Article about the station

The School-Seismograph Station
of the
Städt. St.-Michael-Gymnasium
Monschau, Germany

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1. Introduction

1.1 From a school project week to 'Jugend forscht' ('Young researchers')

In the year 1994 a so-called 'Project week' entitled 'Stones alive' took place at our school, the Städt.
St.-Michael-Gymnasium at Monschau in the Eifel (on the Belgian-German border). The theme, which had been created with more of a historical intention, created some problems for several students interested in the field of science. Somebody came up with the idea that if stones came alive, then they move and an earthquake can ensue. And how does one make this earthquake tangible ? - With a seismograph … and so one project team wanted to build such an instrument.

Fig. 1: The project team 'When stones move' in 1994 at the MGM, Monschau

We saw in the (older) literature what a seismograph looks like: So we imagined a seismograph as an instrument that weighs about a ton, is near impossible to move and unwieldy. The literature which was available to us initially was 'The Study of Earthquakes' by H. Jung (1953) and later the standard German work by W. Kertz 'Introduction to Geo-Physics' (1969).

To learn more we rang Professor Dr. Kertz in Braunschweig. He was delighted by our interest in the field of geophysics, but advised us, as he had for some time now been retired to contact his former assistant Professor Dr. H. P. Harjes. - Prof. Dr. Harjes is currently employed as the director of geophysical studies at the Ruhr-University of Bochum, Germany. Prof. Harjes was also interested in our pursuits and wrote to us that despite his knowledge in geophysics he is not an expert in the construction of seismometers. He further wrote that he had spoken to his colleague Professor Dr. Wielandt in Stuttgart who would be glad to help us, being an expert in the field of seismology concerning the construction of seismometers. In addition Prof. Harjes supplied us with important modern literature on the subject.

After a more psychological break we took courage again and phoned Professor Wielandt in Stuttgart. He was thoroughly excited by our intent. After a brief visit to the Seismological observatory of the University of Cologne in Bensberg directed by Prof. Dr. Ahorner an excursion to the Institute for Geophysics at the University of Stuttgart was undertaken by three members of the project team during their summer holidays and prior to the project week. In Stuttgart they received an intensive two-day course in seismology, the construction of seismometers and electronics from Professor Wielandt. And from then on Professor Wielandt remained our 'scientific godfather'.

In Stuttgart we ascertained that nowadays seismographs could easily fit into a jam-jar. Even those instruments, which are specifically designed for the recording of distant earthquakes, are only the size of a small shoebox. Such seismographs are extremely slow swinging, well damped pendulums, (and there are horizontal and vertical pendulums that act as garden-gate pendulums, normal string pendulums or as spring pendulums ...).

The project team received help from many sources; students' parents, former students and alumni, local firms and the institutes of the Technical University RWTH Aachen, as well as the Research Centre in Jülich and additionally the Geological Service of North-Rhine Westfalia in Krefeld helped us with the provision of materials and with the construction of special parts, without which we initially thought we could not proceed.

Professor Wielandt was not to be deterred from attending the beginning of the project week in Monschau, to check that everything was running smoothly and to help out for one day. 'When stones move' was the headline for a week, where 24 people worked together to finally complete the seismograph by the end of the week. It was a matter of some dispute amongst us if the instrument was actually going to work or not. During a visit to Bochum at the conclusion of the project week the whole team was shown how researchers and technicians work hand in hand at a modern geophysical institute by Prof. Harjes and his colleagues.

Back home in Monschau our patience was tested somewhat longer. Finally our seismograph registered earthquake signals from an earthquake in Peru and from a quake in Japan. The efficiency of our school's seismograph in comparison to a professional instrument in the earthquake observatory at the University of Stuttgart is exemplified in the following graph.

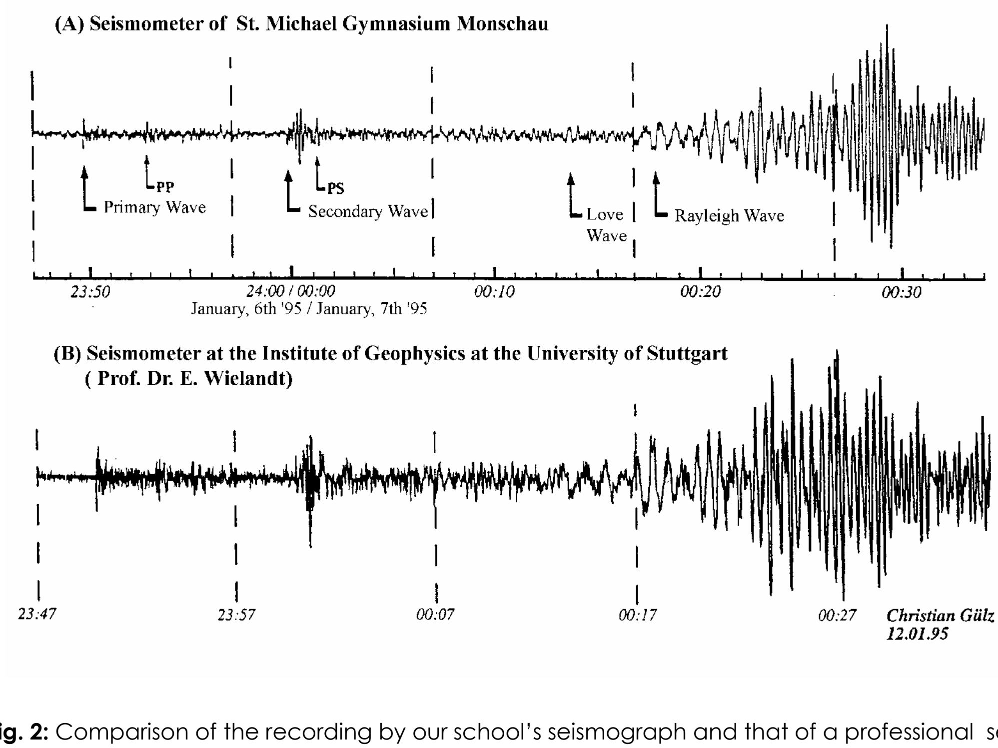


Fig. 2: Comparison of the recording by our school's seismograph and that of a professional seismograph.

Christian Guelz painstakingly executed this graph at the time (our recordings were then recorded on mm-paper and the scale was removed with the help of a hand-held scanner by Christian).

After the end of the 1994 project week to the name of our project "When stones move" the sentence "and go to the competition 'Jugend forscht' " was added.

Fig. 3: Three proud young researchers and their seismograph. From left to right: Sebastian Schork, Thomas Poschen and Bernd Naeth.

Sebastian Schork, Thomas Poschen and Bernd Naeth built and organised a three-component seismograph station at our school, which possesses a digital remote access. In addition to this they constructed a moveable teaching seismograph, which was conceived to be rebuilt. This will be demonstrated within this article at a later stage.

The three young researchers were state champions in North-Rhine-Westfalia in the field of geo- and space sciences and achieved second place on a national level.

1.2 The seismology team at the MGM Monschau

Surprisingly the project created interest within a number of the school's forms. A workshop was started which has now continued the work of those young scientists for years, the initial group have long since completed their 'Abitur' (A levels) and are engaged in studies and further education. The legacy has been taken up with zeal and been cared for and continued.

We would like to briefly introduce the seismology workgroup at the MGM Monschau:

- Steffi Bauer, Ulrike Kirch and Wiebke Winkens (year 13, 2001/2002), the women experts of the team: natural disasters, ray paths, seismographs
- Claudia Münchrath (year 10), the good soul of our staff – plate movement and earthquakes
- Jens Brandenburg and Sebastian Völl (year 10), plate tectonics and focal mechanism
- youngsters Onat Hekimoglu, Stefan Niebes, David Omanovic, Christian Schmitz and Dirk Victor (year 9), demonstrations: P- and S-wave velocity, on the problem of earthquake prediction
- Max Arndt, Martin Jahnke and Thomas Koch, (year 12), main features of our seismograph, pendulum physics in practice and theory, demonstrations with PC and seismograph
- Thomas Conrads and Jochen Roder (year 13), earthquake waves and their propagation

- Martin Jansen and Christian Ruf (year 13), frontmen of the team: data acquisition and evaluation of seismograms

Fig. 4: The seismology team of the St.-Michael-Gymnasium Monschau.
Front row from left to right: Christian S., Dirk, Stefan, David; second row: Steffi, Ulrike, Sebastian, Martin Jahnke, Nils, Max; in the background: Christian R., Martin Jansen, Wiebke, Claudia, Jens and Jochen, (absent were Onat, Thomas C. and Thomas K.)

1.3 Earthquakes as natural disasters

As important as earthquake waves are to our exploration of the inner workings of the earth (more on this subject in chapter 2), as destructive and unpredictable they remain even in our highly technical age.

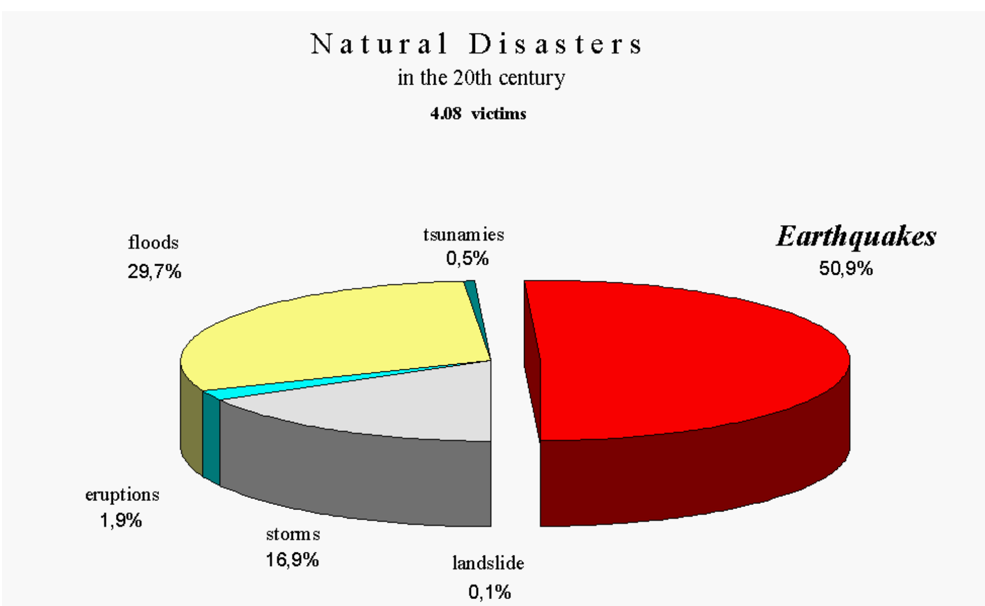


Fig. 5: Natural disasters

More than half of all deaths that are caused by natural disasters are the consequence of earthquakes.

Many of us still remember the news of the terrible earthquake in Kobe, which hit Japan in 1995.

- in twenty seconds the force of eight Hiroshima bombs was released.
- More than 6000 people died.
- Almost 50,000 homes were levelled to the ground.
- The extent of the damage was estimated at 30 billion dollars.

Fig. 6: A highway in Kobe after the massive earthquake of 17th January 1995

The only existing possibility to live with earthquakes is to build in an earthquake safe way.

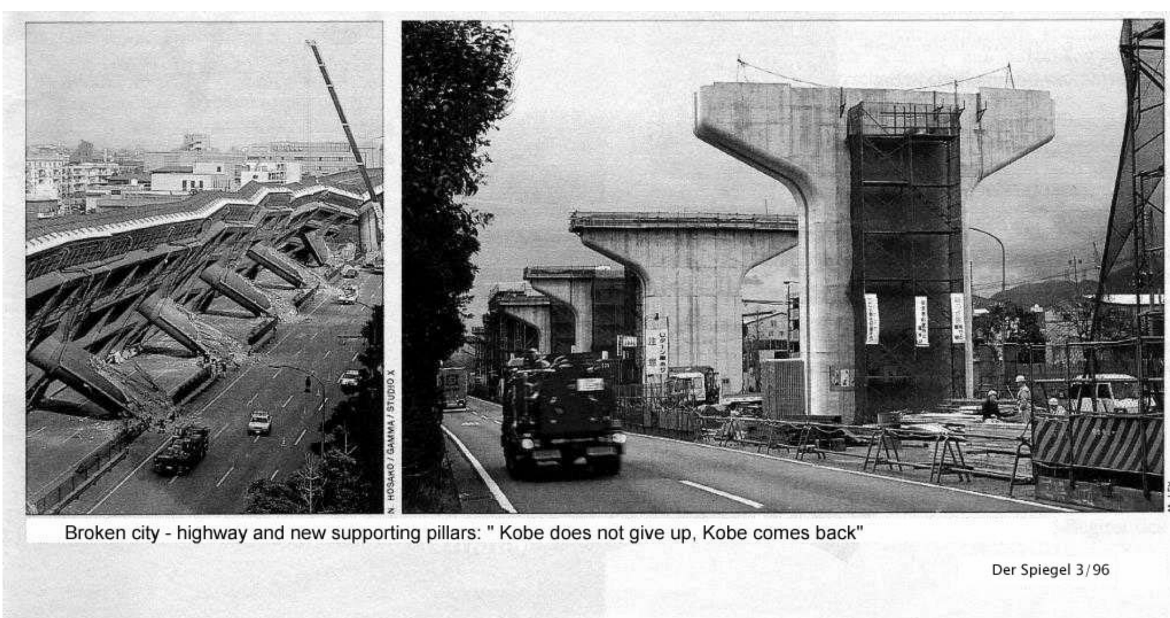


Fig. 7: A highway in Kobe after the quake in 1996 and its re-building

But even in Europe earthquakes occur that can cause significant damage.

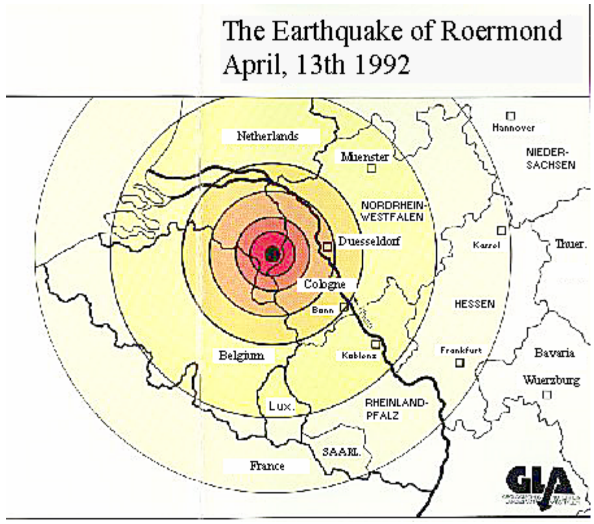


Fig. 8: The epicentre of the Roermond earthquake, 1992, Belgium.

Amongst the German readers of this homepage there may be some who were torn from their sleep on the 13th April 1992 by the earthquake in Roermond in Belgium in the early hours of the morning. Even as far away as Bonn the quake was felt and tiles feel off roofs.

Fig. 9: Consequences of the Roermond quake (1992) in Bonn.

1.4 Causes of earthquakes

The causes of most earthquakes are found in the shell-shaped construction of the earth. The solid ground beneath our feet is in fact only a thin layer. This lithosphere consists of the circa 10 to 70km thick outer crust and the upper part of the mantle of the earth, altogether a circa 100km deep layer. This layer surrounds the earth's sphere which has a diameter of about 12,700km and which contains a restless inner life.

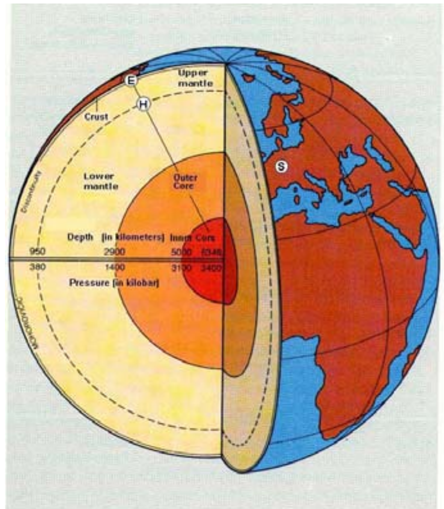


Fig. 10: The onion-like layers of the earth

Below this layer we find the thicker, but less brittle mantle. Beneath this is in turn the earth's core. The high temperatures of the earth's core heat the higher layers. Parts of the earth's mantle therefore are set in motion. In the harder layers of the earth's mantle the heat flows and circulates very slowly, yet their power is great enough to have torn apart the upper lithosphere into various plates during the course of the earth's history.

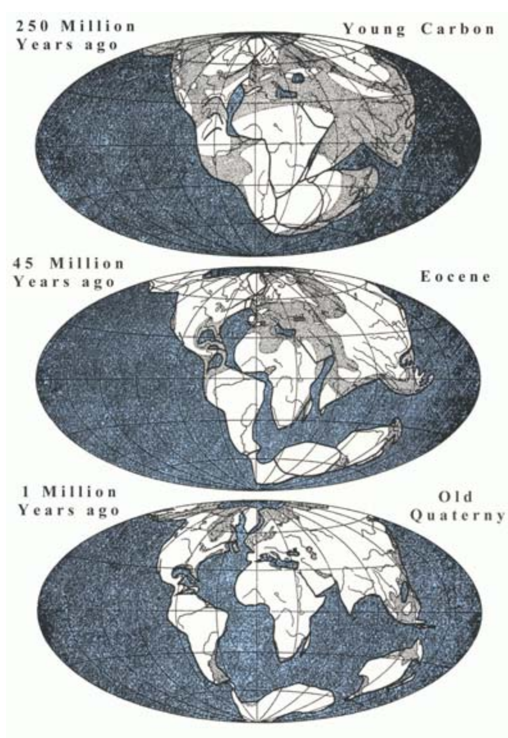


Fig. 11: The movement of continents

Even today these plates are moving against each other (on the seabed this can be up to several centimetres a year).

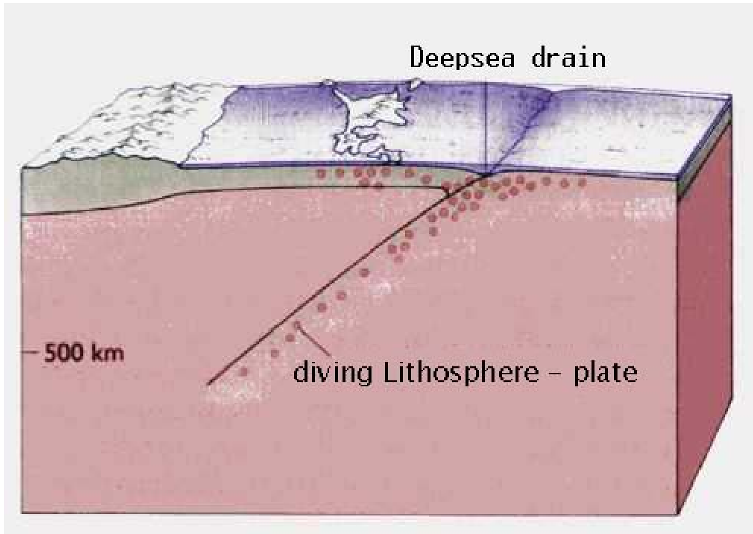


Fig. 12: The movement of tectonic plates

Necessarily neighbouring plates are continuously and repeatedly lodged together. In such a place increasing pressure is built up throughout the years. When the pressure is great enough the hindrance is overcome and the relevant parts of the earth's crust are jerked out of place.

Not all earthquakes have the same cause. On the one hand the lithosphere's plates can displace each other near the earth's surface. In such a crust-quake the epicentre typically lies about 5 to 15km below the surface. Weak crust-quakes sometimes only show a sideways displacement on the earth's surface.

