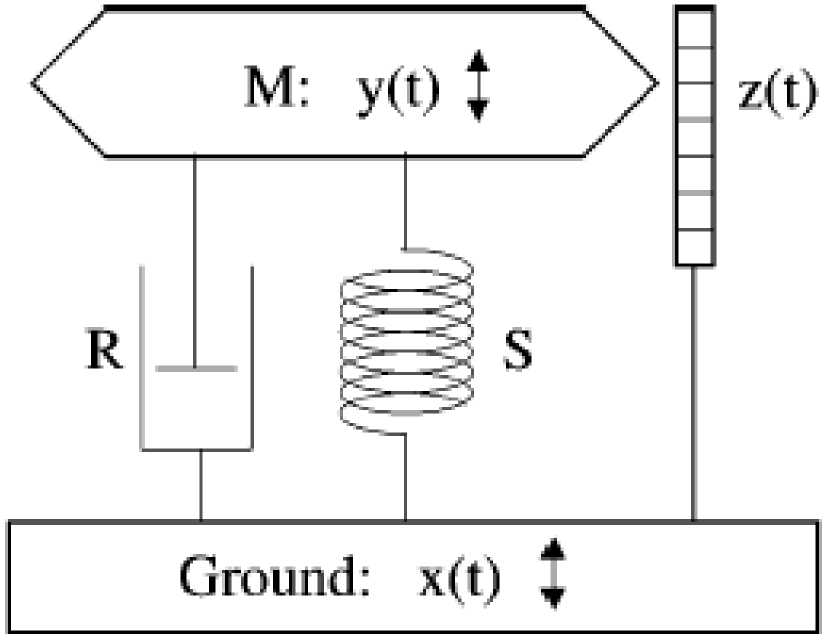
UNIVERSITÀ DEGLI STUDI DI TRIESTE

Applied seismology

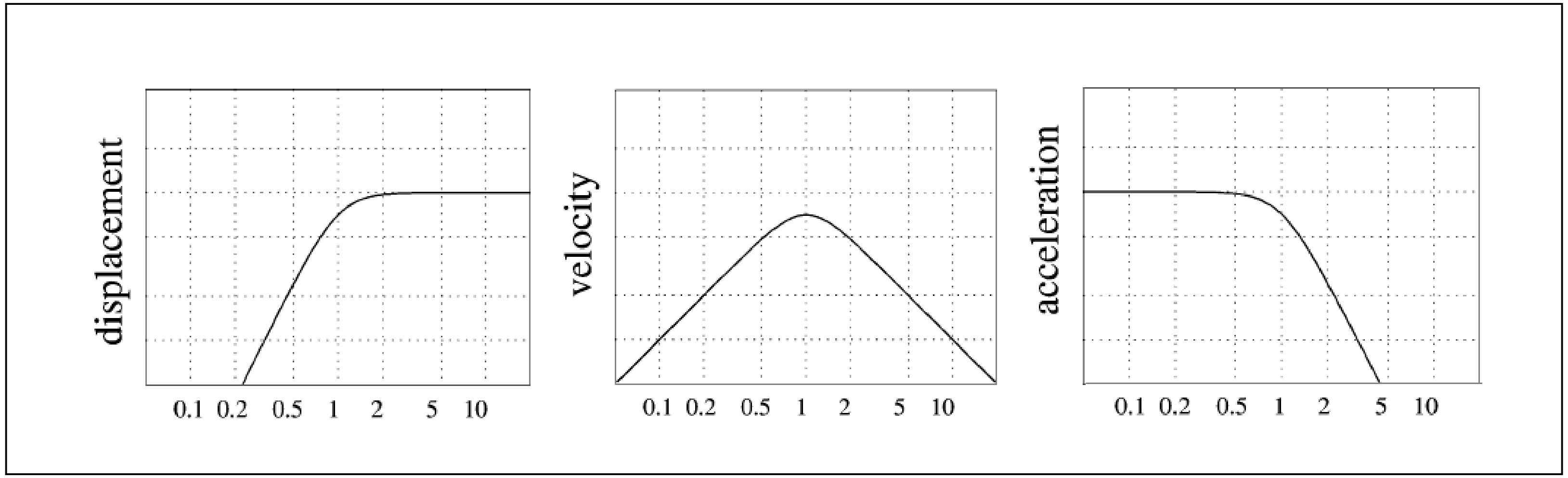
Calibration

Giovanni Costa - costa@units.it

Calibration of a seismograph establishes the relationship between its input (ground motion) and its output (an electrical signal), and is a prerequisite for a reconstruction of ground motion. Since precisely known ground motions are difficult to generate, the equivalence between ground accelerations and external forces on the seismic mass is made use of, and seismometers are calibrated with an electromagnetic force generated by a calibration coil. If the proportionality factor between the current in the coil and the acceleration of the equivalent mass is known, the calibration is a purely electrical measurement. Otherwise, the missing parameter-or the transducer constant of the calibration coil, or the reactivity of the sensor itself-must be determined by a mechanical experiment in which the seismometer is subjected to a known mechanical motion or tilt. This is called an absolute calibration. Since it is difficult to generate precise mechanical calibration signals over a large bandwidth, one does not normally attempt to determine the complete transfer function in this way.



$$M\ddot{z}(t) + R\dot{z}(t) + S\,z(t) = f(t) - M\ddot{x}(t)$$



Curve di risposta di un sismometro meccanico (pendolo a molla, a sinistra) rispetto ai diversi tipi di segnali di ingresso. La frequenza normalizzata è il segnale frequenza divisa per la frequenza d'angolo del sismometro. Tutti queste curve di risposta hanno un angolo del secondo ordine alla frequenza normalizzata 1.

