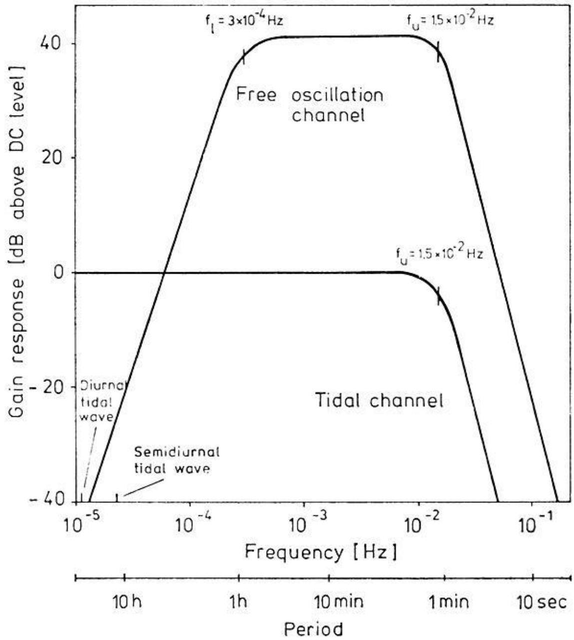


Fig. 1. Amplitude-frequency characteristic of the filtering system for simultaneous recording of tides and free oscillations of the earth

Fig. 1 shows both the amplitude-frequency characteristic of the band-pass and the amplitude-frequency characteristic of the low-pass used for recording earth tides. Due to an appropriate design of the filtering system this low-pass filter can be used for recording free oscillations as well as earth tides. This can be seen from the block diagramm in Fig. 2.

The low-pass filtered signal arrives directly without further modification at the tidal recording system. For the recording of the free oscillations the low-pass filtered signal is high-pass filtered, 110-fold amplified and finally recorded by the recording system. By this disposition of the filters an overmodulation of the free oscillation channel by microseism and tides

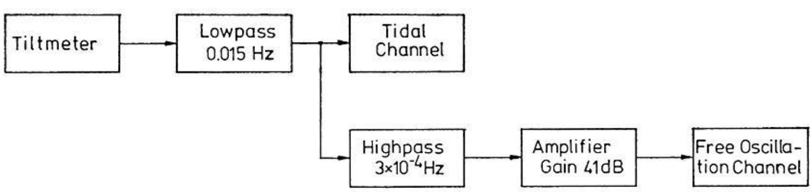


Fig. 2. Block diagram of the filtering system for simultaneous recording of tides and free oscillations of the earth

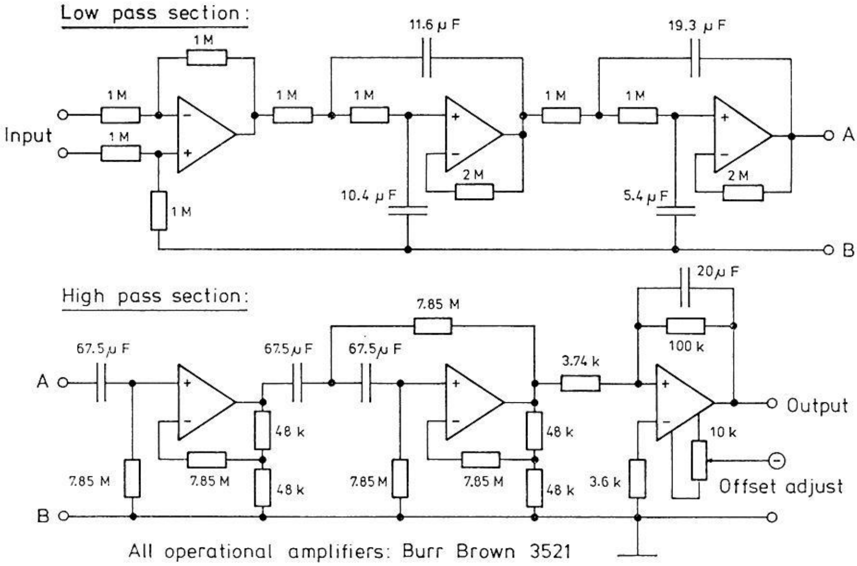


Fig. 3. Circuit diagram of the band-pass filter

is avoided. Due to the low cutoff frequencies f_l and f_u, the high gain in the band-pass range and the large loss of gain above and below the cutoff frequencies (see Fig. 1), the construction of the band-pass filter can only be realized with reasonable expenditure by multipole active filters (Tietze and Schenk, 1971).