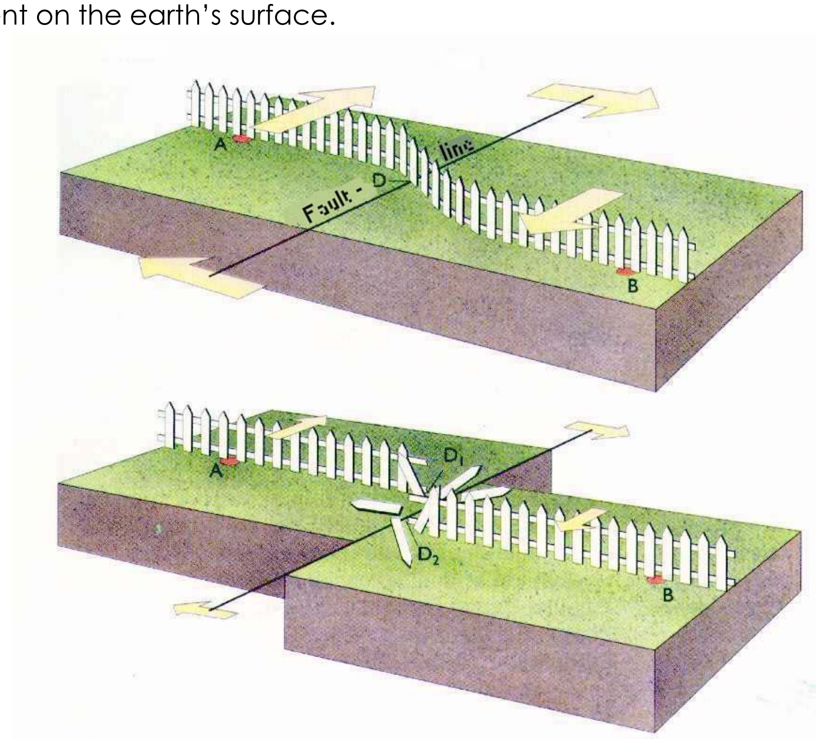


Fig. 13: A basic sketch of the principal 'fracture' hypothesis

The mid-Atlantic ridge has not coincidentally got the same outline as Africa. With the aid of the ‘Seismik’ program by Alan Jones one can show in slow motion how earthquakes have occurred along the ridge in the past.[1]

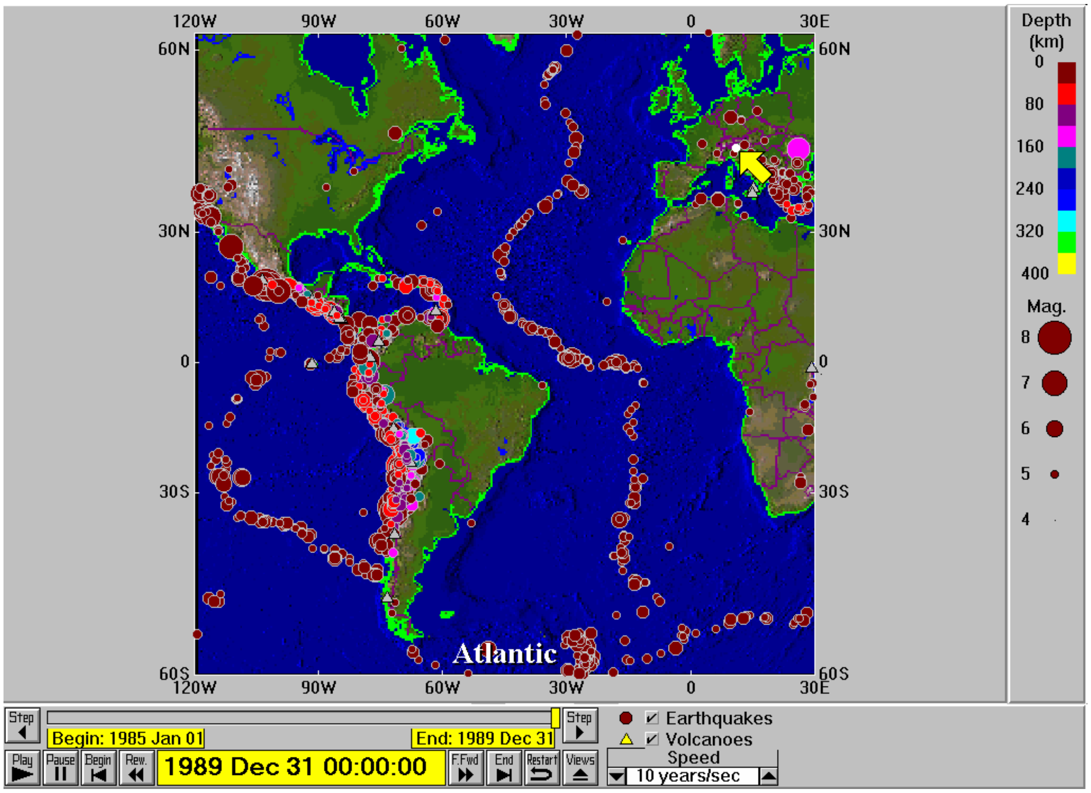


Fig. 16 The epicentres of quakes as they outline the mid-Atlantic ridge

2. On the seismogram as a ‘Journey through the interior of the earth’

A seismogram is fundamentally a report of the journey of earthquake waves through the interior of the earth. Through the exploration of earthquake waves we have ascertained how our earth is made up even in its very depths (compare Fig. 10). Remember: even the deepest continental drills have only reached about 10km below the surface, the radius of the earth being circa 6000km.

Before we become more familiar with the various types of earthquake-waves, here is another aside about epicentres of earthquakes. The actual centre of a quake within the earth is named ‘Hypocentre’ (marked H in Fig. 10) whereas that place which lies perpendicular to this on the earth’s surface is named ‘Epicentre’, (marked E in Fig. 10).

We distinguish between two types of quake-waves; body waves and surface waves. All wave types are visible within the following graph.

[1] This program can be found at http://www.geol.binghamton.edu/faculty/jones/

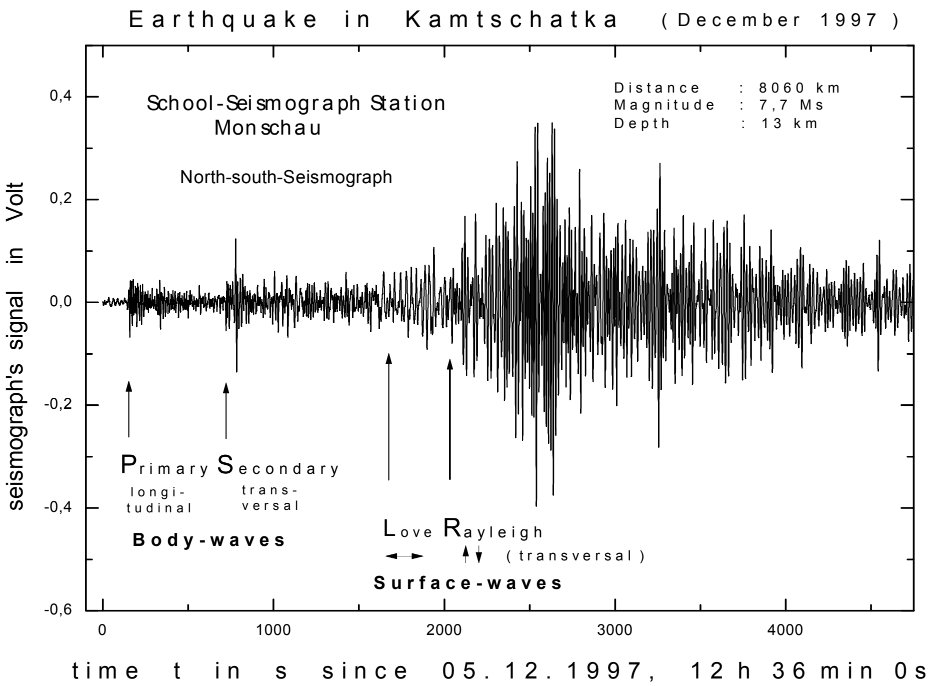


Fig. 17: An earthquake in Kamchatka

The surface waves expand, as the name indicates, near the earth's surface and so progress from the epicentre E to the station S (compare Fig. 10). They reach the station somewhat later than the faster body waves, which go more directly through the earth from epicentre H to the seismographic station S.

We will remain for the moment with the subject of surface waves, which are transverse waves. One distinguishes between two types of propagation, which are both named after English physicists.

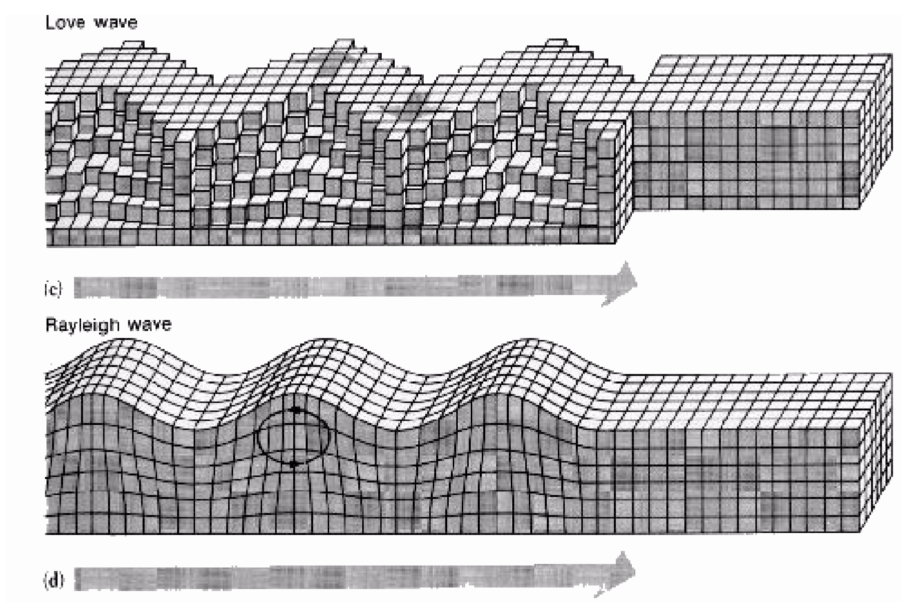


Fig. 18: The propagation of earthquake waves in the earth's crust: surface waves

First we receive the faster ‘Love Wave’ at our station. This wave makes the earth oscillate horizontally. Following on from this we receive the ‘Rayleigh Wave’ that makes the earth’s surface oscillate up and down. The amplitudes of the surface waves rapidly decrease with increasing depth.

As the surface waves are, so to speak ‘imprisoned in the earth-crust’, they only expand two-dimensionally and lose far less energy than body waves. The surface waves are therefore those that create such disastrous damage in buildings, as well as in water and gas pipes and electricity lines.

It is Charles Richter’s merit to have invented a scale from which the strength of an earthquake can be calculated using instrumental measurements. For earthquakes that are recorded by a standardised seismograph (Wood-Anderson) having a maximum focus distance of 600 km Richter proposed his original scale. He used the largest displacement in the seismogram to calculate a value for the strength of an earthquake. (A different scale is the scale for earthquake-intensity, which is based on the destruction of buildings etc. caused by the earthquake.) – In correspondence to the astronomical scale for the brightness of stars Richter called the calculated value “magnitude”. Later on seismologists extended Richter’s scale to the recordings of earthquakes with larger focus distances.

Charles Richter (1900 – 1985), the man who invented the Richter – Magnitude – Scale

Fig. 19: Charles Richter (1900-1985) who conceived the idea of the ‘Richter scale’.

The magnitude scale is a logarithmic scale, i.e. a quake with a magnitude of 6 has the tenfold amplitude as one with magnitude 5 and one hundred times as strong as a quake with magnitude 4. For scientific seismology the Richter scale is nowadays no longer as important as in the past. Today press, broadcasting and TV use the scale mainly to classify an earthquake.

Let us now examine body waves.

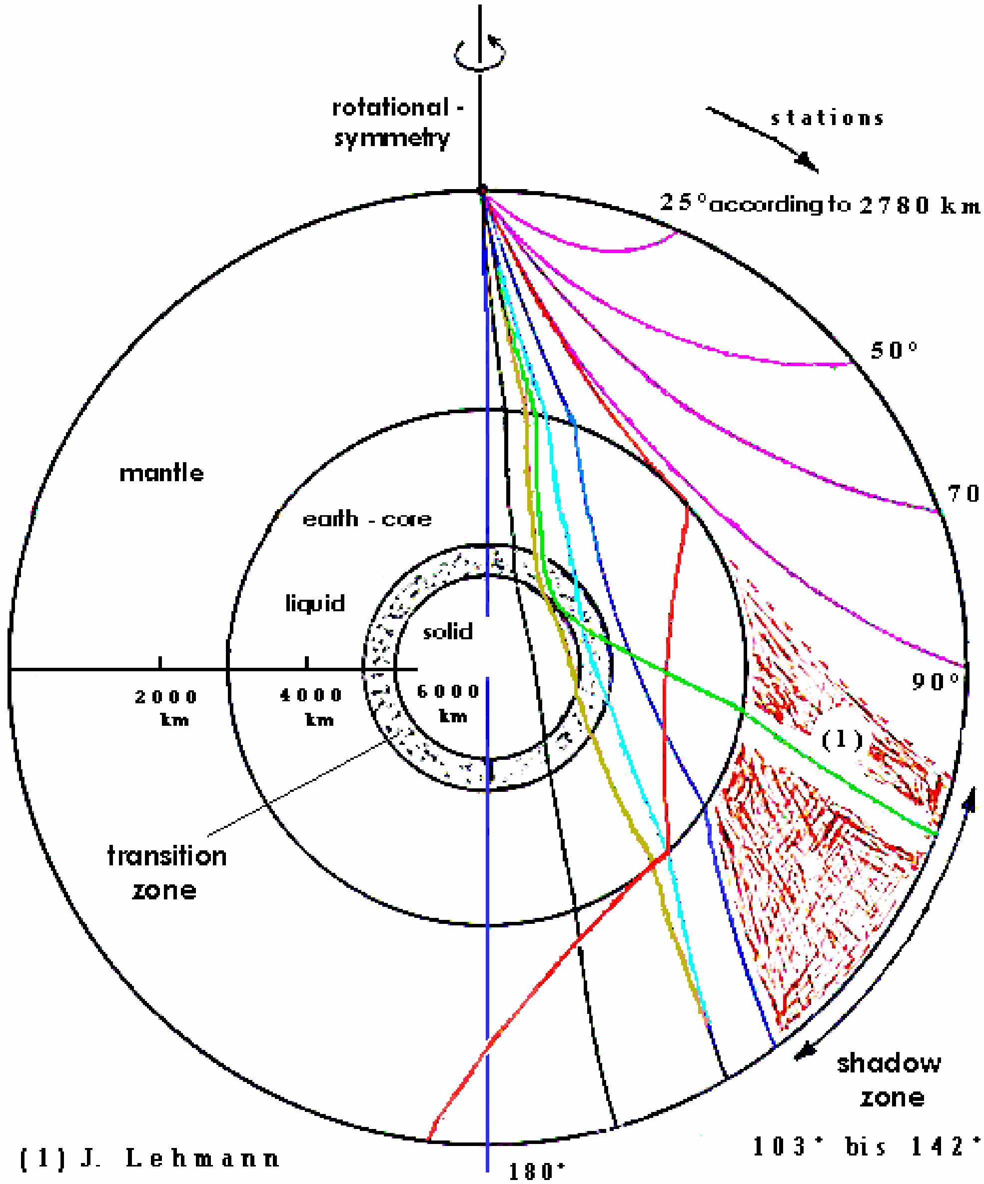


Fig. 20: The propagation of earthquake waves within the earth: body waves

As one can see from the above graph, body waves do not propagate in a straight, but in a curved line within the earth. This can be explained in comparison with optics. The index of refraction decreases according to depth while the speed of propagation increases. (This is caused by the modules of elasticity for shear and compression increasing even faster than density with increasing depth).

Body waves that hit the outer liquid core of the earth are partly reflected and partly refracted into the liquid core where they then only exist as longitudinal waves. When the body waves exit the earth's core they are again broken and are partly converted to transverse waves.

One can clearly see in the graph that every earthquake has a so-called ‘shadow-zone’. Quake waves can only reach this zone via complicated and manifold reflections. This is why seismological stations situated within this zone can only barely register the quake.

Also in body waves two wave types are distinguished, one of which is faster than the other.

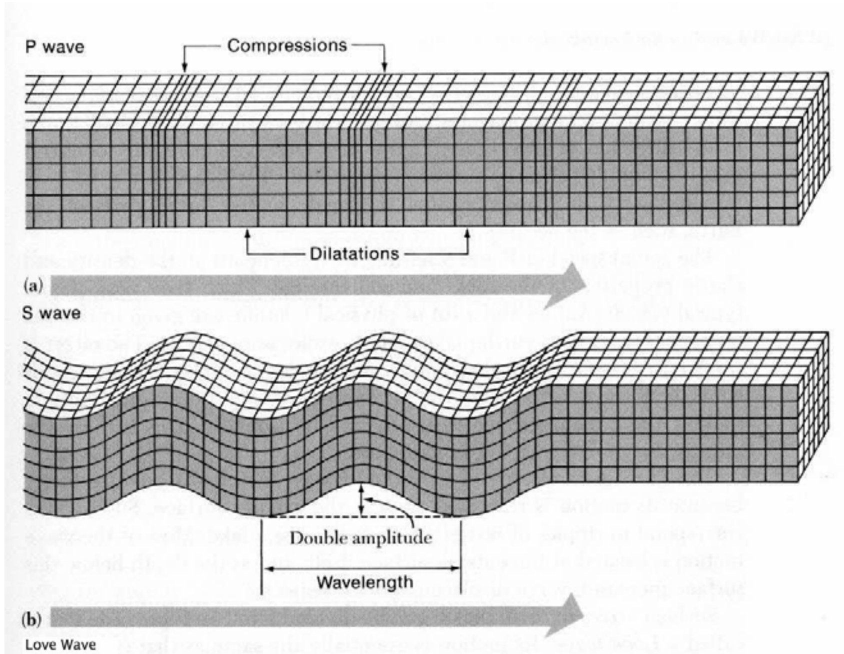


Fig. 21a: Body waves

The faster wave is a longitudinal wave. How it propagates can easily be shown in a model made of coupled bar-pendulums, e.g. by suspended broomsticks, coupled with elastic bands. One begins by diverting a pendulum in the direction of propagation. But even a long ‘soft’ helical spring (‘Slinky’) can demonstrate this (see fig. 21b, upper panel).

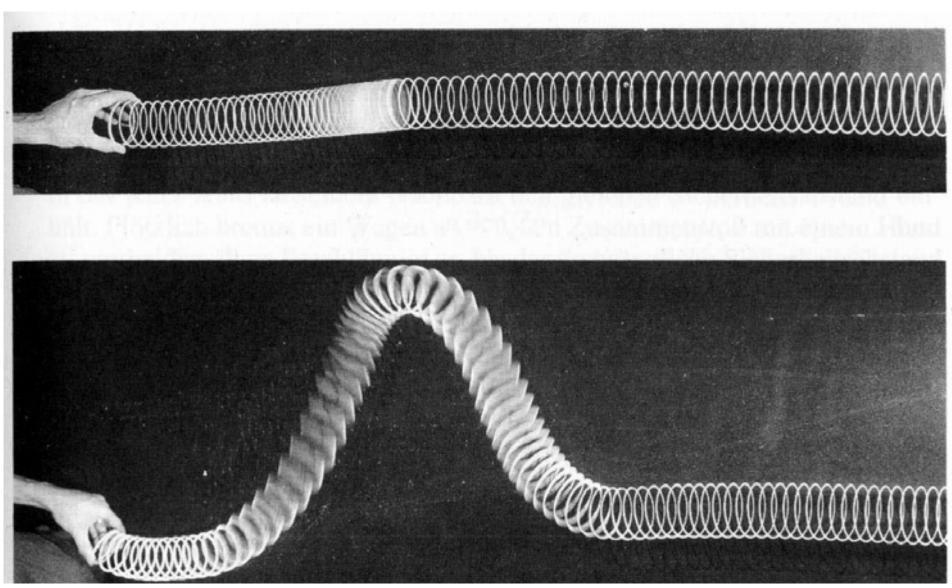


Fig. 21b: Model for the propagation of P- and S- waves

As the faster wave logically reaches the station first the longitudinal body wave is named **primary wave** or for short P-wave. The slower wave is called **secondary wave**, in contrast to the P-wave it has transverse propagation. This type of propagation is demonstrated in the broomstick model if one initially deflects the first pendulum transversely to the direction of propagation. Analogously the deflection of the 'Slinky' spring takes place (fig. 21b, lower panel).

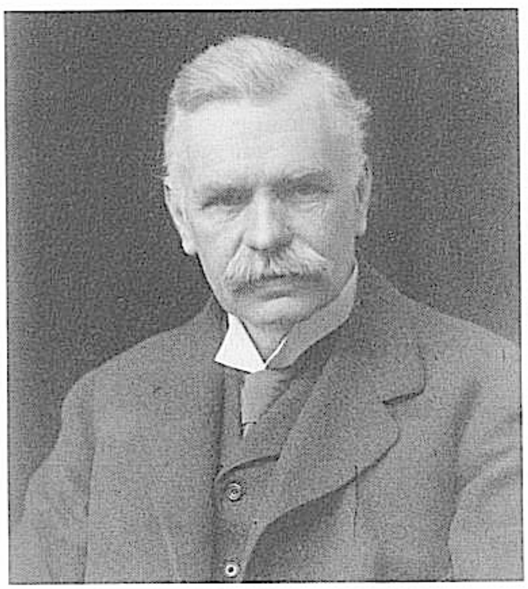
Both models also demonstrate that the transverse wave (S) takes considerably longer than the longitudinal wave (P) to transmit information.

With the arrival signals of the P and S waves (see fig. 17) one can determine the distance of the station to the quake's epicentre and can thus determine the origin time of the quake.

This subject will be further examined in chapter 6 'On the evaluation of a seismogram'.

The distance Δ between epicentre and station is measured in degrees of angles. One can measure those angles with an halfcircle ruler, as one can find on any terrestrial globe to ascertain the latitude of any place. For example the distance between Germany and Japan is about 90˚ degrees. That means – in accordance with the primary definition of the meter – a distance of 10,000 kilometres.

In conclusion to this chapter it should be again pointed out that it is only through earthquake waves that we can discover how the earth is built in its interior. We review fig. 10 again: Richard Dixon Oldham discovered the liquid core of the earth in 1906 and Inge Lehman discovered the solid core, which floats within the centre of the liquid core.



Richard Dixon Oldham (1848 - 1936)
the earth core's discoverer

Inge Lehmann (1888 – 1993), discoverer of the inner earth – core

Fig. 22: Richard Dixon Oldham and Inge Lehman

During precise analyses of seismograms Inge Lehman occasionally found P-waves in the 'shadow-zone' (103˚ to 142˚) , as can be seen in fig. 20a by example of the 'green' body wave "(1)". So it became obvious that the solid core of the earth caused these signals of reflection.