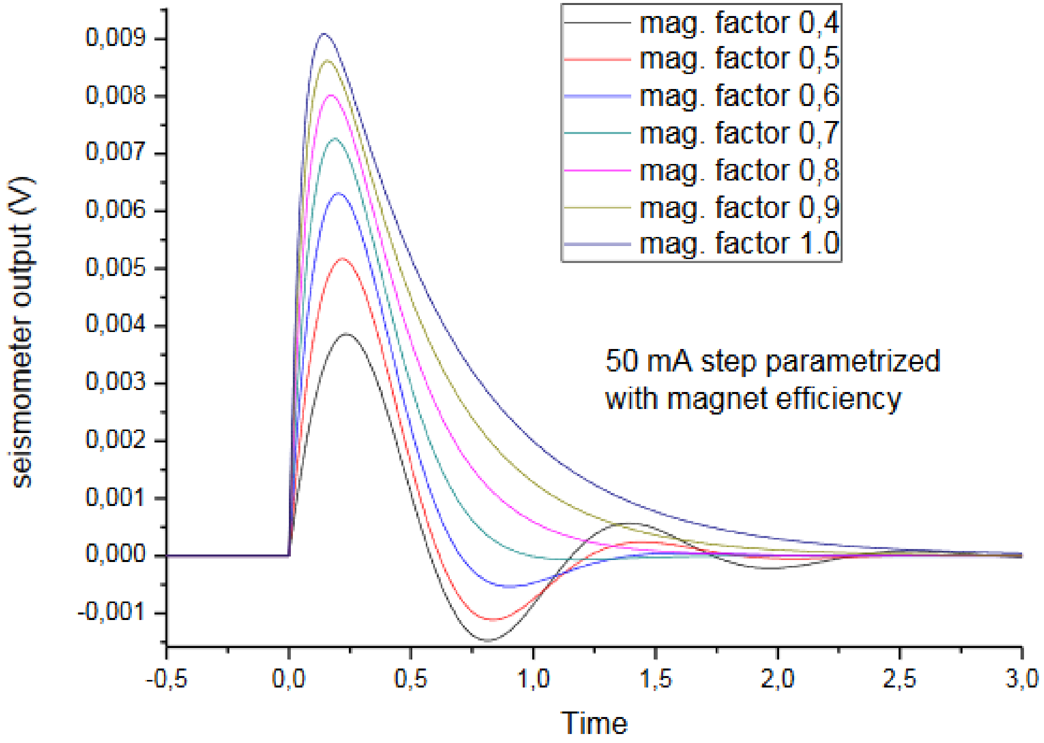
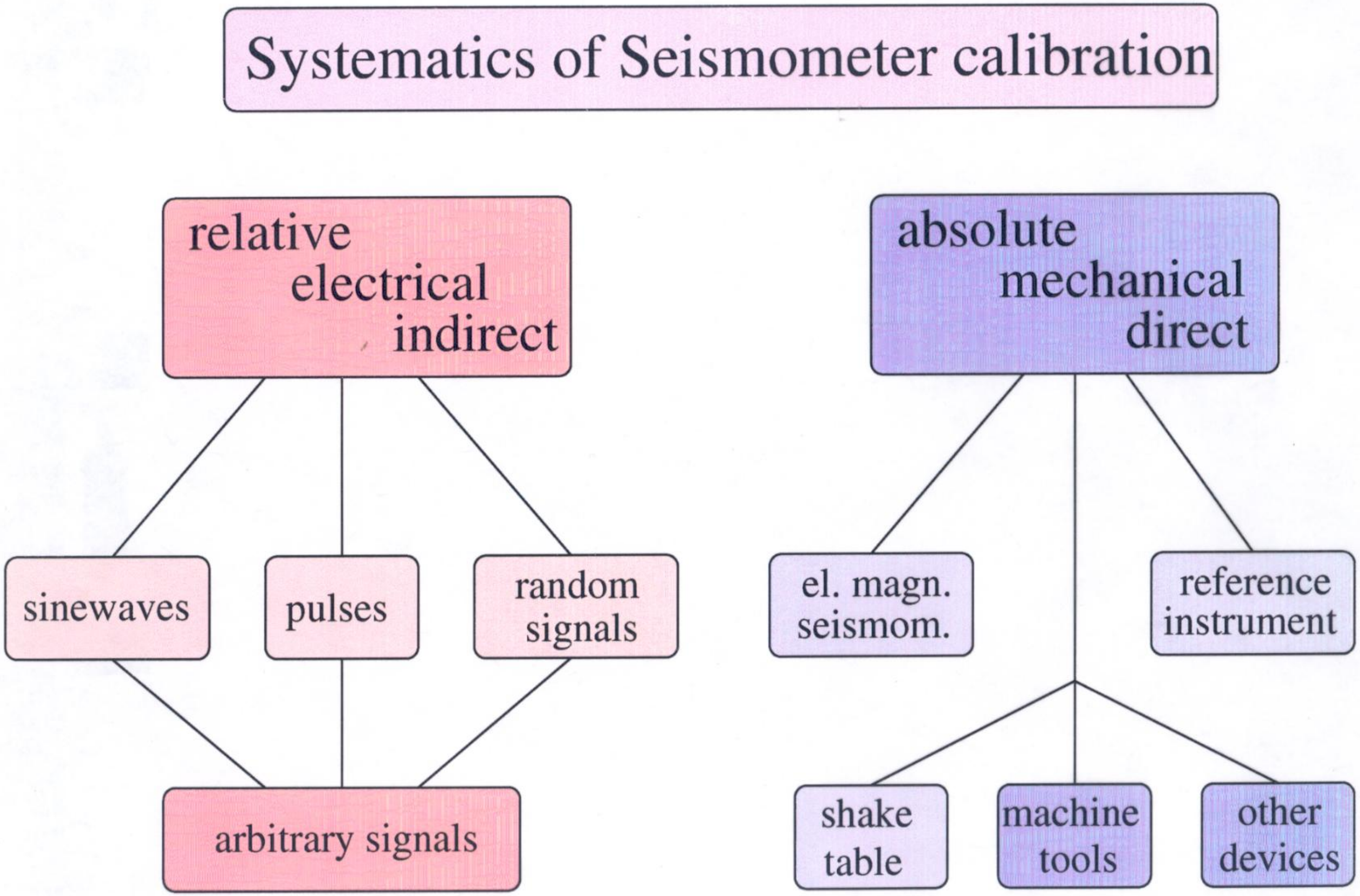