Fig. 3 shows the circuit diagram of the complete band-pass filter.

As active elements high quality, low drift and low noise operational amplifiers were used. By this, in spite of high gain an excellent stability of the output voltage and a very low noise level of the complete electronic device is achieved. Of course, a considerable amount of circuits had to be applied, as can be seen in Fig. 3.

As already mentioned above, the low-pass filter which is part of the band-pass filter was used for filtering in the tidal channel. Therefore, it had to meet some further special requirements, e.g. with regard to the calibration of the tiltmeter. Details about this are given elsewhere (Große-Brauckmann, 1973).

3. Electronic Release Mechanism

The recording of the earth's free oscillations which in general are excited by larger earthquakes is sensible only, if the time resolution of a record is sufficiently high enough, i.e. the rules according to the sampling theorem have to be considered (Blackman and Tukey, 1958).

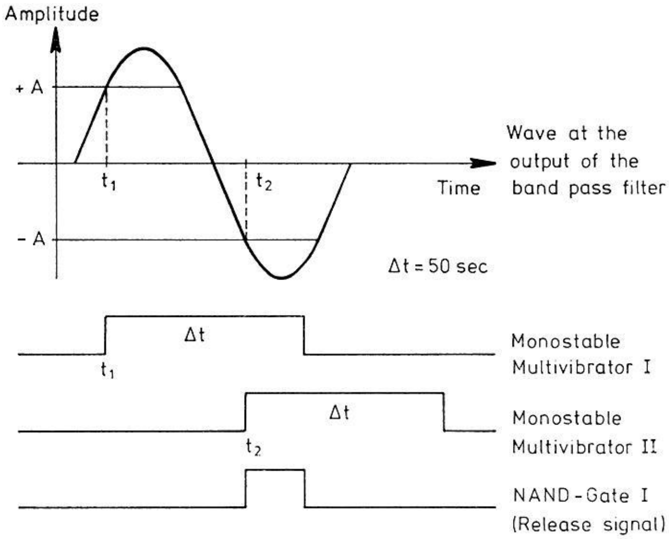


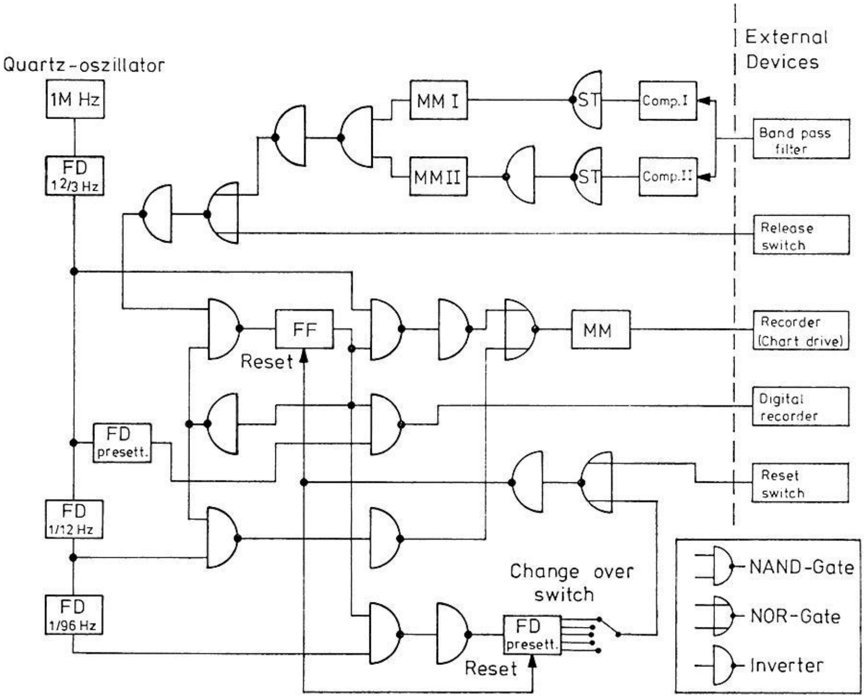
Fig. 4. Demonstration of the trigger process

To avoid aliasing the Nyquist frequency $f_N = 1/2\,\Delta\,t$, where Δt is the sampling interval, has always to be higher than the highest frequency appearing in the record. By filtering the signal, as in our case, the upper band-pass frequency f_u can be taken as a criterion for the highest appearing frequency. With a cutoff frequency of $f_u = 0.015$ Hz (see Fig. 1) it can be considered that the sampling interval Δt has to be much smaller than 33 sec.