In view of the current possibilities of electronic amplification stronger earthquakes can even be registered in the 'shadow zone'. Therefore we could register the strong seaquake in the Flores - Sea on the 17th June 1996 (magnitude 7) with a distance of Δ = 112,04˚ from the epicentre very clearly.

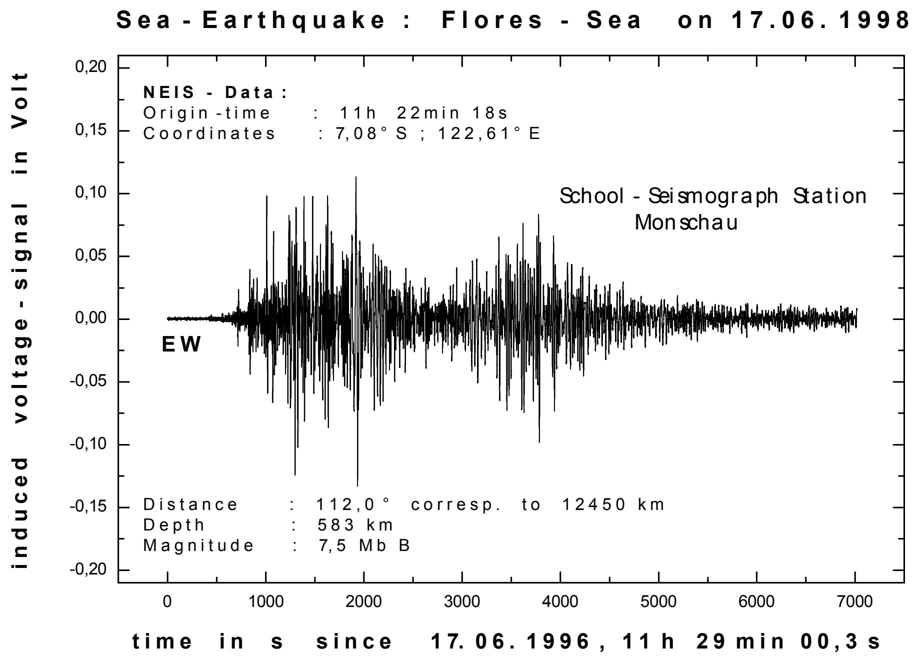


Fig. 23: A sea-quake in the Flores – Sea that lies in the shadow zone of Central Europe

The arrival time of the signals in Monschau according to the running-time table is: 11h 40min. 55sec.

Measured were:

- with the North-South seismograph: 11 h 40 min 55.2 sec
- with the East-West seismograph: 11 h 40 min 53.4 sec
- with the vertical seismograph: 11 h 40 min 58.2 sec

We now want to show the details of a seismogram of an earthquake in the vicinity of the island of Taiwan recorded by the seismograph set in our school.

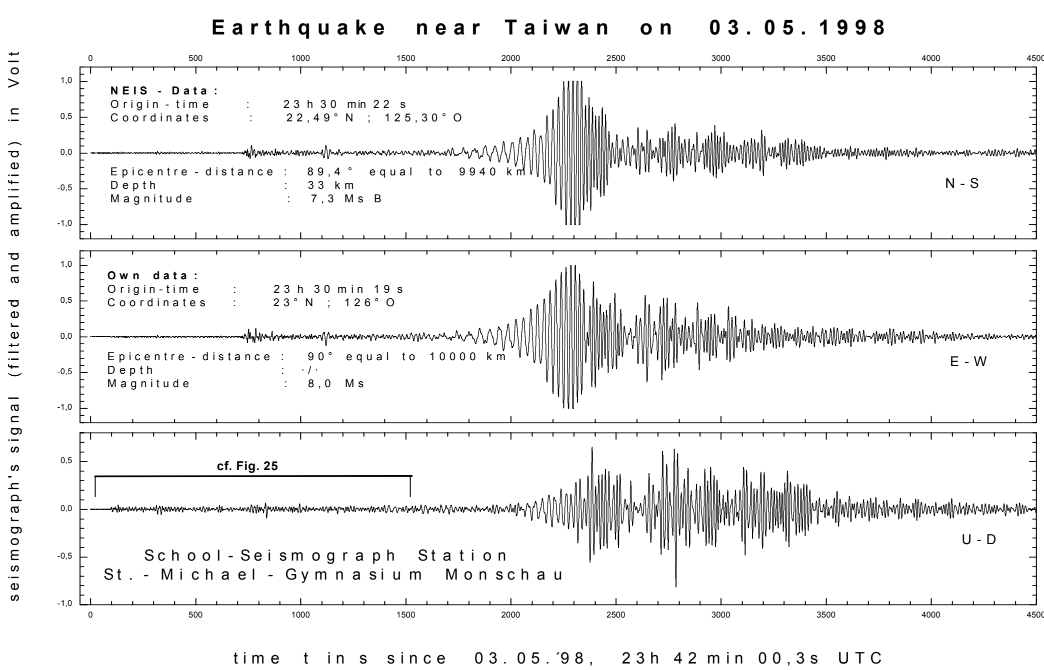


Fig. 24 The Taiwan earthquake of 3rd May 1998

The first 1500 seconds of the seismogram appear as follows;

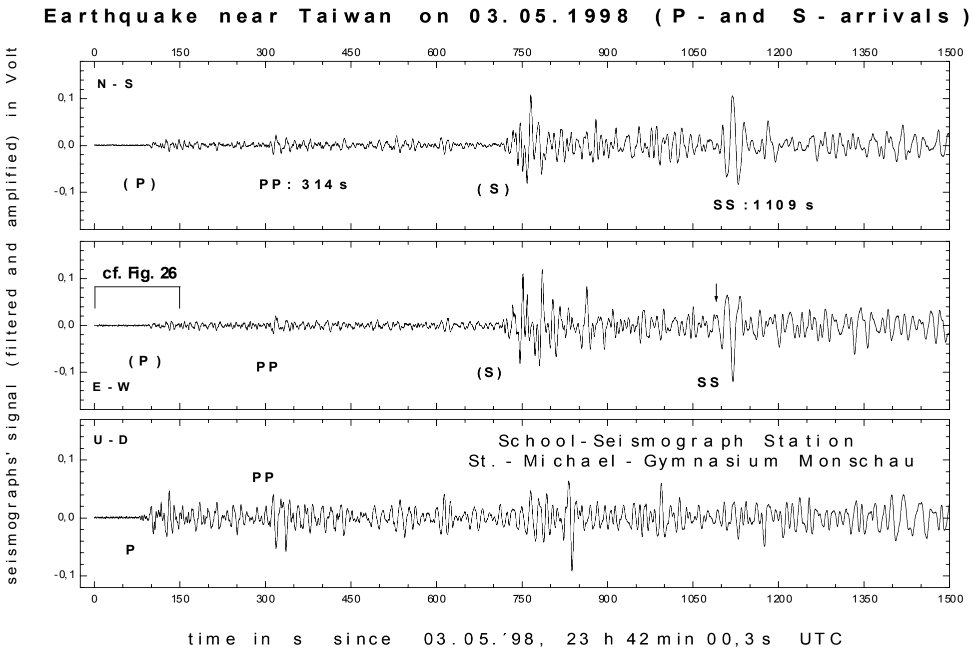


Fig. 25: The first 1500 seconds of the Taiwan seismogram

And our seismograph registered the first 150 seconds as follows,

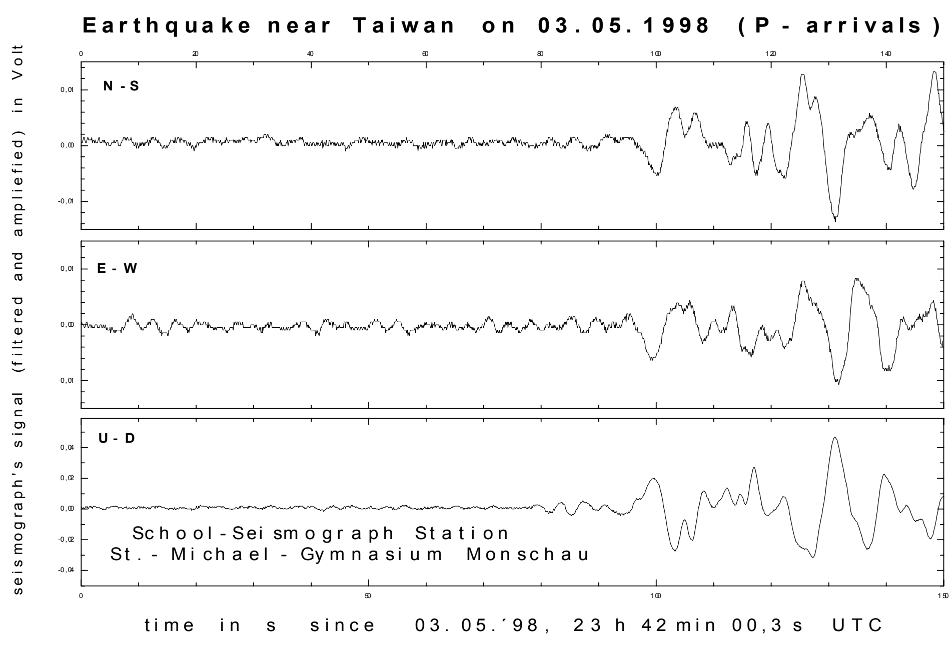


Fig. 26: The first 150 seconds of the Taiwan seismogram

3. The basic functions of a seismograph

3.1 Seismographs and Archimedes' point

A seismograph is conceived to record movements of the earth, which are caused by earthquakes. An observer who is himself situated on the ground moves with the quake and the ground. Because of this he cannot sense the absolute movement of the ground, as the ground does not move relative to the observer (fig. 27 upper section).

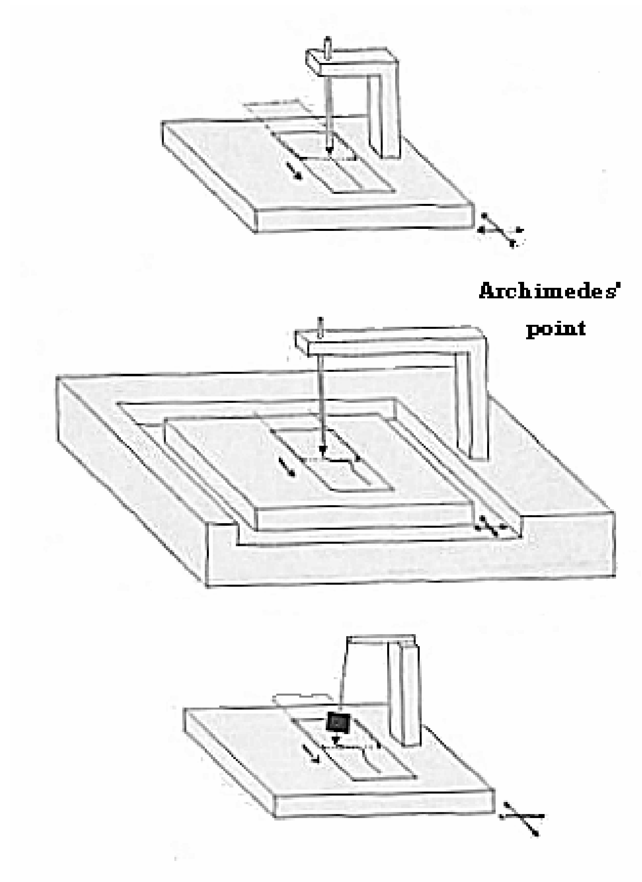


Fig. 27: Archimedes' point and seismographic pendulum

The observer should be at a point of absolute inertia not affected by the earthquake (fig. 27, central section). As such an Archimedes point is not available, it is simulated by a pendulum, the suspension of which is secured to the moving ground (fig. 27 lower section).

The movements of the ground incur the oscillation of the pendulum during which the pendulum, due to the inertia of its mass 'drags behind' the oscillation of the ground. During the moment of displacement the pendulum appears to move, whereas in fact it is nearly static and it is the ground itself which is moving.

If one now records the movement of the pendulum a picture of the earth's oscillations is created:
a seismogram. The seismogram does not directly repeat the earth's oscillation but one can calculate this from the seismograph's readings. We shall return to this point again at a later stage (see chapter 5).

3.2 Normal laboratory pendulum and seismographic pendulum in comparison

We resume: The seismograph executes a forced oscillation. The way in which this oscillation occurs, however is completely different to what we are used to from 'usual' forced oscillations in a laboratory (see fig. 28).

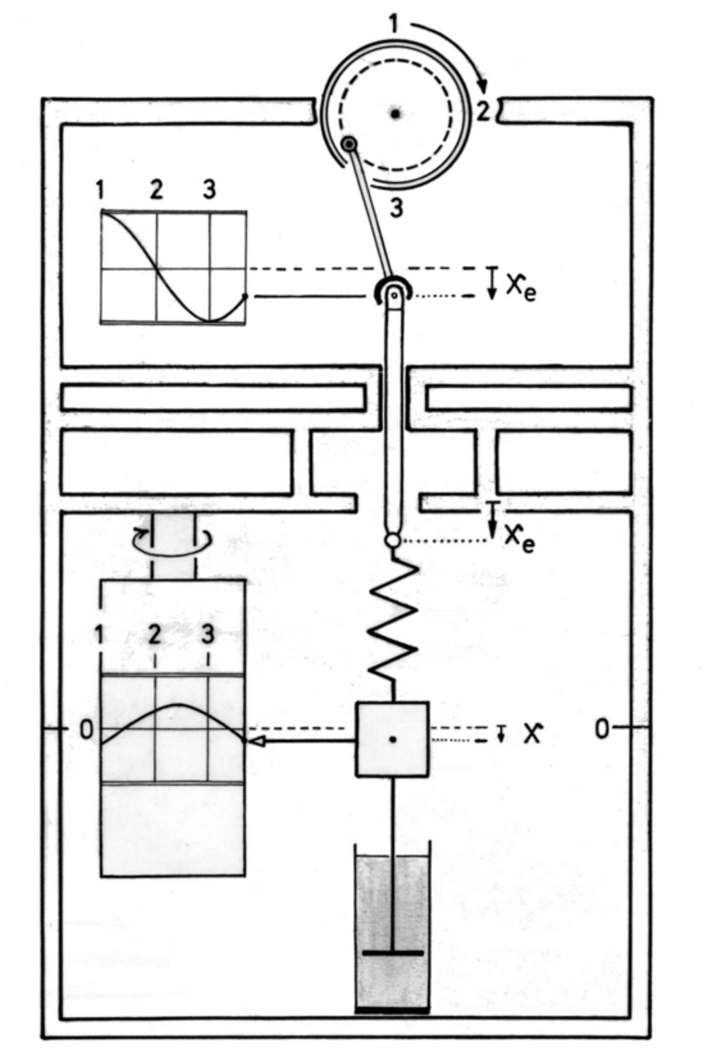


Fig. 28 Usual forced oscillations in a laboratory

The illustration above shows us the familiar scene in which a spring-pendulum is made to oscillate regularly. The upper end of the pendulum is periodically moving up and down. Balancing the forces causing this harmonic movement with $x_A = a_o \cos(\omega t)$ we receive for the upper end of the spring

$$m\ddot{x} = -R\dot{x} - D\cdot(x - x_A), \quad \text{so:}$$

$$m\ddot{x} + R\dot{x} + Dx = D a_o \cos(\omega t)$$

In the case of seismographic oscillations however the whole laboratory is oscillating in keeping with the earth's movements, (fig. 29). There x shows the ground-movement in relation to a part of the earth that is not subject to the quake (so called 'inertial frame'). x is the displacement of the pendulum and x_m is the absolute movement of the pendulum in the inertial system.

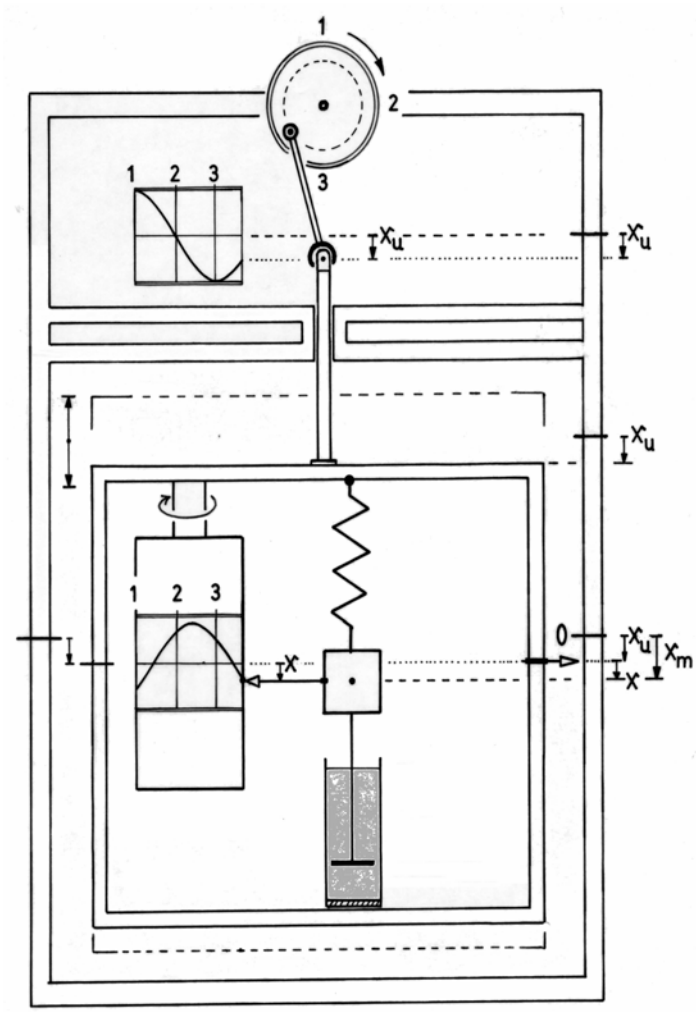


Fig. 29: Basic sketch of the creation of seismographic oscillations

Obviously: $x_m = x_u + x$ as well as: $m\ddot{x}_m = F_D + F_R$;

so: $m(\ddot{x}_u + \ddot{x}) = -Dx - R\dot{x}$, ,

or: $m\ddot{x} + R\dot{x} + Dx = -m\ddot{x}_u$.

If the ground oscillates harmonically to $x_u = a_o \cos(\omega t)$ then we conclude:

$$\boxed{m\ddot{x} + R\dot{x} + Dx = m\, a_o\, \omega^2 \cos(\omega t).}$$ *(Seismograph - Equation for x).*

In the first seismographs at the beginning of the last century the recording of received signals was directly and mechanically connected to the seismographic pendulum. In this method of recording the friction of the pendulum's pencil on the paper must be overcome. For this reason the body of the pendulum (so called 'seismic-mass') was of significant weight. The 17-ton Wiechert-Seismograph, which remains in use even today at the University of Göttingen, is a famous example of this.
Such seismographs are masterpieces of mechanical engineering. Even a small touch with a feather sets the heavy apparatus visibly in motion.
A significant progress in sensitivity (and ease of use) was the touch-free registration via electromagnetism. In this way the dynamo-principle was exploited. To the seismographic

pendulum's "boom" a coil is attached, which is placed into a horseshoe magnet being in turn fixed to the ground. As induced voltage is proportional to velocity, one does not measure displacement with a modern seismograph, but instantaneous velocity. If one knows the so-called 'generator constant' of the system 'Induction-coil - Magnet' (compare chapter 4.3) then one can calculate velocity and displacement of the pendulum.

The seismograph equation is again differentiated and one concludes:

$$\boxed{m\ddot{v} + R\dot{v} + Dv = -m a_o \omega^3 \sin(\omega t)}$$ *(Seismograph equation for v)*

The following figure illustrates an overview for the different resonance curves for forced oscillations for the 'normal laboratory pendulum' (left), for the 'classic seismograph' with a direct registration of displacement and for a modern seismograph with velocity registration.