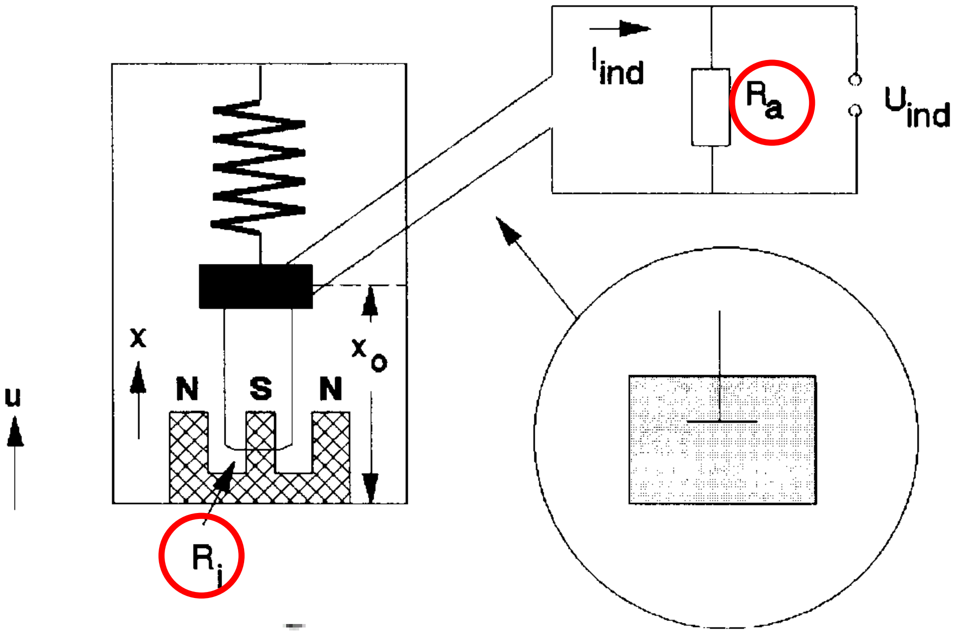
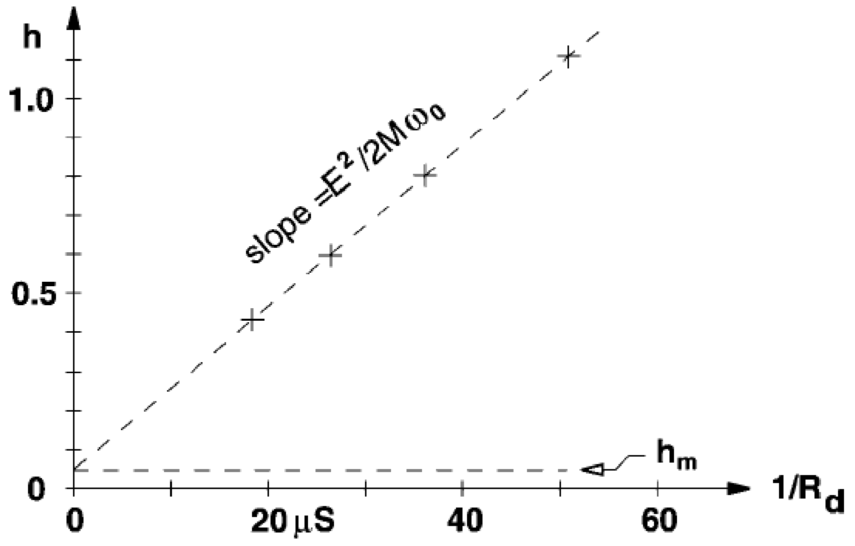