The earth is relatively seldom prompted to free oscillations. This is especially true for the generation of the lower spheroidal and torsional harmonics. Therefore it is not advisable to record constantly with a high sampling rate of more than 2 measurements per min. To avoid the processing of quite a lot of useless data an electronic release mechanism was developed to start the recording system at the beginning of a larger earthquake.

The principle of this mechanism is based on the recognition of surface waves, as these periods are still in the transmission range of the band-pass to a certain extent. In contrast with ordinary seismology it is not important for recording free oscillations to record the first signal of an earth-quake precisely, as it can be assumed that the oscillations last for a longer time.

As a criterion for an event which triggers the recording system a wave was taken at the output of the band-pass, with a period not greater than 100 sec and a given amplitude. The long period was chosen, as owing to the dispersion of the surface waves the waves with long periods arrive



FD - Frequency-Divider, MM - Monostable-Multivibrator, FF - Flip Flop (Bistable)
ST - Schmitt-Trigger, Comp - Comparator

Fig. 5. Block diagram of the release mechanism

first. Only if both conditions are complied with, the recording system is started.

Fig. 4 shows this trigger process for further explanation. If the amplitude of a surface wave exceeds a certain desired quantity A, the monostable multivibrator MM I is triggered by a comparator. At the output of MM I a signal is now available for 50 sec. If the negative half-wave reaches the value -A, the other monostable multivibrator MM II is triggered. In case the period of the arriving wave is not longer than about 100 sec there is a time interval Δt during which at the outputs of both multivibrators a signal is available. A NAND gate responds in this time interval and the recording is started by a trigger circuit.

Fig. 5 shows the block diagram of the whole release mechanism.

Between two events an analogue recorder records the signal coming from the band-pass, with a chart speed of 15 mm/h. This record is used for continuous checking. On arrival of an event the chart speed is 20-fold increased and simultaneously a digital recording system is set in operation. The advantages of a digital record are, above all, the full resolution and the high dynamic range of >100 dB. After a certain time which is presettable the recording systems are switched off automatically. At present this happens after about 30 hours. At prolonged free oscillations this period can be extended as desired.

4. *Noise*

For the interpretation of records the signal-to-noise ratio is fundamental. As causes for noise in the frequency band of earth's free oscillations the following sources are under consideration:

band-pass filter,
mechanical part of the tiltmeter,
electronic part of the tiltmeter,
low-frequency microseism,
local tilting of the ground in the ambient area of the site.

The noise resulting from the band-pass can be measured rather simply in the laboratory independently of all other influences. It reaches about 4% of the total noise. The noise caused by the mechanical and electronic part of the tiltmeter can be measured by locking the tiltmeter in the borehole and thus eliminating all noise resulting from external influences. The amplitude of the instrumental noise of the locked pendulum amounted to 50% of the total noise, as sources being possible:

Brownian motion within the capacitive transducer, which transforms the movements of pendulum into electric signals (voltages). This is most clear if one considers that a voltage of 100 mV at the output of the band-pass is equivalent to a movement of the pendulum's detector plate of 2 Å (2×10^{-10}m).
Current noise of the transistors and operational amplifiers used for the electronic system of the tiltmeter and the band-pass filter.
Thermal noise of resistors.

Probably the main part of the instrumental noise is given by the electronic noise. An argument for this assumption is that the spectrum of the instrumental noise shows a characteristic increase of the amplitudes with increasing periods which is typical for noise caused by transistors and operational amplifiers. In our opinion this gives the chance to decrease the noise level of the tiltmeter even more by improvements in the electronic system.

During quiet periods, the total noise consisting of instrumental and microseismic noise reaches an amplitude (peak-to-peak) of 60 mV at the

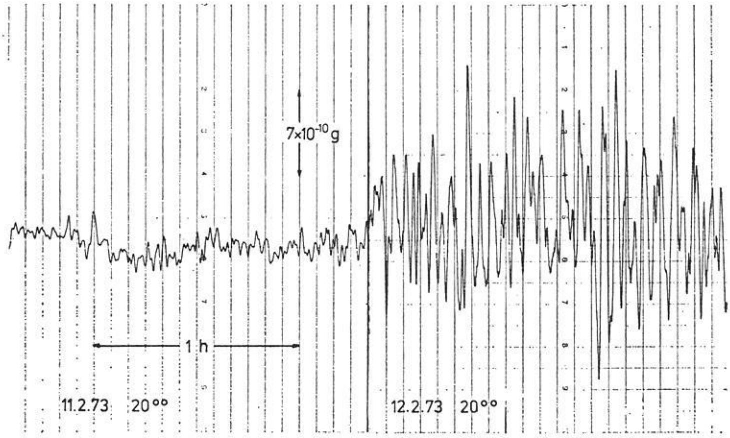


Fig. 6. Noise in quiet and unquiet time intervals. Sensitivity is not changed

output of the band-pass. This voltage is equivalent to an acceleration of 2×10^{-10}g or a tilt of 4×10^{-2}msec arc (maximum amplitude of the earth tides 35 msec). But the noise level can be increased by the influence of external effects. Fig. 6 shows an example.