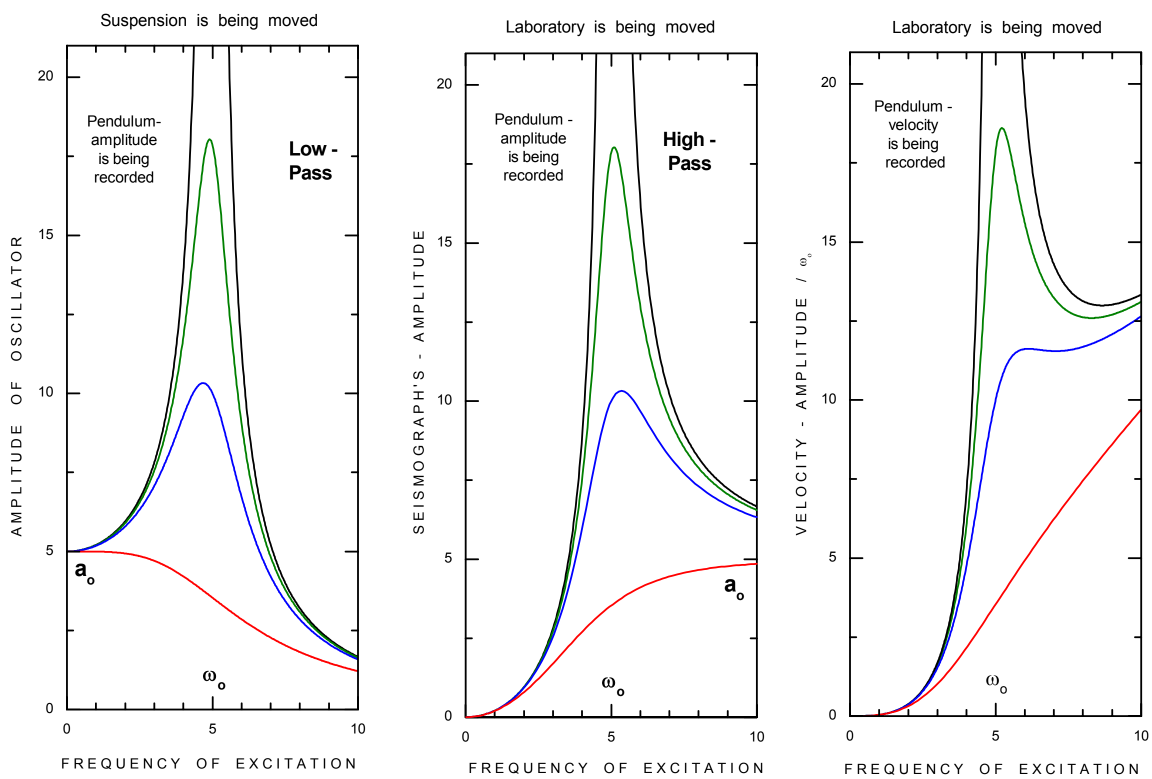


Fig. 30: Resonance curves

If one standardises the amplitude to the exciter's-amplitude, the graph reveals the so-called

'transfer-function': $H(\omega) = A_o(\omega) \; / \; a_o$.

3.3 Seismograph requirements for the registration of distant earthquakes

We will concern ourselves with the details of constructing a seismograph in chapter 4. For the registration of teleseisms in general a seismograph needs to fulfil the following requirements:

a. As in all seismographs the pendulum component is damped significantly, as otherwise it would - once disturbed - oscillate with its own frequency and therefore overshadow or falsify the incoming signals. If the pendulum is sufficiently damped it quickly returns to its initial position after each movement and is ready to receive new signals. So the damping functions similarly to the dashpot of a car: If the damped pendulum swings freely after an initial displacement the second 'swinging' would only amount to 1/23 of the initial displacement (this damping does not allow the pendulum to achieve displacement-resonance and the seismographic coil always remains within the magnetic field of the permanent magnet).

b. The pendulum must be very sensitive, so that it can perceive the weak signals of distant earthquakes.

c. During their journey through the earth, the earthquake waves are expanded in time and space. Earthquake signals that last about 10 seconds in the vicinity of the epicentre may excite a seismograph at a distance of 10,000km for an hour or more. Therefore the signals from distant quakes have a very large period of oscillation. This long period of oscillation, in our case being circa 20 seconds, can only be recorded with a seismograph that has a long eigenperiod (one therefore often speaks of 'long-periodical seismographs').
If one wanted to use a string-pendulum for a seismograph pendulum, the string would have to be extremely long: for a period of 20 seconds it would have to measure about 115 meters. How to realize such a long-period pendulum within a housing of reasonable size will be explained in chapter 4.

4. On the construction of our seismograph

4.1 From the 'garden gate principle' to the horizontal seismograph

Our seismograph is a horizontal pendulum, which oscillates similarly to a garden gate; one often speaks of the 'garden gate principle'. A garden gate should not always remain open, but falls shut of its own accord. This is achieved by attaching the upper hinge somewhat further away from the upright post than the lower hinge. The time it takes for the door to fall shut depends on the angle between the hinges and the upright post. Is this angle of inclination small then the door closes slowly, if increased the door closes more quickly.

Before we describe details of our homemade seismograph, the following sketch shall explain why our horizontal seismograph contains the 'garden gate principle'.

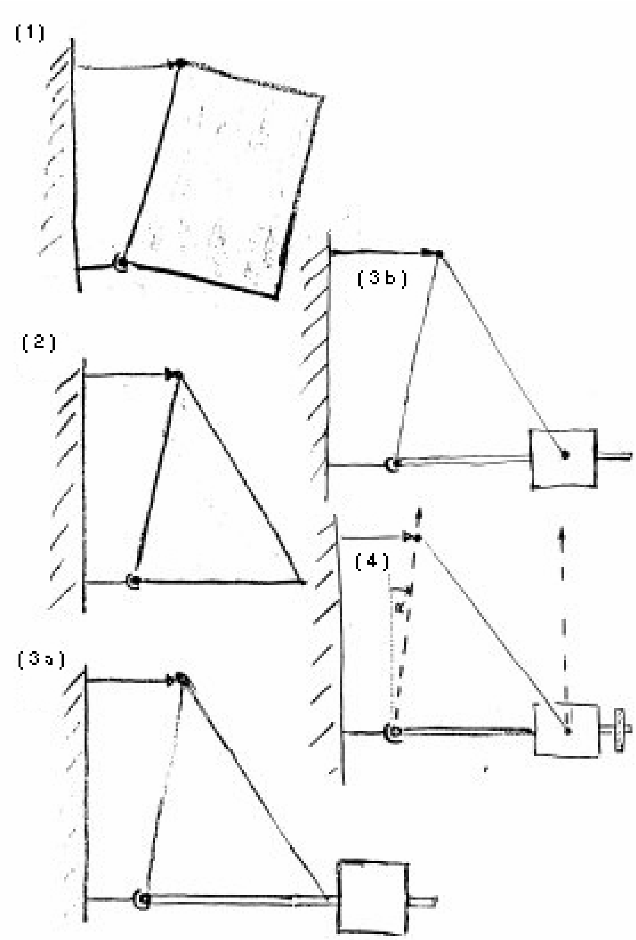


Fig. 31 The metamorphosis of a 'garden gate' pendulum

The first detail shows (if somewhat exaggerated to prove a point) a garden gate. In the second stage the inner parts of the gate are 'removed' so that only a frame remains, of which the lower strut is horizontal. In the third stage this "boom" is lengthened to become a pendulum's rod on the end of which is placed a stone (with a central hole) as a pendulum weight. The part of the garden gate extending from the upper hinge is replaced by a wire, the ends of which are attached to either side of the weight at the height of the pendulum's boom. In the last stage we can now attach the induction coil to the boom and remove the part of the frame that connects the hinges.

If one describes the length of the pendulum's rod as b (the distance between the lower hinge point and the centre of the pendulum weight) then one can calculate the pendulum's period with the aid of the acceleration of the earth g and the angle of incline α as follows:

$$T = 2\pi\sqrt{\frac{b / \tan\alpha}{g}} \quad .$$

The size $L^* = b / \tan\alpha$ is the 'equivalent pendulum length' of a string pendulum with the same period T of oscillation as the garden gate pendulum: as one can see one finds L* by erecting an upright perpendicular to the (horizontally mounted) pendulum weight and consequently make it create a section with the straight line that runs through both hinge points. With a pendulum length of one meter and an angle of incline of 0.5˚ (which is easily adjusted in our pendulum) there results the pendulum length of $L^* \approx 115$m.

4.2 The fixed mounting of the seismograph - pendulums in our station

We have attached the two stationary horizontal pendulums in our school's cellar to walls as is shown below.

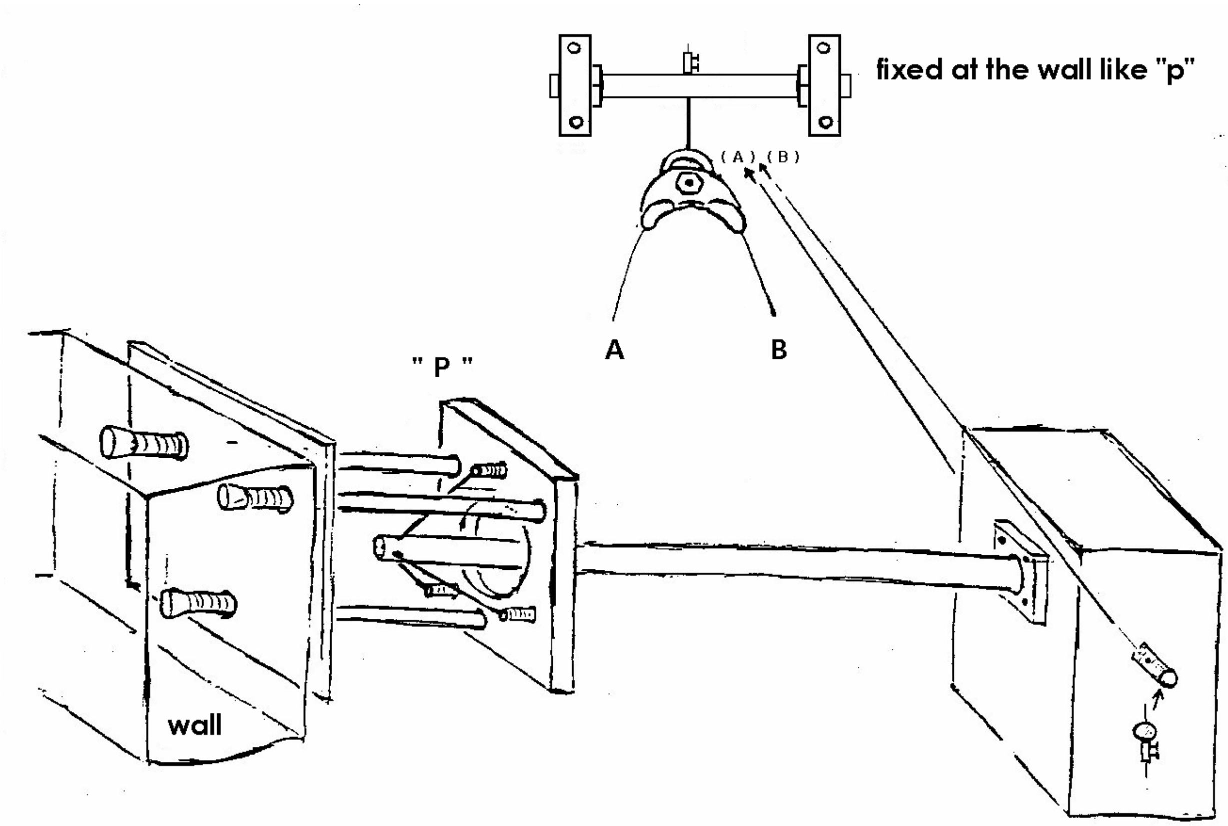


Fig. 32 Fixed suspension of the two horizontal seismographs at our station

The upper bearing was copied from the front brake of a bicycle; a short wire is fed through the pipe of a bored threaded pin that is held by two small aluminium boards that are in turn fixed to the wall with screws. The metal part of an electrical lamp-insulator holds the wire to the upper side. At the other end of the wire we have fixed a part of a front break of a bicycle. In this is hung the wire-loop, both ends leading to the sides of a block of concrete. The wire is fixed again here with the aid of pipes and clasps.

The lower bearing, that is the bearing of the pin-ended support, is achieved by three wires, which together create a tetrahedron and act as a ball and socket joint. Our young scientists were particularly proud of this setting: knife-edge bearings and pivots, which are often used in homemade seismographs tend to wear easily over time. In our setting only inner friction of the wire is present.

Altogether we can therefore say: five wires suspend our pendulum, so that only one degree of freedom remains for its movement.

The following photo shows the seismograph room of our station as it is appears when the seismographs are protected against drafts by Styrofoam housings.

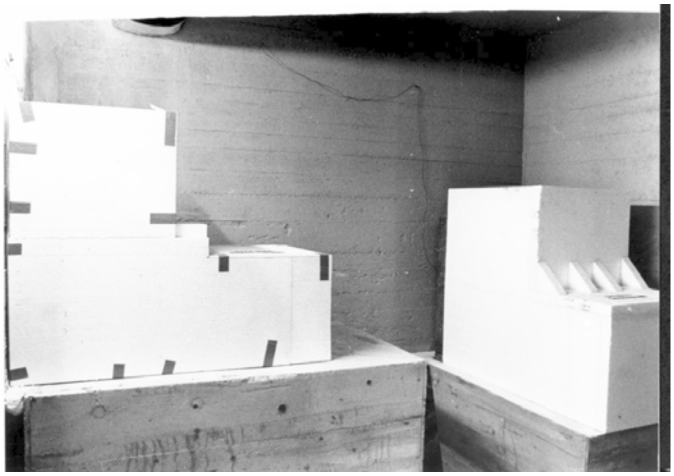


Fig. 33 The seismograph room 1 at the St. Michael Gymnasium Monschau

When one removes the protective housings one can see both horizontal seismographs.

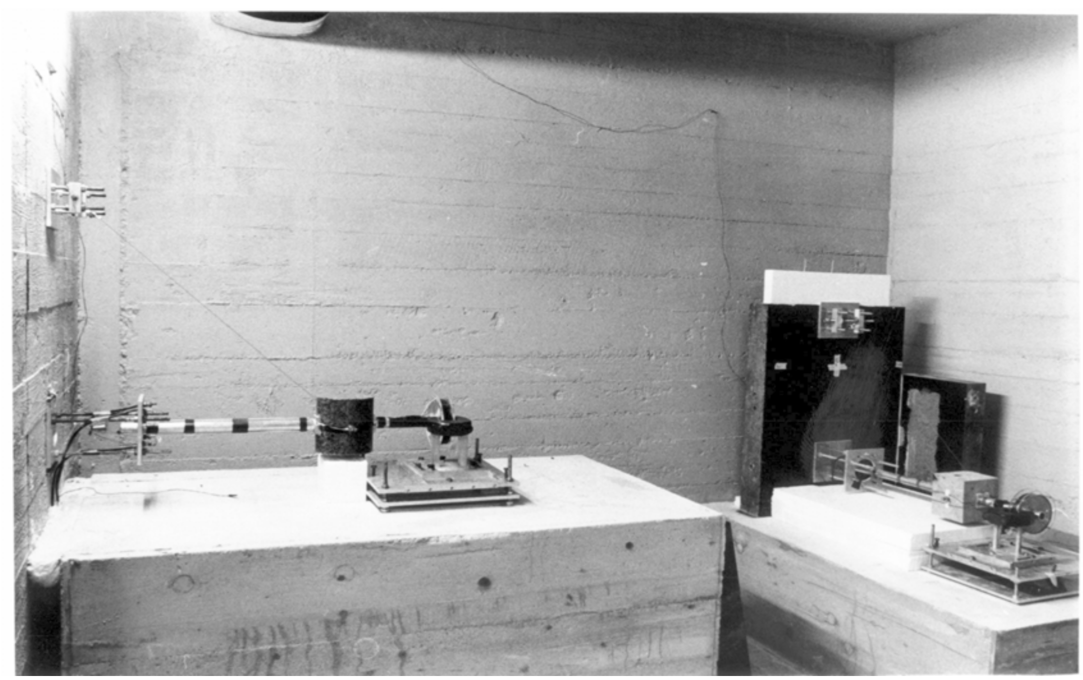


Fig. 34 The North-South seismometer (left) and the East-West seismometer of our station

The velocity to voltage converter unit of the east-west seismograph is shown in the next photograph. The magnet, which was once part of a mass-spectrometer that was kindly donated to the project by Dr. Dittmer of the Siemens Scientific Research Laboratory in Aachen.

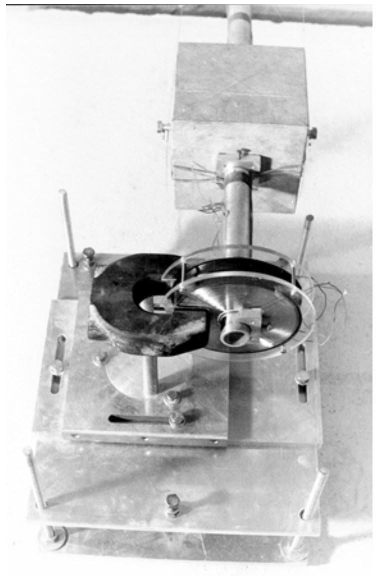


Fig. 35 The velocity to voltage converter unit of the East-West seismograph

The housing of the paper-recorder of our station in one of our halls was donated by the father of one of our students. Here we can see when an earthquake has taken place. The feed-velocity of paper is approximately 1cm per minute, consequently the looped tracker paper of circa 4.8 meters length takes about eight hours for a full cycle. During this cycle the recording nib of the TY-writer is moved 1cm to the right. The paper is thus filled spirally during the course of a week. At the end of the week the nib is placed between the first two old lines, a pencil with a different ink-colour is inserted and in this way the paper can keep recording for two weeks running.

Fig. 36 The sight-recorder of the earthquake station at the MGM Monschau

4.3 On the construction of the moveable teaching seismograph

Here we see a basic diagram of our teaching seismograph, as it was built by our young scientists Bernd, Sebastian and Thomas. The diagram does not show the side struts.

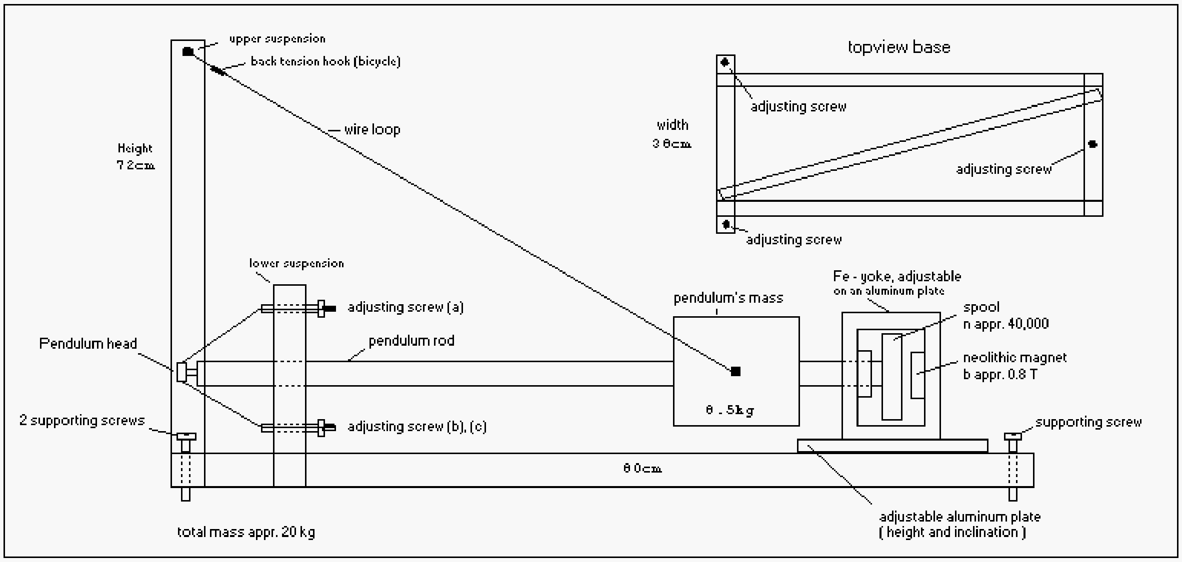


Fig. 37 Sketch of our teaching seismograph

Adjusting the supporting screws on the outer frame easily changes the period of oscillation of our pendulum. As the instrument is placed on the ground one is relatively independent of the movements of the building when the seismograph is placed upon the basement-floor of the building. The following photograph shows the teaching seismograph from the top.

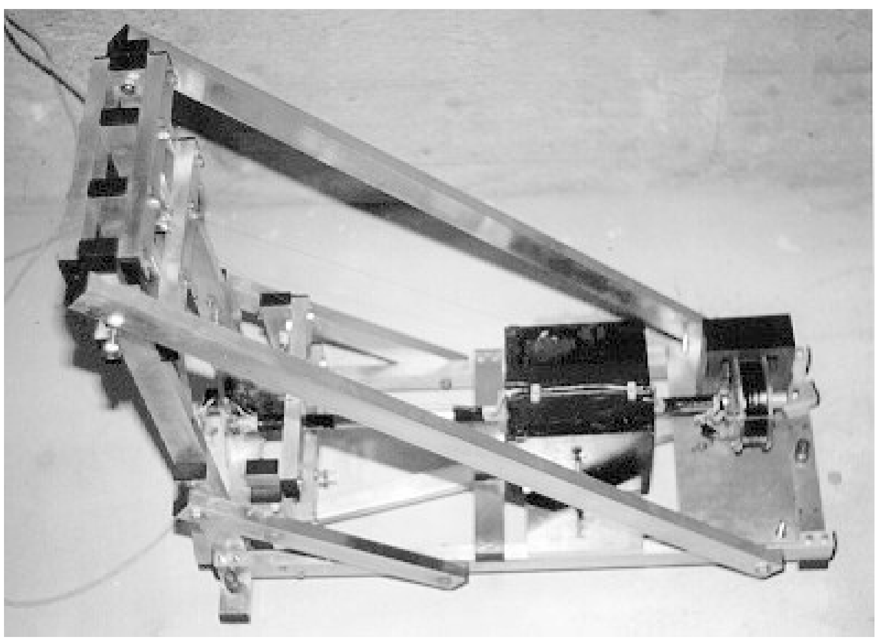


Fig. 38 Photograph of the teaching seismograph

The registration of the pendulum's oscillation is electronic. We attach a coil to the pendulum, which has about 40,000 coils of varnished wire (diameter 0.16mm). On one side this coil is placed within a strong permanent magnet. In the yoke both permanent magnet-blocks create a magnetic field of about 0.8 Tesla (we will be happy to forward information on technical details to anyone who sends us an email).