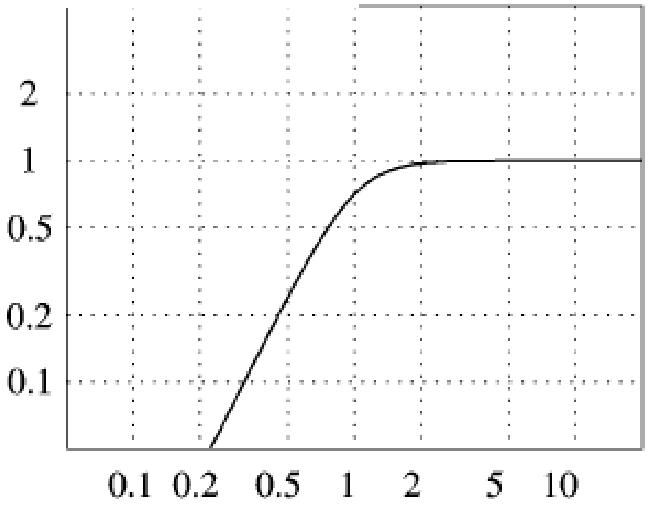
Figura 10. Uscita del sismometro S-13, caricato con 700 Ω ed eccitato con un gradino da 50 mA. La famiglia di curve è ottenuta parametrizzando l'intensità del magnete, con fattori da 0.4 (magnete vecchio) ad 1 (magnete in buono stato).