Within 24 hours the noise was increased 5 times by the influence of a cyclone with strong gale.

5. Samples of Results

The gain of the registration system has been chosen in such a manner that the actual amplitudes of the earth's free oscillations are large enough for the analogue registration. Due to the small dynamic range of the chart recorder and the large amplitudes of the surface waves a considerable overmodulation has to be put up with at the beginning of the record. The digital registration system which is started simultaneously with the chart recorder has a dynamic range of 102 dB. Thus any overmodulation can be avoided by choosing the gain of the digital registration system appropriately.

An example demonstrating the function of the release mechanism is shown in Fig. 7.

The complete arrangement for recording the earth's free oscillations has been installed in early 1973 and is operating after a few small modifications and improvements continuously. It is in the nature of things that sufficiently big events to cause free oscillations take place seldom. Therefore, we have just recorded only a few events since the beginning of our measurements. Fig. 8 shows an example of such an event the parameters of which are given in Table 1. For comparison the spectrum of the ambient noise is given as well in the figure (solid line).

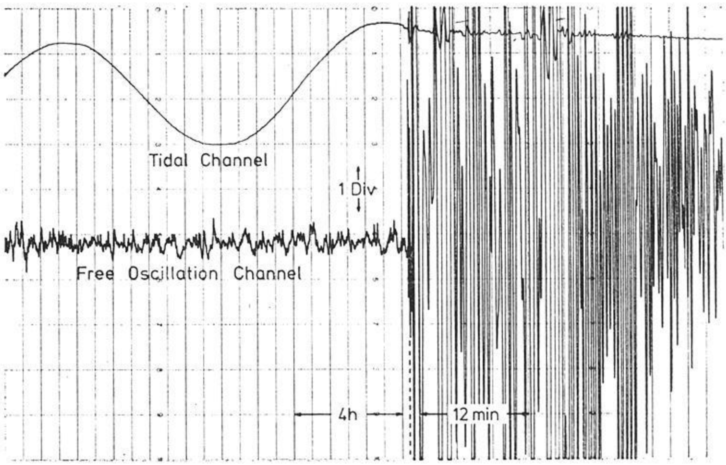


Fig. 7. Example of the function of the release mechanism at the beginning of an event. After release the speed of recording of both channels is increased from 15 mm/h to 300 mm/h. Tidal channel: 1 div $\triangleq 4 \times 10^{-8}$g. Free oscillation channel: 1 div $\triangleq 3.6 \times 10^{-10}$g

Table 1. Parameters of the observed earthquake (from Norsar Seismic Events Summary, issued 4 July, 1973)

Origin time	June 24, 1973 03.04.12 GMT
Epicentre	42 °N, 146 °E
Location	Hokkaido, Japan
Source-received distance	71°
Body wave magnitude	6.0

We demonstrate a preliminary interpretation using one of the latest model calculations (Dziewonski and Gilbert, 1972). In figure 8 only peaks were marked which could be identified. Due to large amplitudes of the surface waves the record was overmodulated in the first hours. That is why this part of the signal could not be used for harmonic analysis. The signal which was actually used for the analysis begins 2 h 50 m after arrival of the release signal and takes 16 h 59 m. Fig. 8 shows the harmonics with a frequency up to 6.3×10^{-3} Hz.