4.4 On the generator-principle and generator constant

When the pendulum is set in motion the generator principle comes into action. Movement induces electrical voltage in the coil, which is greater, the faster the pendulum moves. It is known, that

$$\text{Force} \cdot \text{Distance} = \text{Work} = \text{Voltage} \cdot \text{Electric Current} \cdot \text{Time}$$

is valid. If we re-arrange this we conclude;

$$\frac{\text{Force}}{\text{Electric Current}} = \frac{\text{Voltage}}{\text{Distance / Time}} = \frac{\text{Voltage}}{\text{Velocity}} = \text{constant} = S\,.$$

Remember: $\left|U_{\text{induced}}\right| = n\,\dot{\Phi} = n\,\frac{d}{dt}(B \cdot A) = n\,B\dot{A} = n\,B\,\frac{d}{dt}(\ell x) = n\,B\,\ell\,\dot{x} = n\,B\,\ell\,v$,

wherein n is the number of the coil's windings; B the value of the magnetic induction; ℓ the length of that part of each wire, seized by the magnetic field.

Additionally we have for Lorentz' force: $F_{\text{Lorentz}} = n \cdot J \cdot \ell \cdot B$

Therefore: $\frac{F_{\text{Lor.}}}{J} = n \cdot \ell \cdot B = \frac{\left|U_{\text{ind.}}\right|}{v}$ *Generator-Constant* $S = n \cdot \ell \cdot B$

So the induced voltage is proportional to velocity, the fraction is a constant. If one then uses the pendulum in an experiment as an ampere balance, as is shown in the following figure;

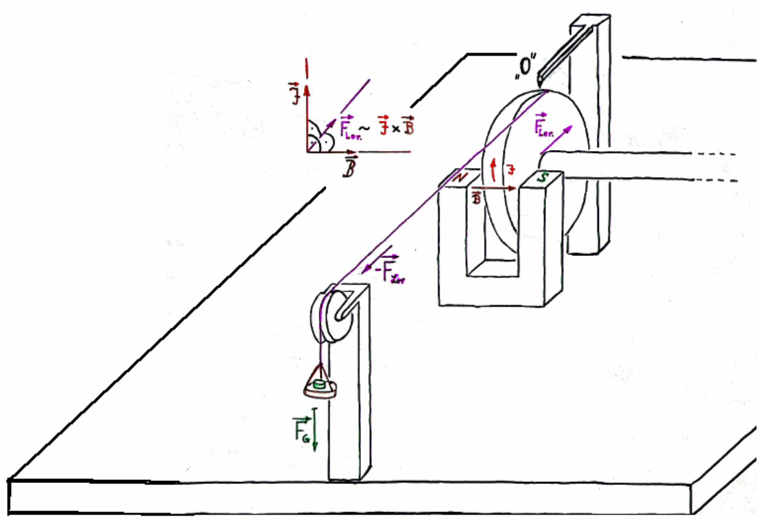


Fig. 39 Static determination of the generator-constant S with an ampere-balance

then one can determine the generator-constant S of the pendulum by static means. From this the velocity of the pendulum that corresponds to a given induction-voltage can be calculated as follows;

$$\boxed{v = \frac{U_{\text{ind}}}{S}}\,.$$

The following diagram shows the result of such a measurement for S ;

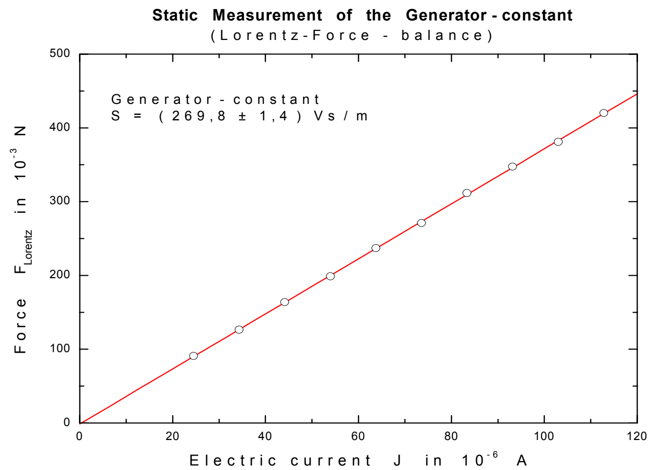


Fig. 40 Measurement of the generator constant

For our horizontal seismographs we measured approximately: S = 250 N/A = 250 Vs/m

There is also the possibility to determine the generator constant dynamically with the help of an Hall-probe. In this case the Hall-probe is attached to the pendulum in the vicinity of the magnet. Firstly one records the Hall-voltage with the help of a precise voltmeter and the corresponding displacement of the pendulum measured accurately by a µm-screw. Then secondly one allows the pendulum without additional damping to swing freely and records simultaneously Hall-voltage and induced voltage within the seismograph's coil. The Hall-voltage signal is recalculated into the matching displacement signal. One differentiates the displacement numerically with an appropriate PC-software and thus receives the velocity of the pendulum in relation to time. The two sets of data from a measurement at the North-South seismograph of our station can be seen in the following diagram.

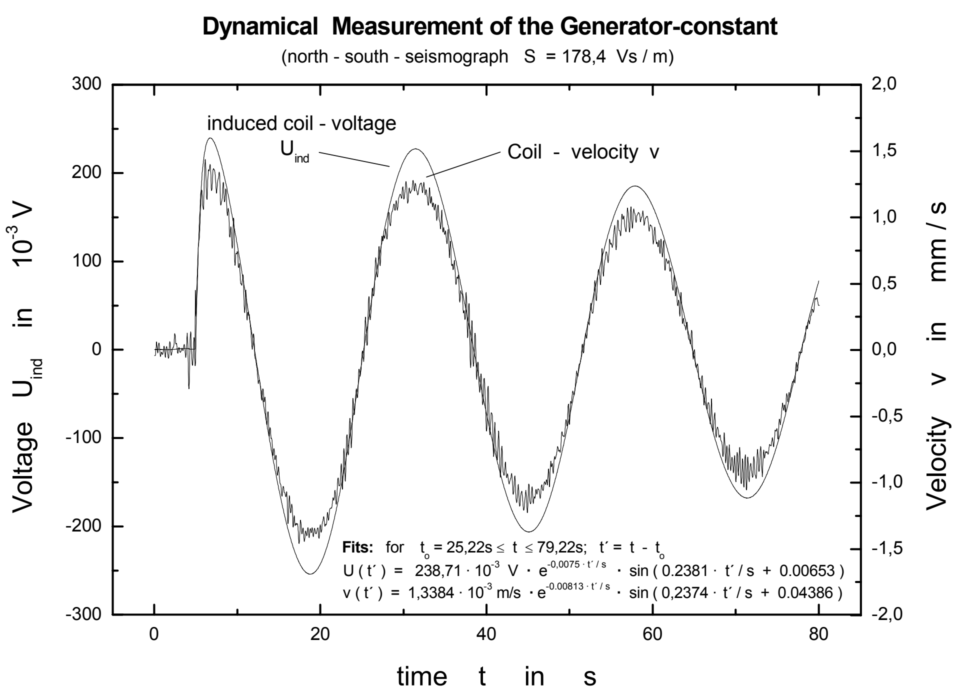


Fig. 41 The dynamic determination of the generator constant

How one can deduce the movement of ground from the voltage signal will be discussed in the following chapter.

5 On the data processing

5.1 The journey of a signal from the ground to the computer

Earthquake waves set the ground in motion. This movement causes the pendulum's suspension and the magnet of the seismometer to move which in the case of our teaching seismograph are both fixed to the frame, which in turn is placed on the ground. In the case of the stationary seismometers of our station the suspension and the magnet are securely fixed to the building. Each pendulum however is not statically bound to the ground but is – as described above – suspended by several wires. Therefore it inertly follows the movement of the ground.

The journey of a signal from the ground to the hard-drive disk of a PC is outlined in this next illustration.

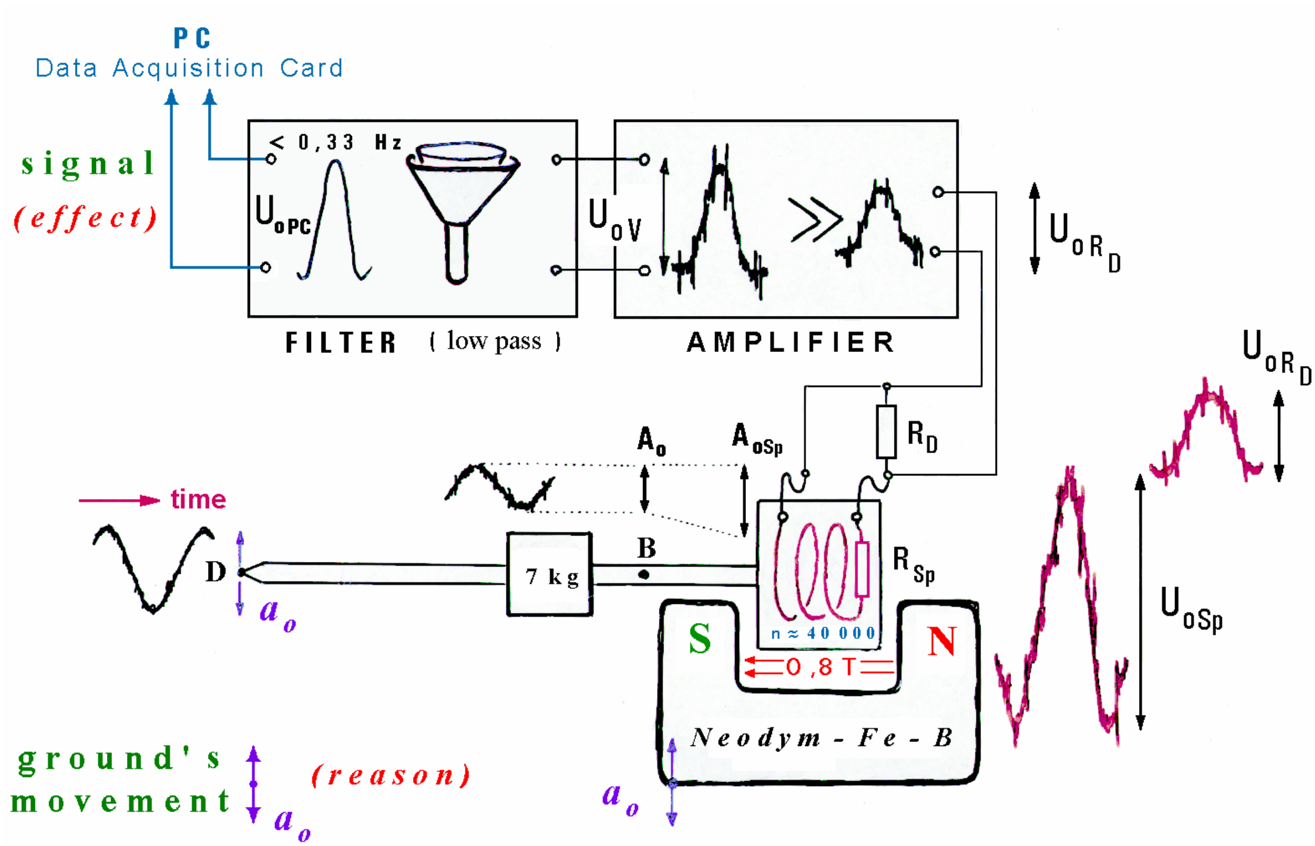


Fig. 42 The journey of a signal from the ground to the PC

The amplitude of the ground's movement relative to an inertial frame will be known as a_o. At point B on the pendulum ('centre of movement') one can imagine the entire mass of the pendulum at one point. The distance D to B is therefore the reduced length of the pendulum. So the centre of movement B moves relative to the laboratory with displacement A_o, which is constantly somewhat smaller than the ground displacement a_o, conditional to a properly damped seismometer (see following illustration).

Coaxially to the pendulum's boom we have fixed a coil with many turns of wire (circa 40,000). This induction coil is situated within a strong magnet (0.8 Tesla) on one side. Such magnets are easily available and not too expensive.

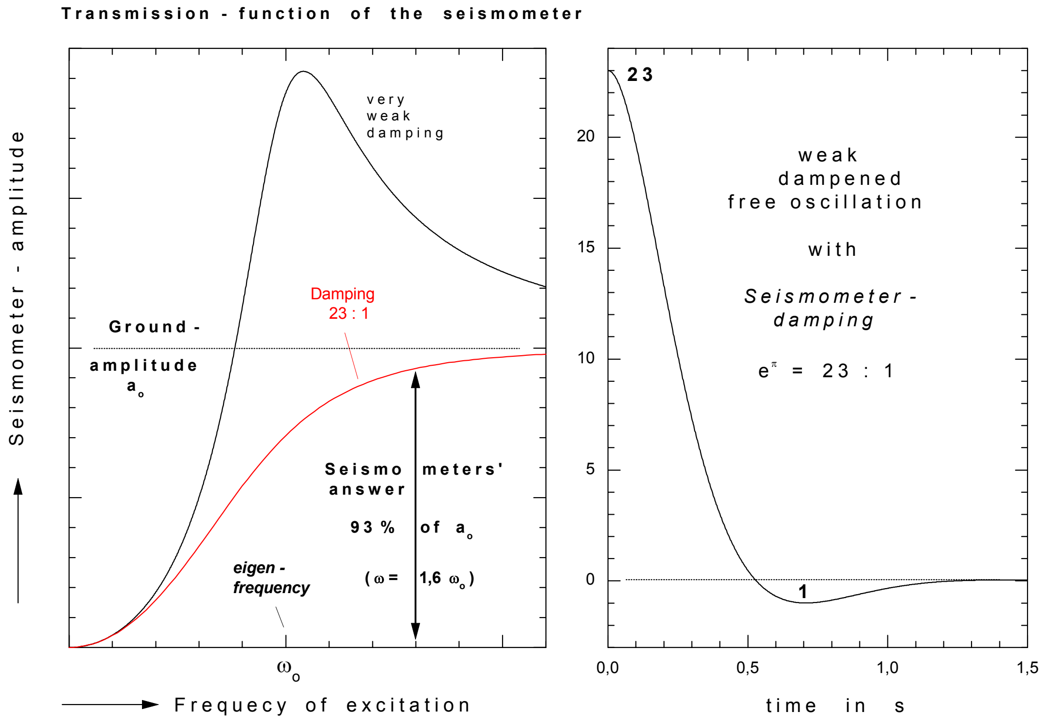


Fig. 43 Transfer function for the seismometer displacement for two differing strengths of damping vs. free oscillation of the seismometer in the case of 'seismograph damping'.

As the coil has a longer lever than the centre of movement, the displacement A_{oSp} is slightly larger at the coil than at B (indicator-enlargement). In the coil that is moving we now have an electric current, exactly as is the case in a bicycle dynamo. One can therefore determine an electrical voltage U_o at the coil that is proportional to the velocity of the movement of coil and magnet relative to each other.

Because of the electrical current that flows in the coil, a magnetic field is generated around it. This magnetic field however acts against the field of the permanent magnet ('Lenz' rule'). In this manner the movement of the coil and with it the movement of the pendulum is damped. This effect is comparable to the electric brakes of a streetcar. The damping of the seismometer's pendulum can easily be tuned with the help of a damping resistor R_D, which is switched parallel to the induction coil.

The electrical working-signal is also measured at this damping resistor. An amplifier finally enhances this weak signal. However, as well as amplifying the signal, one also amplifies the background noises, such as produced by passing vehicles or students walking and running in the vicinity.

Therefore the amplified signal U_{ov} is fed through a filter where all frequencies higher than 0.33 Hz are removed. The amplified and cleaned signal U_{PC} can now be saved in the PC for future examination.

Apparently each step of the signals' journey can mathematically be reversed. We could just as easily calculate the initial ground movement from the signal on our PC. This is evidenced by the following mathematical chart analysing the movement of the ground, which was brought about by the P-wave of the Ascension earthquake of the 18th February 1996 (the seismograph of the quake will be further examined below).

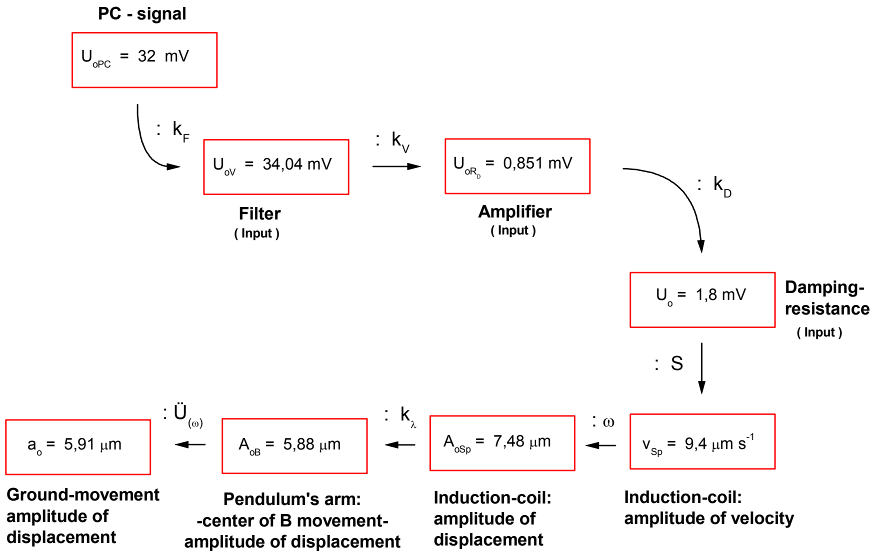


Fig. 44 The way back from the PC-signal to its cause - the ground-movement

Here the voltage-signal stored in the PC amounts to 32 millivolts. To this amplitude the filter has reduced the signal from 34,04 mV at the input of the filter. Since that voltage is caused by 40-fold amplification (i.e. k_V = 40), at the input of the amplifier you find a signal of 0,851 mV, which is leaving the damping-resistance R_D. To that value the voltage is reduced from the original induction-voltage of U_o=1,8 mV by ohmic resistance of the coil of the seismograph. That means - with a generator-constant of S = 191,5 Vs/m - a velocity-amplitude of v_o = 9,4 µm/s for the movement of the induction-coil.

For a period of 5s the deflection of the coil is 7,48 µm. At the center of movement the deflection is reduced by k_λ and so is just A_{oB}=5,88m. Due to the angular frequency $\omega = 2\pi/T$ and the adjusted mechanical damping γ of the pendulum you can calculate the ground-amplitude a_o with the help of the transfer-function H(ω) from A_{oB}. (Cf. the diagram for the transfer-function above.)

5.2 *The amplifier-filter-unit of the seismograph*

The amplifier-filter-unit of the seismograph is simply constructed from few component parts. The voltage supply for the Ic's can be bought as a kit for self-assembly at an electronic shop. – The amplification-factor k_V is adjusted by the ratio $(R_2 + R_3) / R_2$, the cutoff frequency f_{Grenz} of the low-pass filter is determined by $1 / [\, 2\pi \cdot (R_4 C_3 R_5 C_4)^{0.5} \,]$. The rest can be taken from the following circuit diagram.

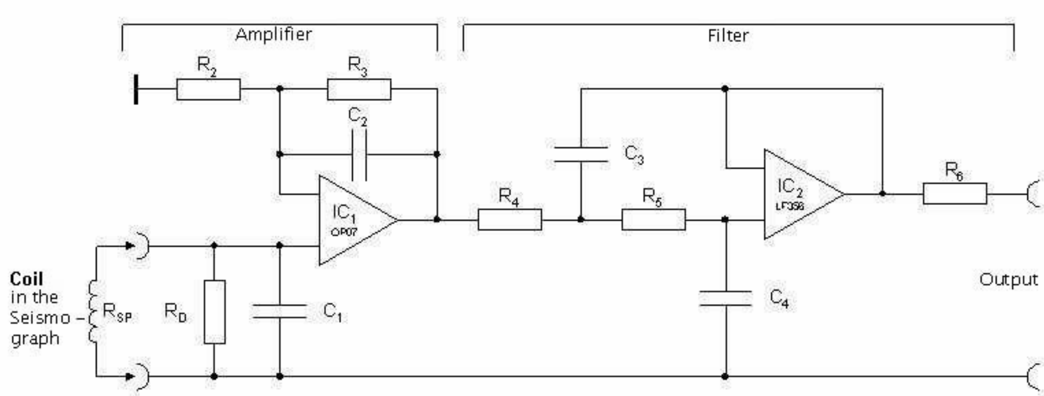


Fig. 45 Circuit-diagram of the amplifier-filter-unit of the seismograph

5.3 The digital remote reading of our seismological school-observatory

Special about our seismographic station is the possibility of "phoning" the seismographs with the help of a conventional modem and a simple terminal program: so you can download the registered signals of the 3 seismographs in seven files concerning the last week on your PC at home and then evaluate them. One download takes about 7 min.

With the terminal-program and some self-developed software the members of our seismic-team can watch the signals generated by the three pendulums live, choose single traces and zoom them up to the size which is needed.

The authorized operation crew can give the pendulums an impulse by touching a key and can so check if the pendulums can swing without hindrance.

Anybody who sends us an email can become a member of our mailbox users. The mail should contain
some personal information, (Name, address, school or institute, telephone number, PC used). The data is checked and you will get an account (with password) to use our data in the mailbox. The only requirement is a terminal-program, e.g. „Hyperterm" by „Windows '95" and a modem.