Systematics of Seismometer calibration
relative electrical indirect
sinewaves
pulses
random signals
arbitrary signals
absolute mechanical direct
el. magn. seismom.
reference instrument
shake table
machine tools
other devices



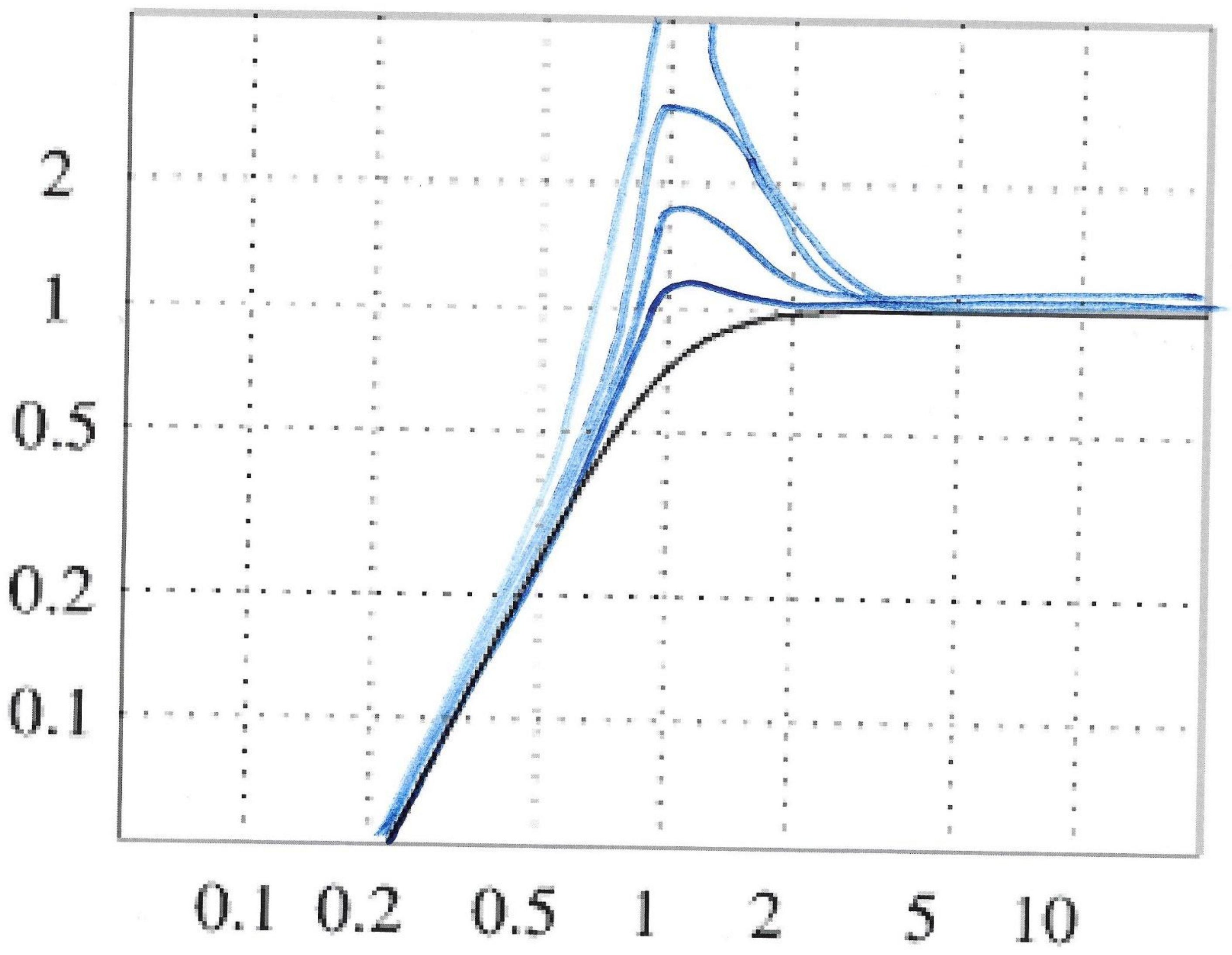


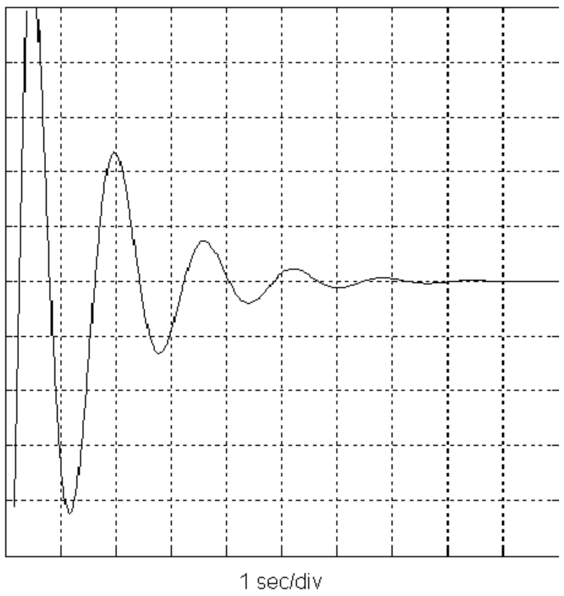
$$R_d = R_{coil} + \bar{R}_{load}.$$

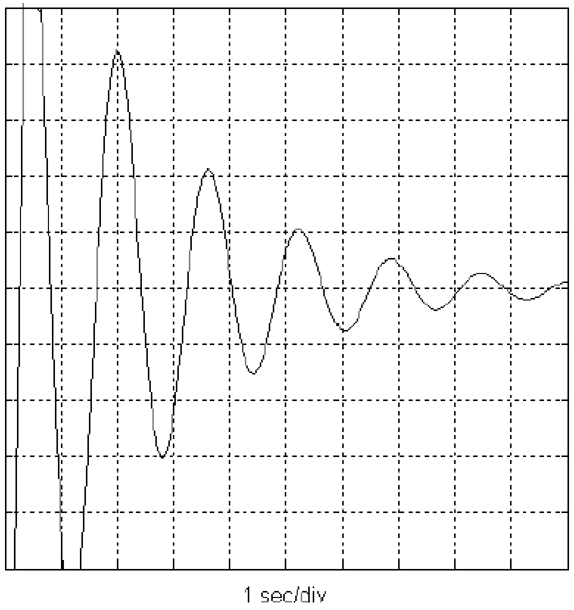


Determination of generator constant from a damping diagram versus total damping resistance $R_d=R_{coil}$ + R_{load} Horizontal units are microsiemens (reciprocal Megohms).

The total damping is chosen equal to $1/\sqrt{2}$ as to obtain a flat response.