At the moment we are working on the improvement of the interpretation method. It is desirable to get a better resolution of the harmonic analysis. The free oscillations of the earth excited by smaller earthquakes only last a short time, provided that they actually occur. Leaving the sampling interval Δt constant the resolution of a harmonic analysis is directly proportional to the length of the interval processed. Therefore, smaller

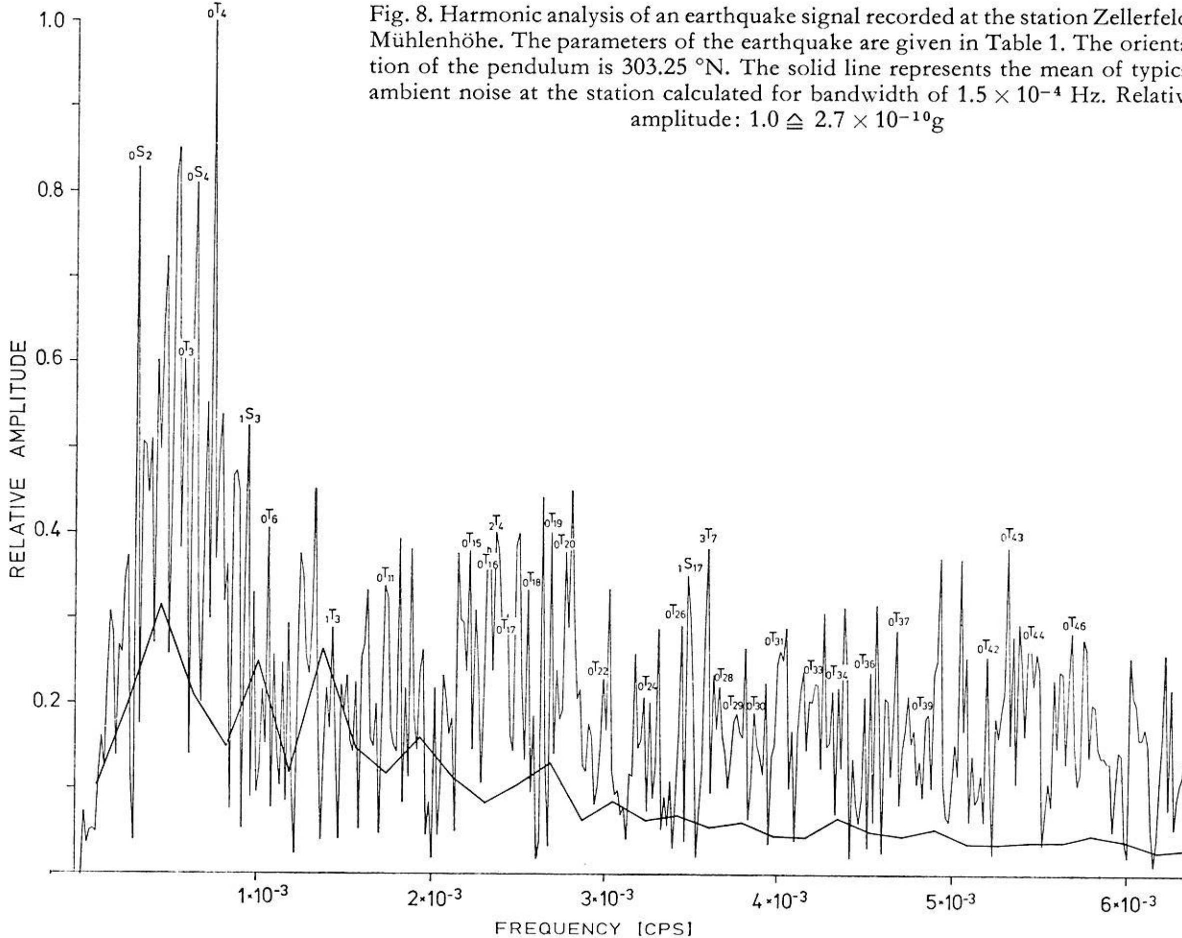


Fig. 8. Harmonic analysis of an earthquake signal recorded at the station Zellerfeld-Mühlenhöhe. The parameters of the earthquake are given in Table 1. The orientation of the pendulum is 303.25 °N. The solid line represents the mean of typical ambient noise at the station calculated for bandwidth of 1.5×10^{-4} Hz. Relative amplitude: $1.0 \triangleq 2.7 \times 10^{-10}$g

earthquakes do not only yield a smaller signal-to-noise ratio but a poorer resolution of frequency as well. Methods used on other subjects are investigated to raise the resolution of the frequency analysis (Paul, 1972).

6. *Conclusion*

This paper deals with the experimental requirements for recording the earth's free oscillations with the Askania borehole tiltmeter. It could successfully be proved that a further important field of application was found for this instrument. These results could be achieved because of the modern possibilities of electronic filtering and the advantageous signal-to-noise ratio in the measurements which are dependent on the tiltmeter itself, the installation in 30 m deep boreholes and the digital recording system.

The next step will be, as soon as a suitable gravity meter will be available, to develop a system for recording not only the horizontal but also the vertical acceleration.

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