The following illustration presents the layout of our seismological school-observatory as it was built by our former students Bernd Naeth (calibration and data analysis), Sebastian Schork (electronics and software) and Thomas Poschen (mechanical constructions).

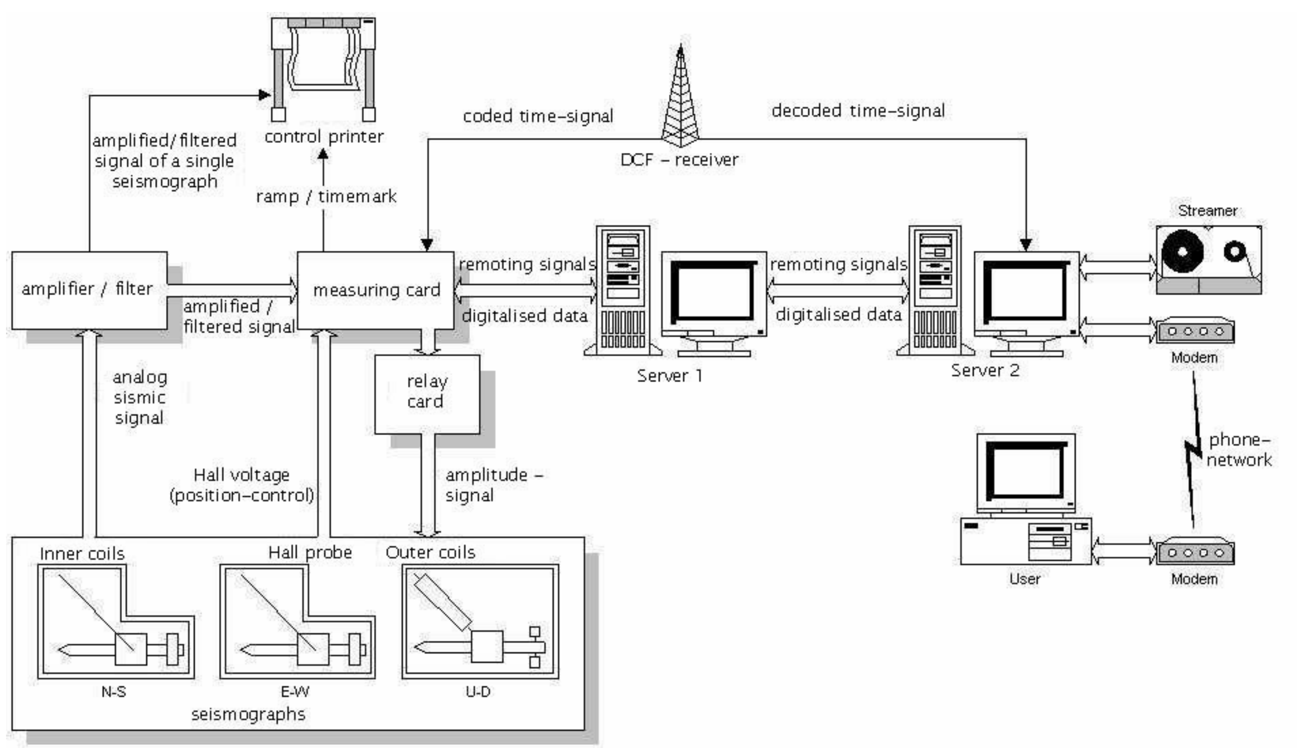


Fig. 46 Layout of the seismological school-observatory of the St.-Michael-Gymnasium Monschau, (Germany)

The control room of our station is presented in the next figure.

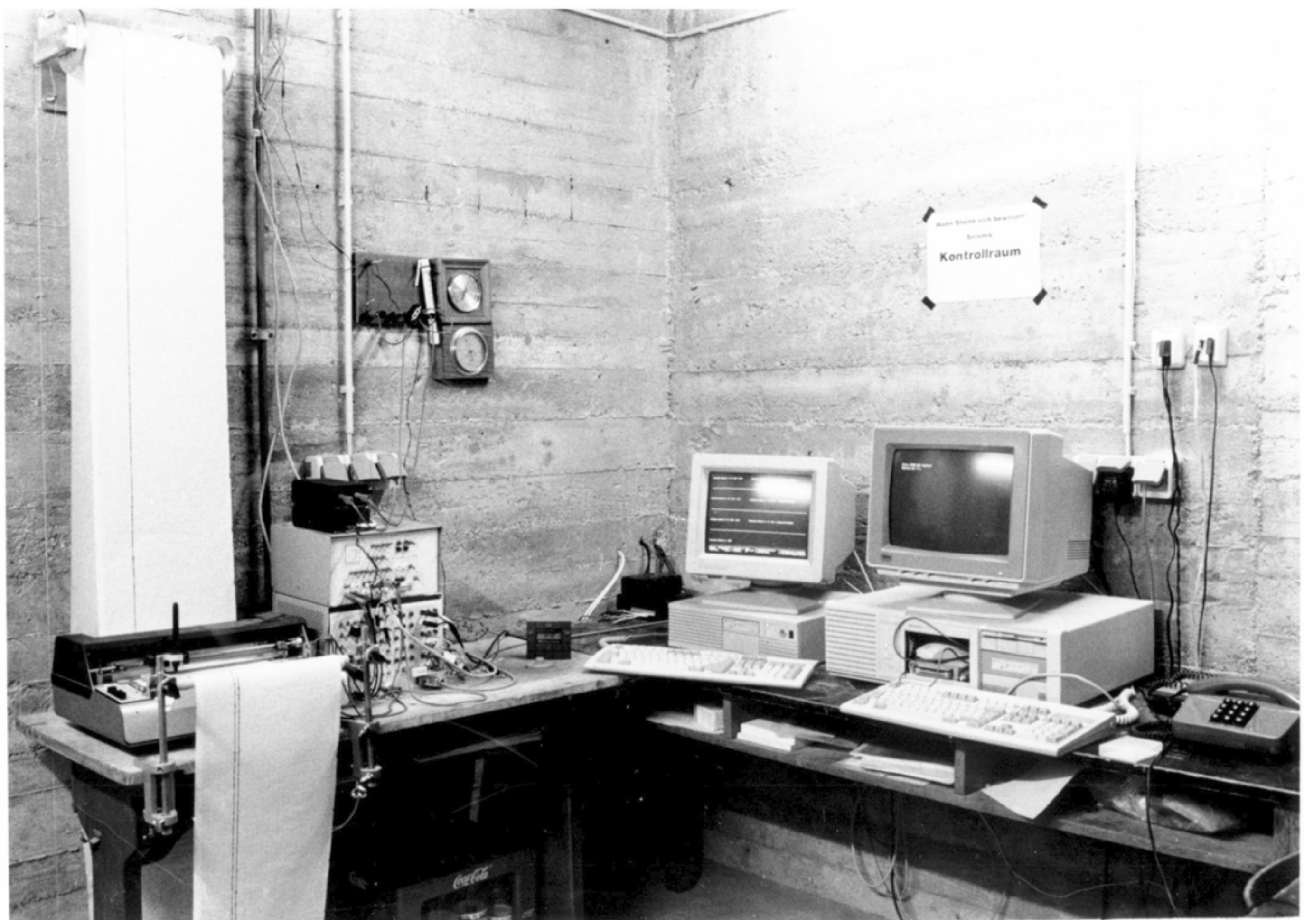


Fig. 47 The control room of our school-seismograph station

6. On the evaluation of a seismogram

As referred to in chap. 2, the determination of the arrival-times (starting time of the first swing) both of the primary- and secondary-wave is essential for the evaluation of the source parameters. Now we want to present the individual steps of a simple analysis of a seismogram as we do it in our seismic-team.

We evaluate the seismogram recorded from the Ascension-earthquake (island off Western Africa) on
18. 02. 1996.

(1a) Calculation of the distance between the origin of the earthquake and our station: *the epicentre-distance*.
(1b) Determination of the time at which the earthquake broke out : *the origin time*
(2) Fixing the strength of an earthquake : *the (surface-) magnitude* (position on the Richter-scale)
(3) Fixing of the geographical coordinates (latitude and longitude) of the epicentre : *the „localisation" of the earthquake*

Before we start discussing the routine procedure of evaluating a seismogram let us take a general look at the recording units of a seismographic station.

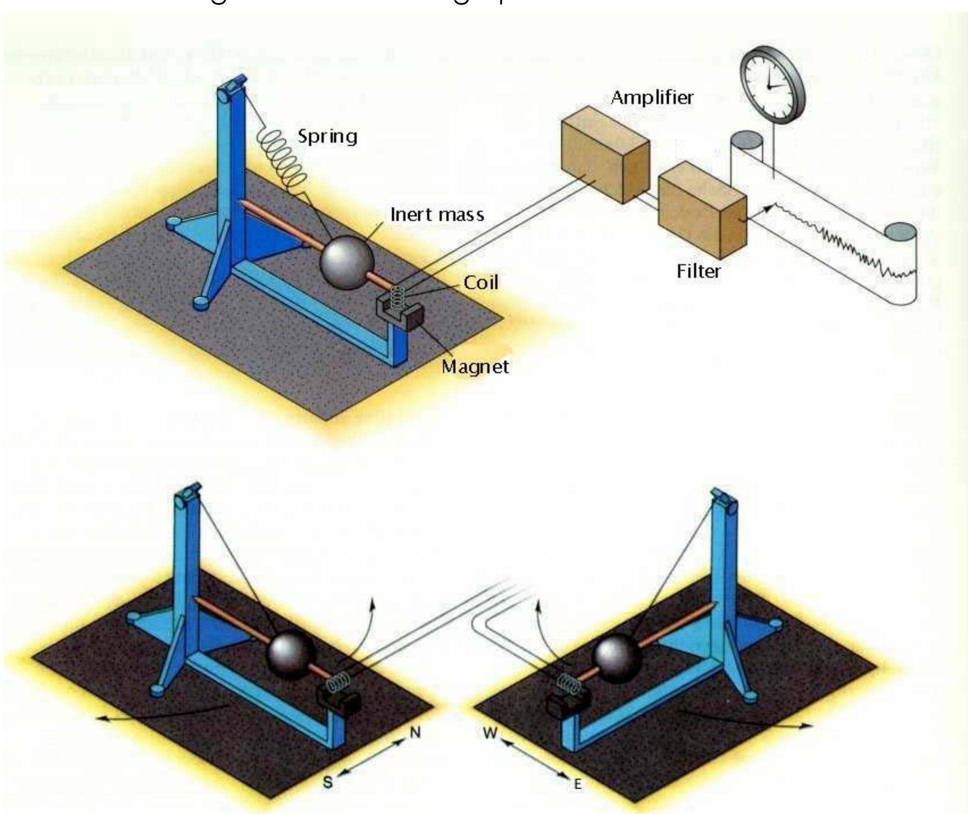


Fig. 48 The three components of a seismographic station

A complete seismographic station observes the waves of an earthquake in all the three spatial dimensions. This is usually done by two horizontal seismographs, one of which swings from north to south, while the other one swings from east to west. The third dimension is caught by a vertical seismograph, also called up-down or z-seismograph. – A complete seismogram of an earthquake therefore always consists of three components: a North-South-, an East-West- and an Up-Down-Seismogram.

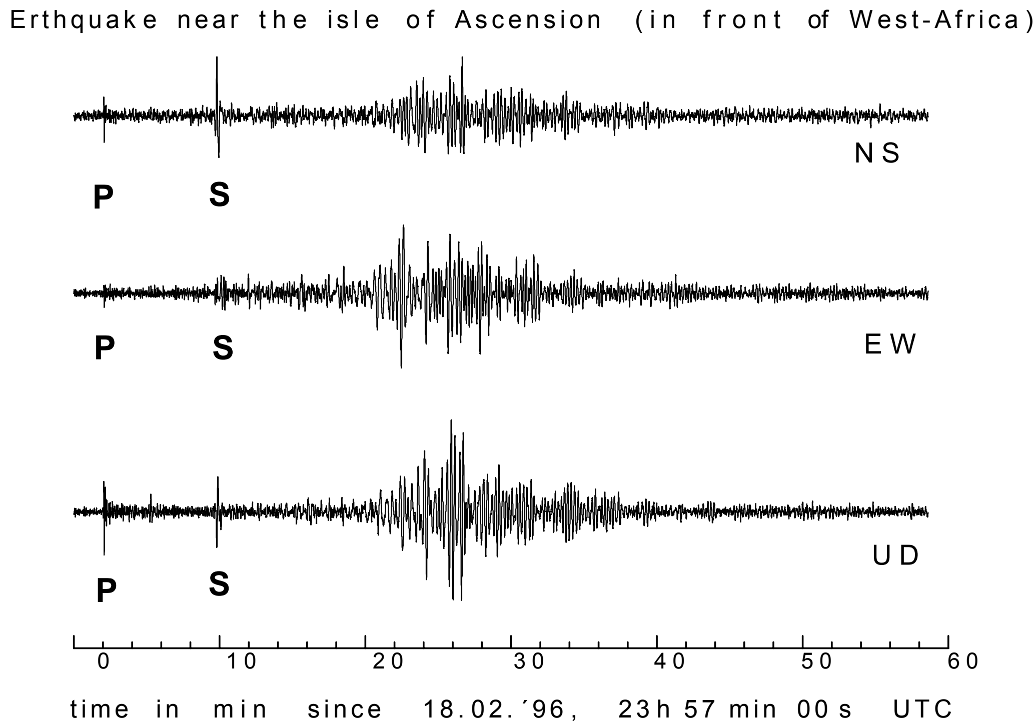


Fig. 49 P- and S-waves arrive simultaneously in all the three components (3d-seismogram)

This seismogram shows the synchronous arrival of the primary wave "P" and the secondary wave "S" very clearly in all the three readings of the seismogram.

6.1 Epicentre-distance and origin time

The first step we take when evaluating a seismogram is the fixing of the distance from our seismographic station to the epicentre and the calculation of the origin time, i.e. the time when the earthquake really happened. For this purpose we need the time-interval between the arrivals of the P-Wave and the S-Wave. We pick up that information from of the North-South – seismogram : for the Ascension-Earthquake this means Δt_{PS} = 461 s.

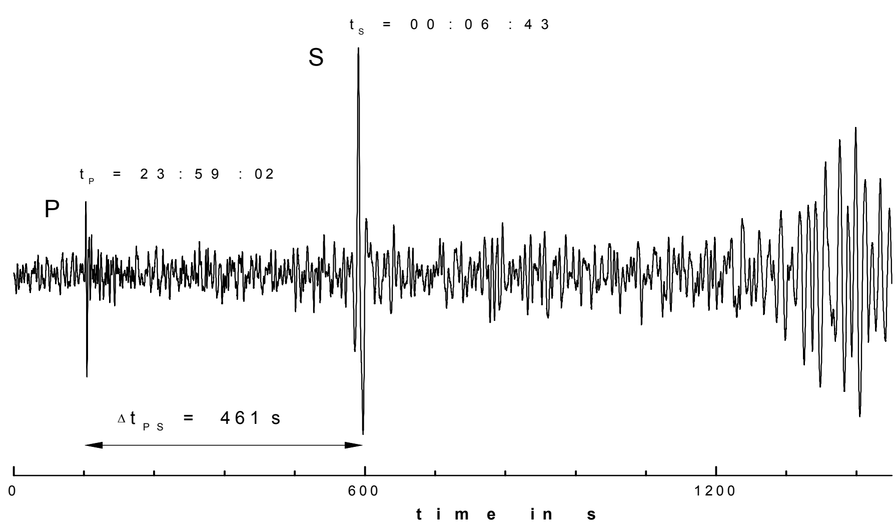


Fig. 50 Fixing the time-interval between the P- and S-arrival

For many years seismologists have empirically determined the values of the travel-times of various earthquake-waves: this means the running time of the corresponding signals from the epicentre to the station. This work was done for as many distances as possible and for many types of waves: here we need the travel-times of P- and S-waves. The measurements are summed up in the following “travel-time diagram“.

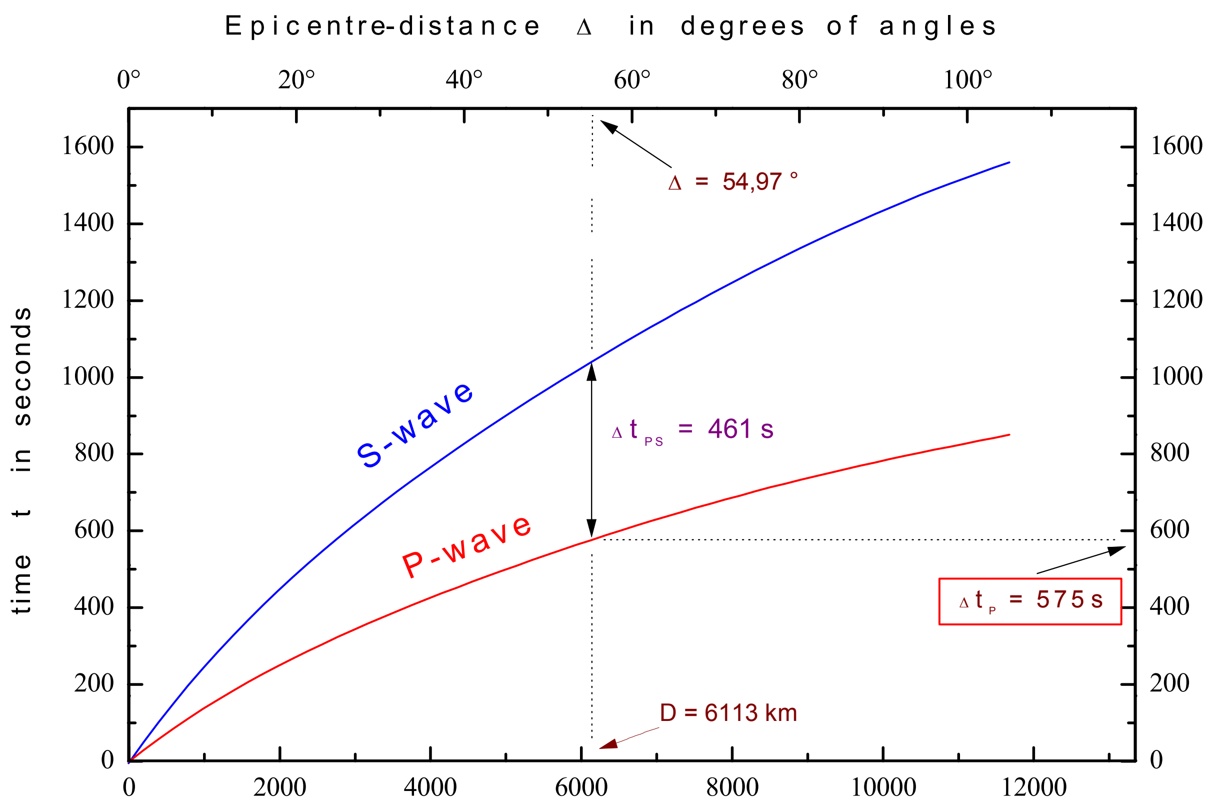


Fig. 51 travel-time diagram for P- and S-Waves

Pick up the interval Δt_{PS} from the seismogram and fit it in between the travel-time curves of P- and S-wave: from this unequivocal position you can fix the epicentre-distance by drawing a line perpendicular to the lower axis: here the epicentre-distance is almost 55°, i.e. about 6100 km.

The horizontal line from the fitting point at the P-wave to the left axis supplies us with the travel-time of the first signal from the epicentre to the station: here that travel time amounts to Δt_P = 575 seconds or 9 minutes and 35 seconds.

The P-wave of the Ascension-Earthquake arrived at Monschau at 23.59h and 2 seconds; if you subtract the travel-time of the P-wave (9 min 35 s) from its time of arrival at Monschau you will get the time at which the earthquake began, the so-called “origin-time“.

Here we therefore get for the origin-time 23.49 and 27s. The official measurement of the “National Earthquake Information Survey (NEIS)“ in Golden (Colorado) differs from our origin-time in just a few tenths of seconds. The “NEIS-Data“ are determined with the help of data coming from many earthquake observatories all over the world. For the Ascension-earthquake the data acquisition was done by 109 stations with at least 3 seismographs each.

6.2 Magnitude

As mentioned above the technical term for the strength of an earthquake is "Magnitude". The media usually refer to the „position on the Richter scale". – We determine the magnitude from that surface wave with the largest amplitude. The magnitude determined by this method is called "Ms-Magnitude", (s = surface).