2
1
0.5
0.2
0.1
0.1 0.2 0.5 1 2 5 10

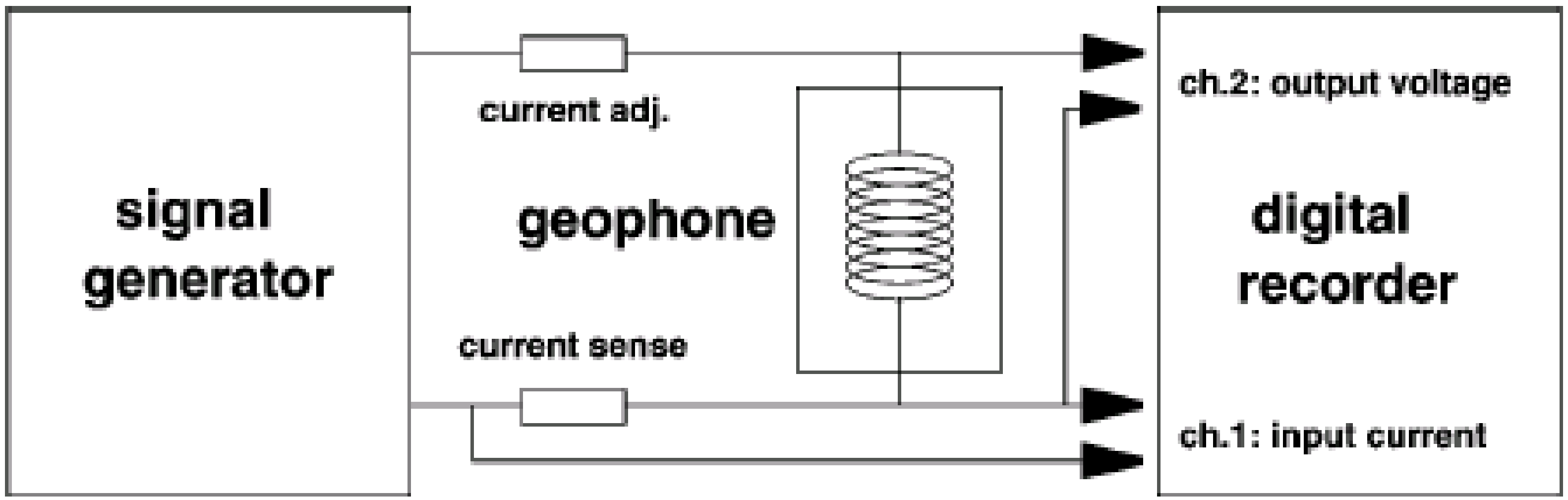


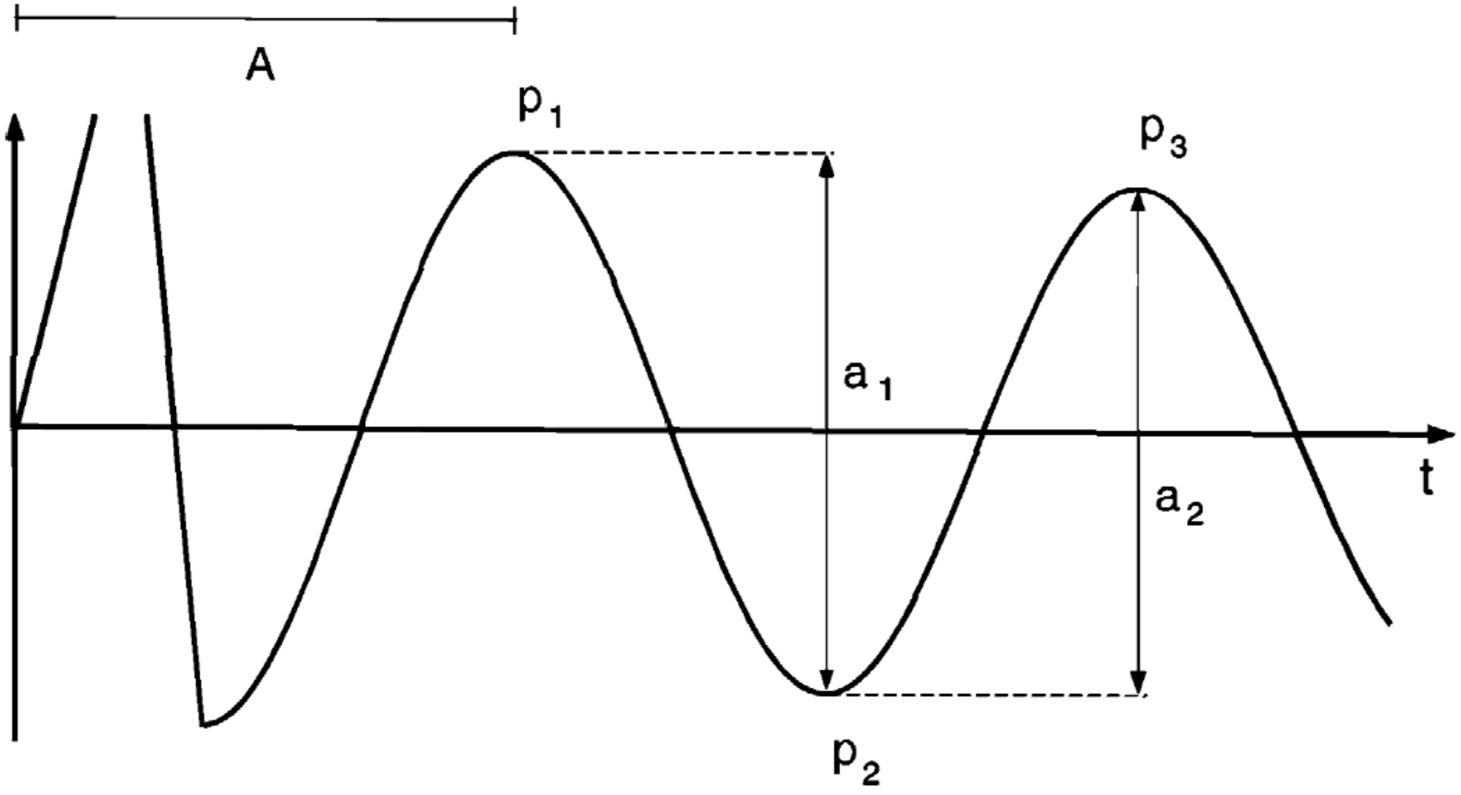


circuito aperto

bobina con resistenza esterna R_a=67 kOhm

bobina con resistenza esterna R_a=1 kOhm

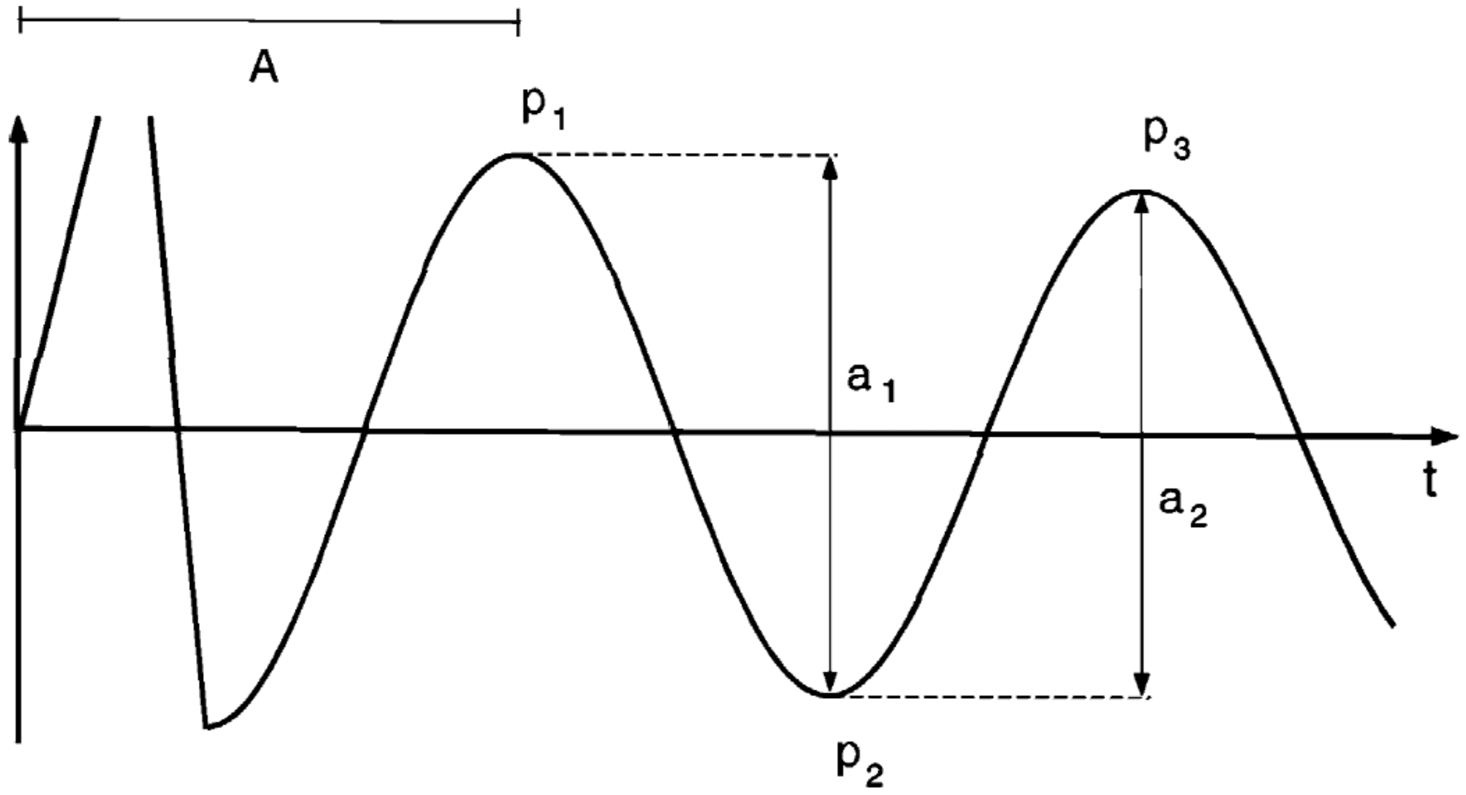

signal
generator
current adj.
geophone
current sense
ch.2: output voltage
digital
recorder
ch.1: input current



Response of a low-damping seismometer to a step pulse.
Damping D is calculated from the equation:

$$D = \frac{1}{\sqrt{\left(\frac{(N-1)\pi}{\ln(a_1/a_N)}\right)^2 + 1}}$$

with a1 as the double amplitude between the first two oscillation peaks (p_1 and p_2) and a_N as the double amplitude between the peaks (p_N e p_N + 1). N should be selected so as to obtain a_N »0,2 ... 0,4 a1



The natural period T_S is calculated from the equation:

$$T_S = T\sqrt{1 - D^2}$$

Period T should be measured by averaging over as many cycles as possible (10 or more) to achieve better than 99% accuracy.

When only analog equipment is available, a sinusoidal test signal can be used as the input of the calibration coil or vibrating table, and the input and output signals can be recorded using a chart recorder or X-Y recorder. On the latter, the signals can be plotted as a Lissajous ellipse from which both amplitude ratio and phase can be read with good accuracy. For calibration of high-frequency geophones, an oscilloscope can be used instead of an X-Y recorder. The period of the signal should be measured with a counter or stopwatch because the frequency scale of sine wave generators is often inaccurate