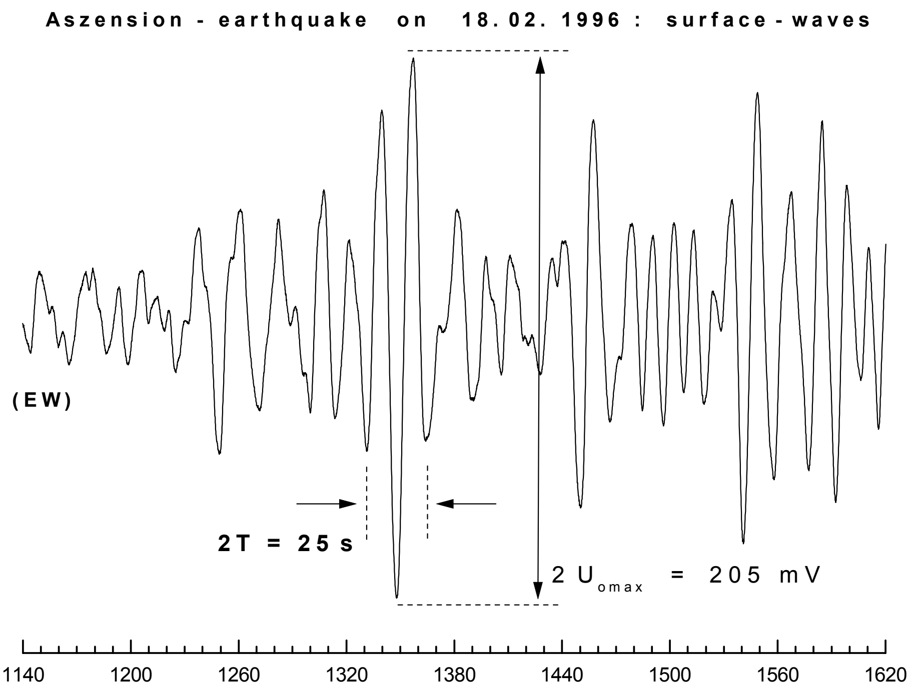


Fig. 52 On the determination of magnitude using surface waves

Our seismogram shows that the largest signal of the Rayleigh-surface wave has got double the amplitude of 205 millivolts. From this amplitude belonging to the period T the corresponding displacement of ground a_o can be calculated in the same manner as described in the previous chapter : with U_o= 205 mV and a period T = 12,5s a ground-displacement with an amplitude of about a_o = 38μm can be stated, i.e. 3.8 hundredth of a millimetre.

International experts have agreed on a formula for calculating the Ms-Magnitude of an earthquake; therefore you need: the largest ground-displacement a_o in the surface waves, the corresponding period T of the movement and the distance Δ to the epicentre.

From this formula released from IASPEI (International Association of Seismology and Physics of the Earth's Interior)

$$M_S = \lg\left(\frac{a_o/\mu m}{T/s}\right) + 1.66 \cdot \lg(\Delta/\deg)$$

we finally get the result M_s = 6.7 . The value published by NEIS is in this case 0.4 smaller. - Even in professional seismographic observatories differences in magnitude up to 1 occur if one compares the data of the single stations. So we remain within those limits.

6.3 *Geographical epicentre-coordinates (localisation by one seismographic station)*

Determining the *geographical coordinates* of the epicentre means calculating *latitude* and *longitude* of the epicentre with the help of results calculated from the data recorded by our three seismographs.

The *mathematical idea* is as follows (congruence theorem LAL) :

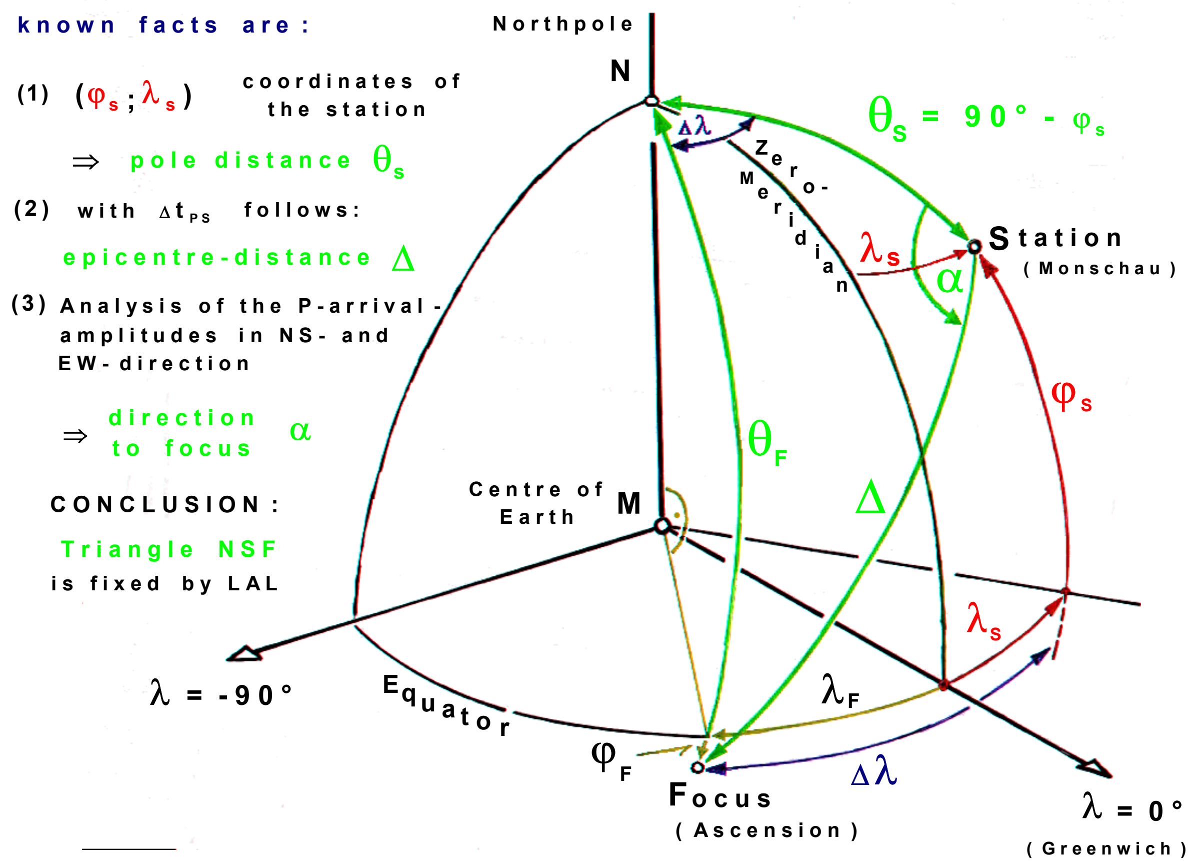


Fig. 53 Localisation – "Cassata"

Here we see the triangle "North Pole – Station – Epicentre – North Pole". We already know two destinators of LAL:

(1) the spherical leg θ_S = "Station – North Pole", since the geographical coordinates of the station are
known.

(2) the spherical distance Δ from the Station S to epicentre H. (We fixed it in chap. 6.1 .)

We finally need a third destinator for the triangle SHN. In our case it is angle α which is formed by the legs θ_S and Δ .

How to fix the angle α of the direction to the focus?

The physical idea is as follows: the very first signals of the earthquake that “knock at“ our three seismographs, reveal the direction the signals come from. So we have to return to the beginning of
the three components of the seismogram.

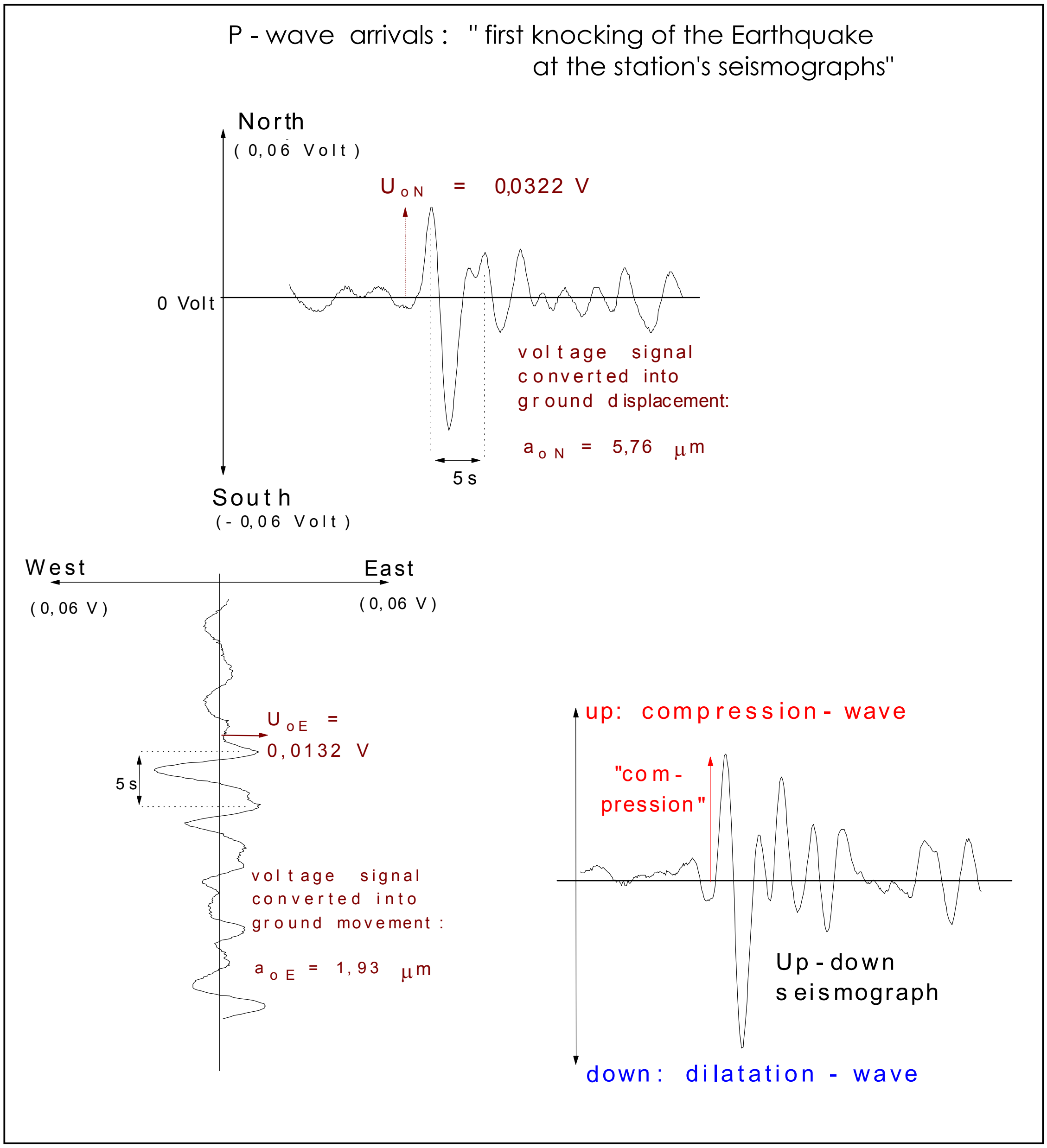


Fig. 54 Analysis of the P-arrivals in a 3d-seismogram

First of all we separately determine the corresponding ground-amplitudes for the P-arrival in the NS- and the EW seismogram. For the Ascension-earthquake we observe

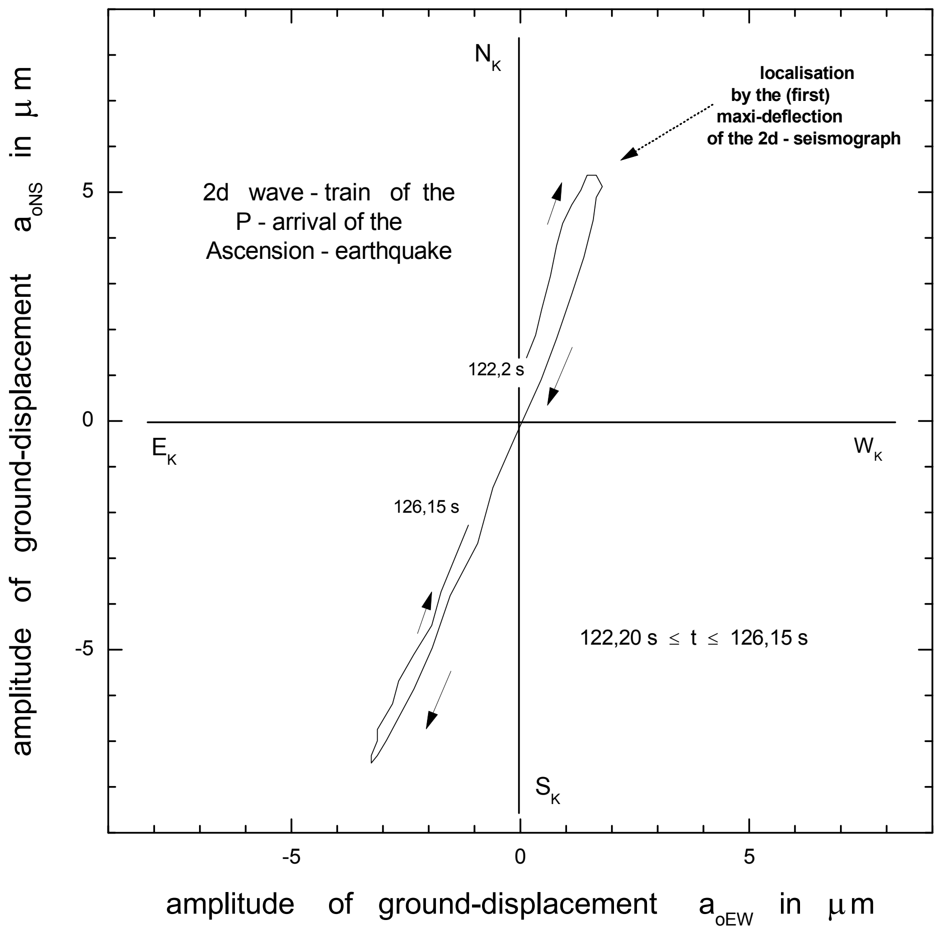
- a ground-displacement of 5.76 thousandth of a millimetre to the North and
- a ground-displacement of 1.93 thousandth of a millimetre to the East.

If one transfers these ground-displacements into a coordinate system of axes, which correspond to the four cardinal points of the compass

A 2 d - seismograph on the " PC " :

(a) Conversion of the voltage-signals into ground-displacement

(b) East - West - movement (X - Axis) and
North - South - movement (Y- Axis) must be put into a diagramm



(Attention : the walls of the basement are not precisly built in NS- & EW - direction)

Fig. *55* two-dimensional ground-movement-diagram

One simulates a two-dimensional movement, which comes up to the frame movement of the historical "Wiechert-Seismometer", (s. Fig. 56).

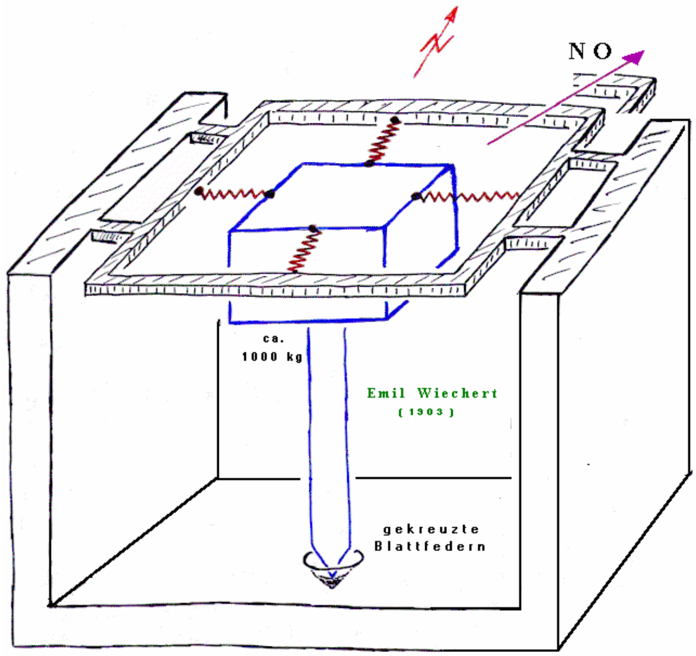
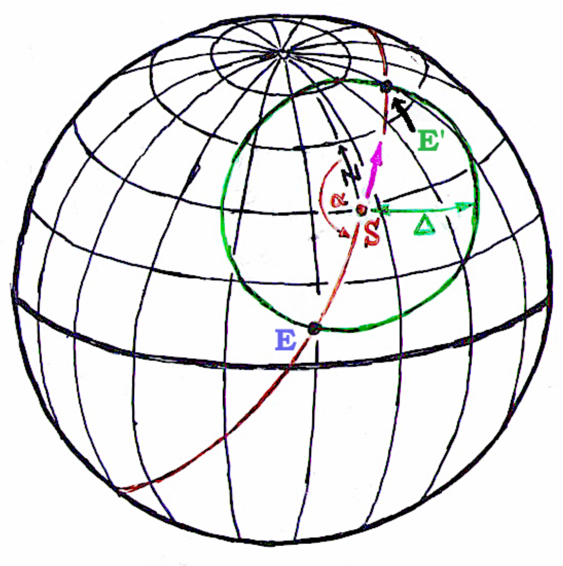


Fig. 56 Wiechert's astatic Seismograph

Obviously the bottom of the casing and the frame of the seismometer (being fixed to bottom) moved to the North-East at the arrival of the P-wave.



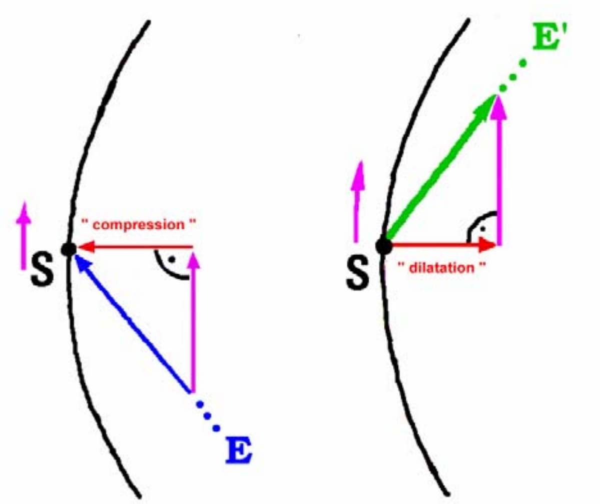


Fig. 57a For localisation

Fig. 57b For decision between H and H'

At this moment of evaluation there are still two points H or rather H' on the globe where the epicentre of the earthquake could lie: angle α defines the great circle through station and epicentre; distance Δ defines a circle round the station having a radius of 6100 km. The two circles have merely got two points of intersection (Fig. 57a). – We must now determine which of the two points represents the epicentre.

However, this can easily be decided with the help of the third seismograph, the vertical seismograph, which is activated by up and down deflections by the waves of the earthquake.

If we make a cut along the great circle through H, S and H' (Fig. 57b) the movement of the apparatus from S towards H' can only have been caused by two facts: *either* the P-wave hit S as an compression-wave from H to S *or* at the station first of all arrived a dilatation-wave moving from S to H'. In the first case the ground must have moved upwards, in the second case downwards. So if the UD-seismograph signals "up" the epicentre is in the point H; if the Z-seismograph first of all shows a downward movement then the epicentre lies in H'. In our case there was an upward movement („compression") at the beginning, so the epicentre lies in H in the South-West.

Instead of using a direct reading of the average guide motion of the "2d-seismograph" - as shown in
Fig. 55 - the determination of the direction gets easier, if one only considers the deviation of the ground in the reversal point of the horizontal movement.

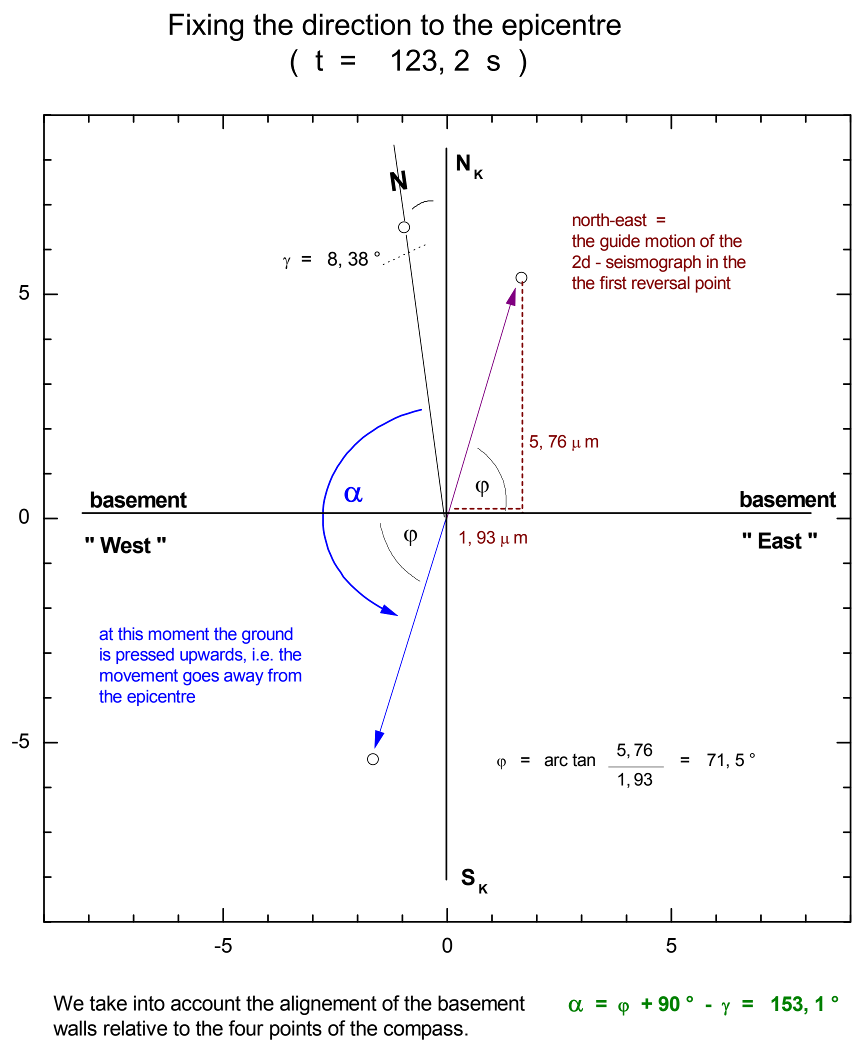


Fig. 58 The calculation of the angle α pointing at the direction of the epicentre

When definitely fixing the angle α between the direction to the focus and the north direction, we still have to consider that the "north axis N_K of the school building" deviates by the angle γ from the actual north direction: to the axis N_K the pendulum arms of the horizontal seismographs are positioned parallel (EW-seismograph) and respectively perpendicular (NS-seismograph).

The result of the calculation concerning all the source parameters determined by us are shown in Fig. 59:

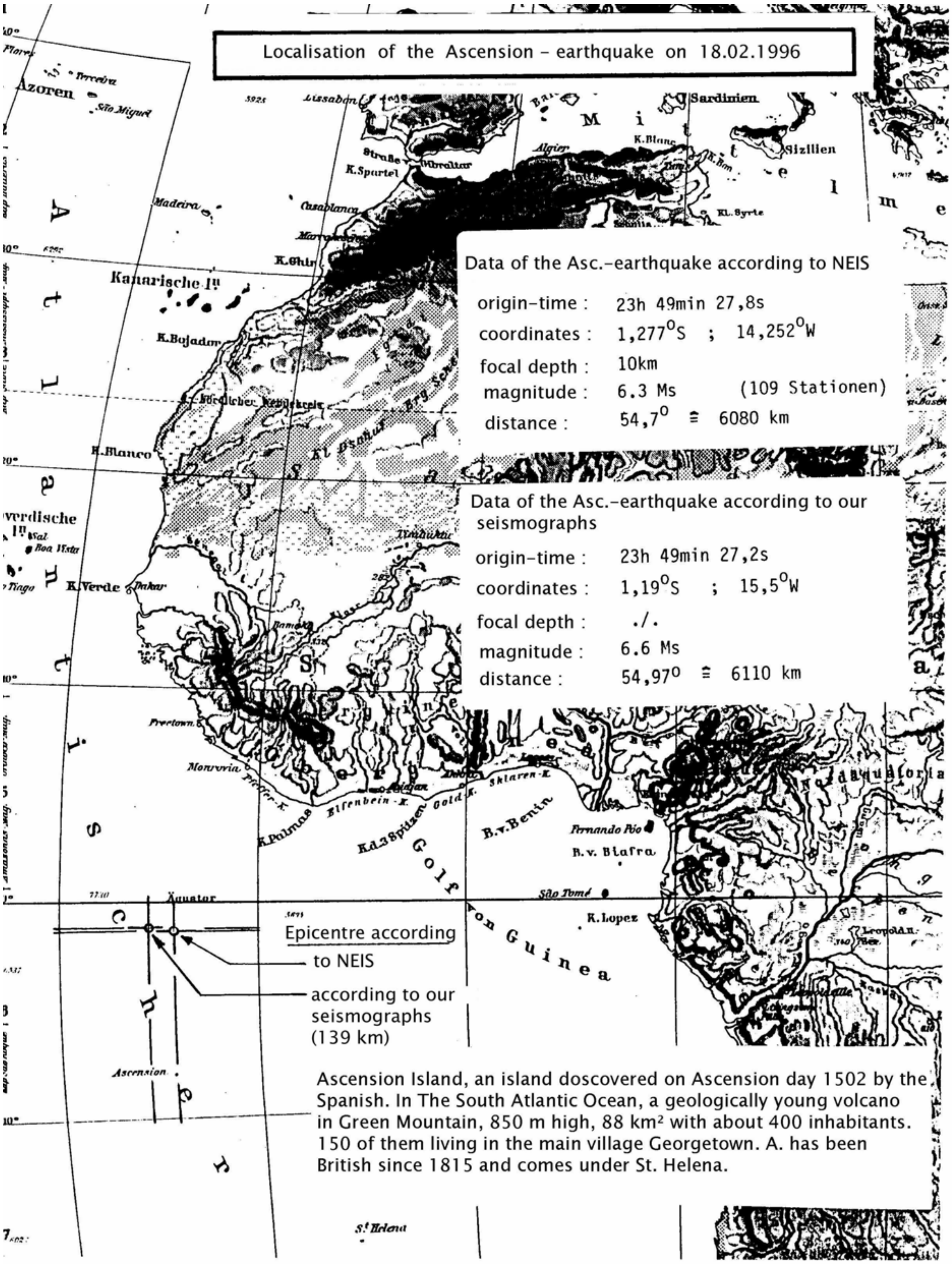


Fig. 59 Localisation of the Ascension-earthquake

So we can state that with the epicentre being about 6000 km away the earthquake was localized with a deviation of merely 139 km.

7. The seismograph as a teaching object - topic: oscillations and waves

Some experimental results are meant to illustrate how a seismograph can help in teaching lessons on the topic 'oscillations and waves'.

First of all it is a real improvement to separately coil some hundreds of windings around the induction-
coil of the seismograph as a supplementary coil. Then you connect the supplementary coil to an AC-generator for low frequencies. Then the pendulum is no longer set in motion in the laboratory by a periodically guided motion of the suspension (with the help of an eccentric) but by a periodically variable force, which directly acts on the pendulum.

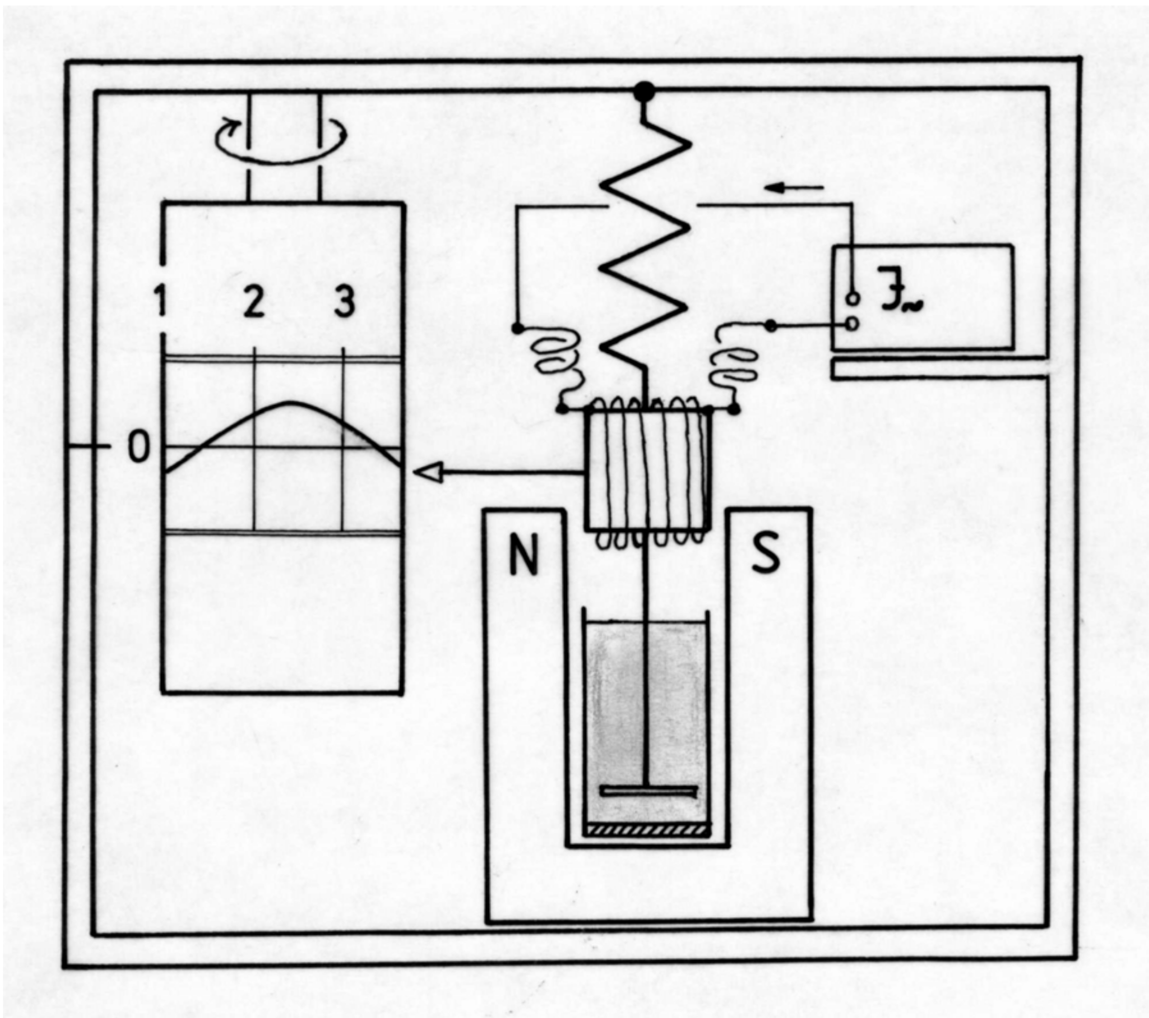


Fig. 60 Simulation of a guided motion of the dashpot by an electromagnetic force

If one registers the motion of the pendulum by the seismometer coil then you can observe resonance of velocity caused by this kind of guided motion. The advantage of velocity-resonance is that a maximum velocity can be observed for every damping value.

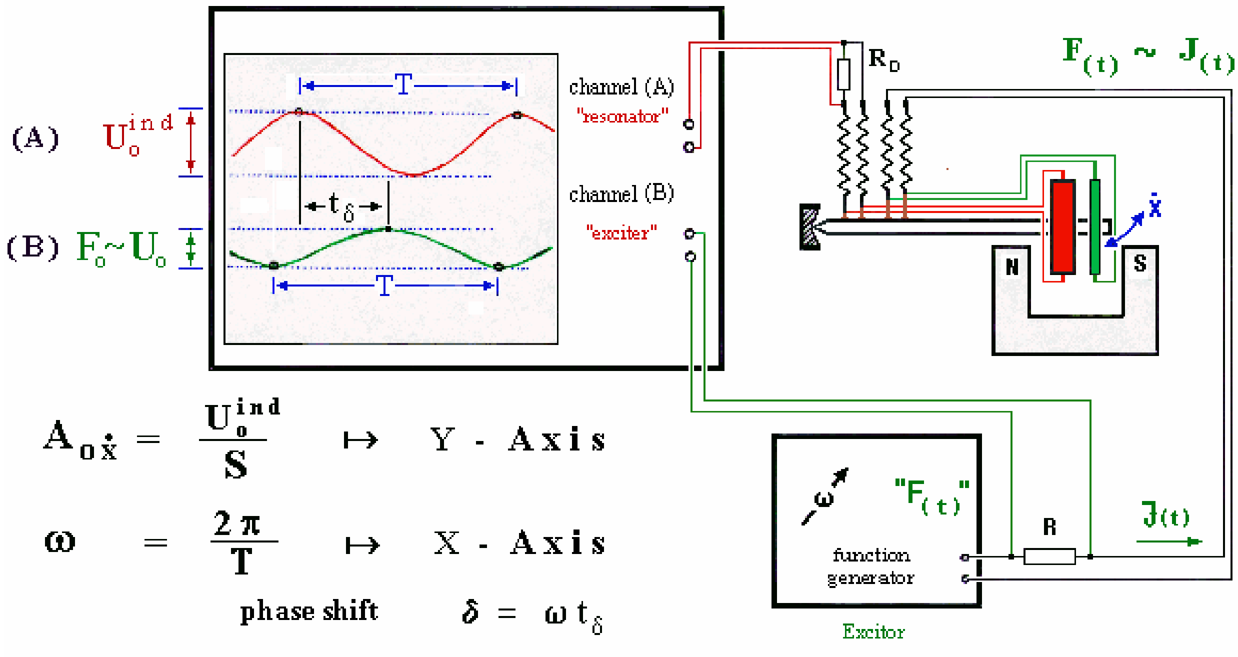


Fig. 61 experimental arrangement for the recording of velocity-resonance

The following illustration shows the result of this resonance experiment.

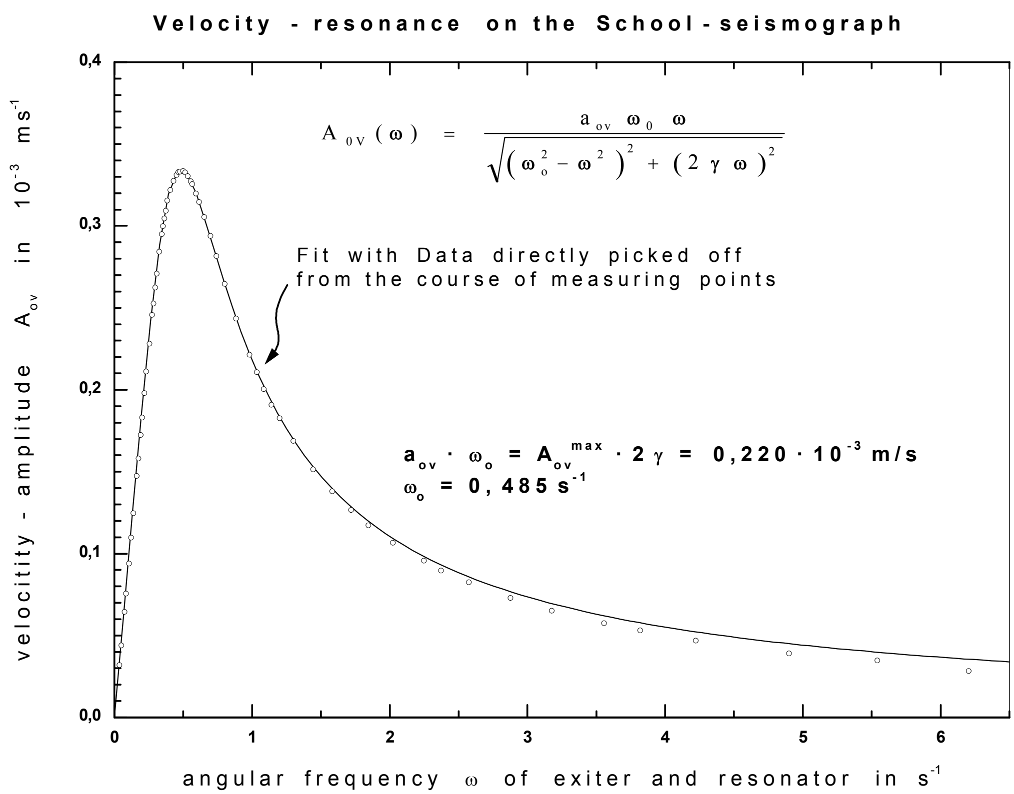


Fig. 62 Velocity-resonance on the school-seismograph

Additionally the phase ellipse can be very clearly shown. If one goes on further evaluation such resonance can produce the following graphs for phase shifting and complex amplitude C_{ov} .

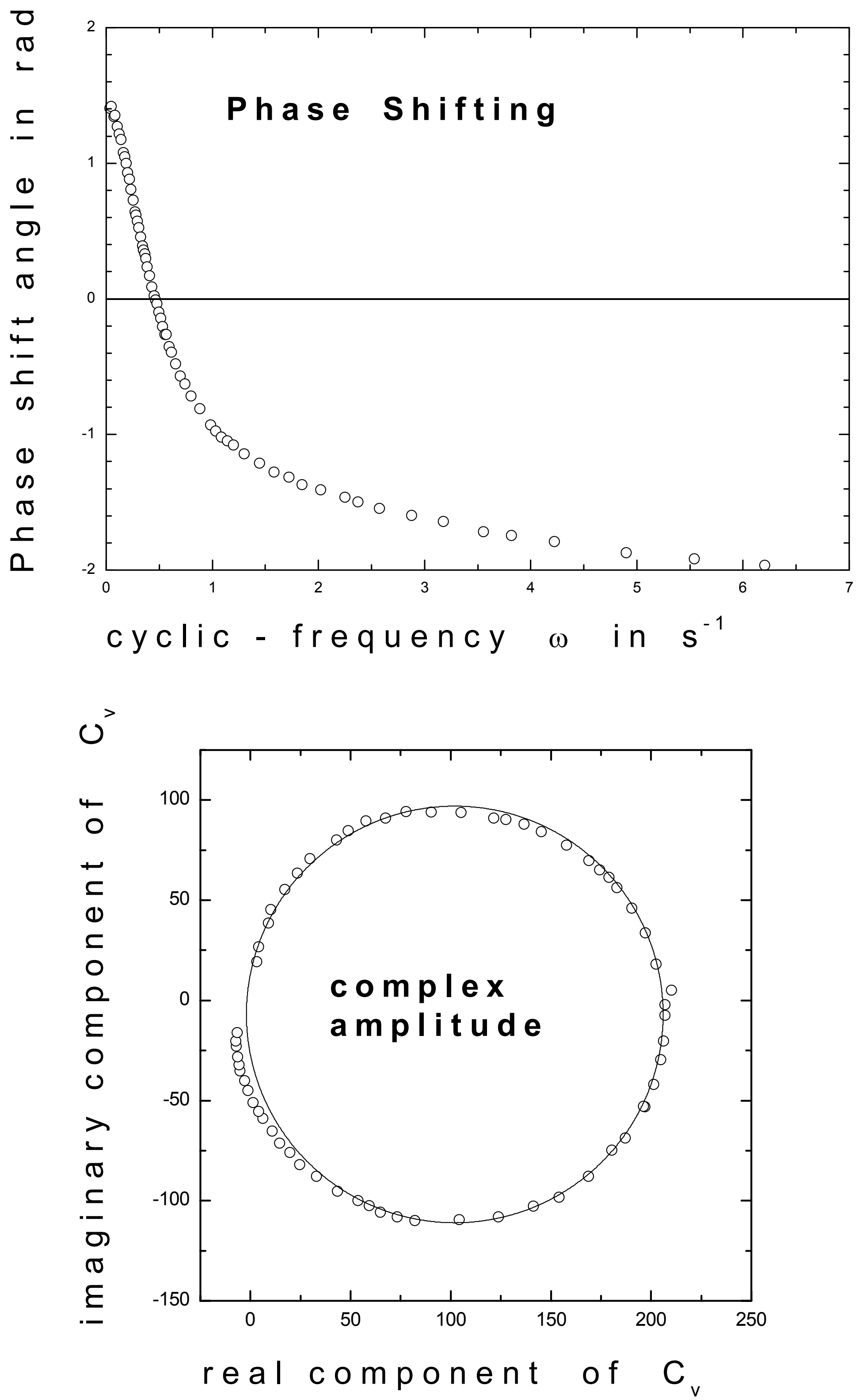


Fig. 63 Phase shifting and complex velocity-amplitude on the school-seismograph

8. List of Illustrations and Bibliography

Fig.1, Fig.4, Fig.2, Fig.28, Fig.29, Fig.30, Fig.31, Fig.32, Fig.39, Fig.40, Fig.41, Fig.42, Fig.43, Fig.44, Fig.51, Fig.53, Fig.55, Fig.56, Fig.57a, Fig.57b, Fig.58, Fig.60, Fig.61, Fig.62, Fig.63 : own photographs, own drawings , own graphics

Fig.2 : Christian Gülz, WWM System Service Messebau, Monschau, Germany

Fig.3 , Fig.37, Fig.45, Fig.46, Fig.54, Fig.59 : Naeth, B. , Poschen, T. u. Schork, S. : "Bau und Konstruktion einer Schulseismographenstation mit digitaler Fernabfrage und Konstruktion eines Lehrseismographen", [Construction and Organisation of a School-Seismograph Station with Digital Remote Control and Development of a Educational Seismograph], Monschau 1996, Wettbewerbsbericht Jugend forscht, Geo- und Raumwissenschaften 1996, [National Young Researchers Competition for pupils and young students in Germany, Partition Geo- and Space-Sciences]; 2nd place in the federal competition; published in Internet : http://www.mgm.monschau.de/seismic

Fig.5 : Sebastian Staiger, Data from the Science Council of Japan, 1989

Fig.6 : Der Magnet **15**, Autumn 1997, Klett, Stuttgart, Germany, p. 2

Fig.7 : Der Spiegel, Hamburg 1996, Nr.3, p. 115

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Fig.18, Fig.21a : Bolt, B.A.: „Earthquakes", New York 1987, p. 28 : Fig. 6c, d ; Fig.s 6 a, b

Fig.20a after : Sawarenski, E.F. & Kirnos, D.P.: "Elemente der Seismologie und Seismometrie", [Elements of Seismology and Seismometry], Berlin 1960, p. 302

Fig. 21 : Tipler, P.A.: "Physik", Heidelberg et al. 1994, Germany, p.427

Fig.33, Fig.34, Fig.35, Fig.47: Photos OStR Wolfgang Furkert, MGM Monschau, Germany

Fig.36 : Photo Dr. Lothar Stresius, MGM Monschau, Germany

Fig. 38 : Photo Dipl.-Phys. Wolfgang Sturm, Staufen, Germany

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		Fig. 36
• Iron Retrail Trade Comp. Scheins, Aachen		*many V-A- screws of various size, (School Seismograph)*
• Market for Buildings & Construction, Josef Thelen, Simmerath	especially Dipl.-Btrw. Dietmar Thelen, former student of the St.-Michael Gymnasium	*special cement, sands and grit for both of the concrete-boards for the station seismographs; for the casings as shield against air-movement for each seismograph: paint, wood-material, a lot of styropor-material with gummer, a tool box*
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