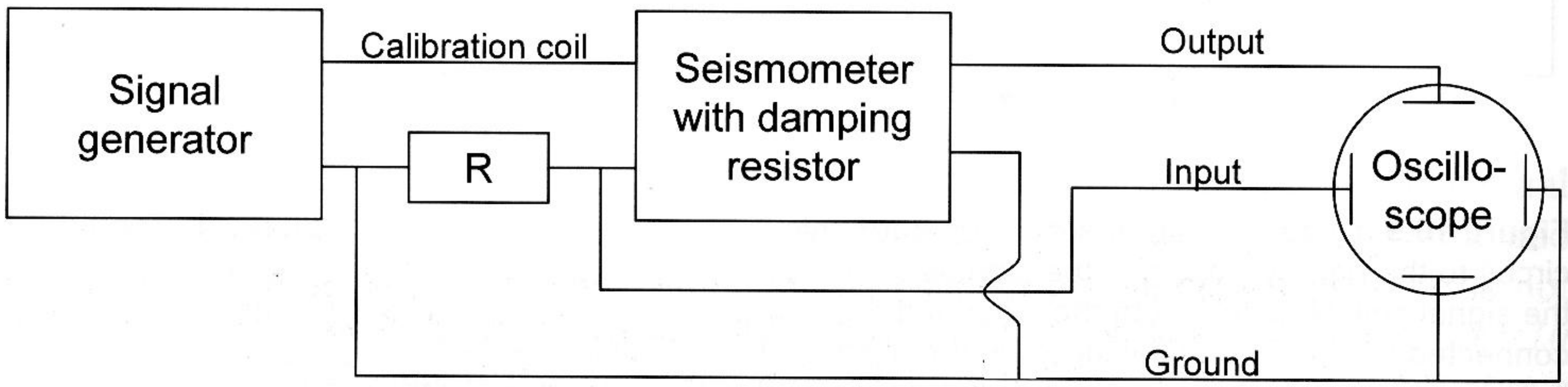
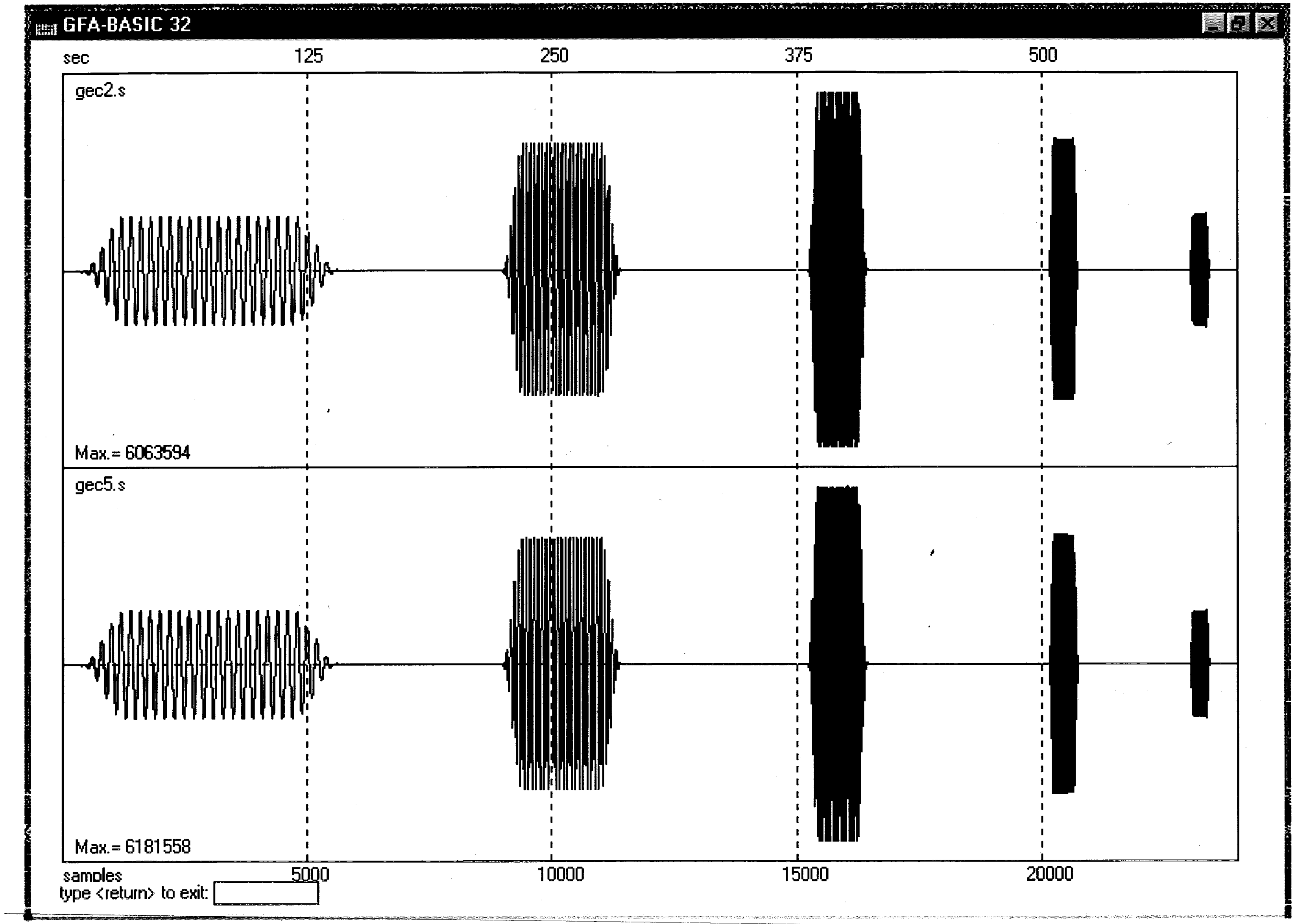


Figure 10.10 Setup for making Lissajous figures.


GFA-BASIC 32
sec
125
250
375
500
gec2.s
Max.= 6063594
gec5.s
Max.= 6181558
samples
5000
10000
15000
20000
type <return> to exit:

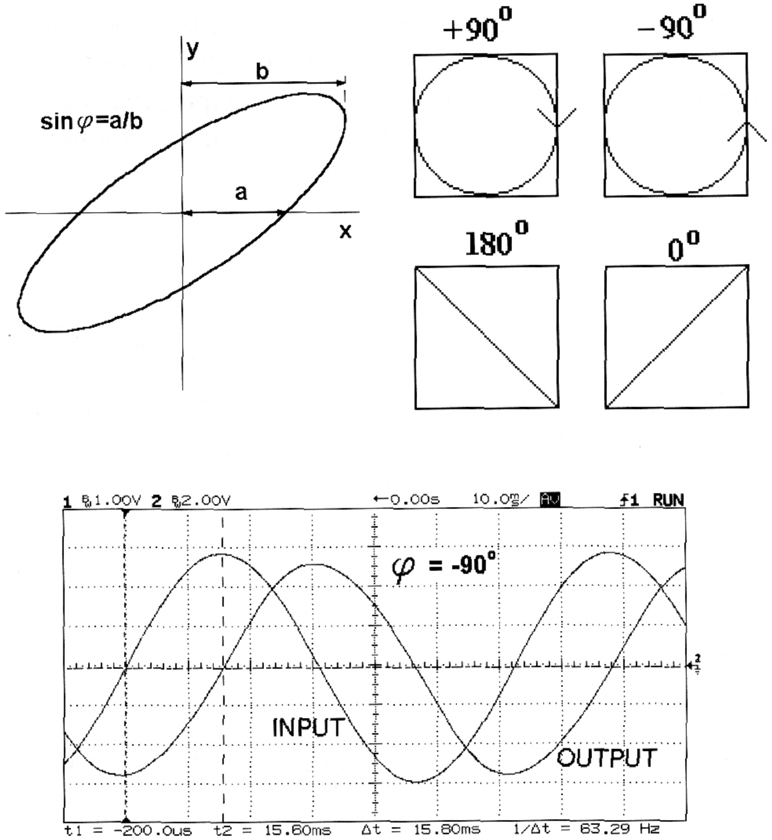
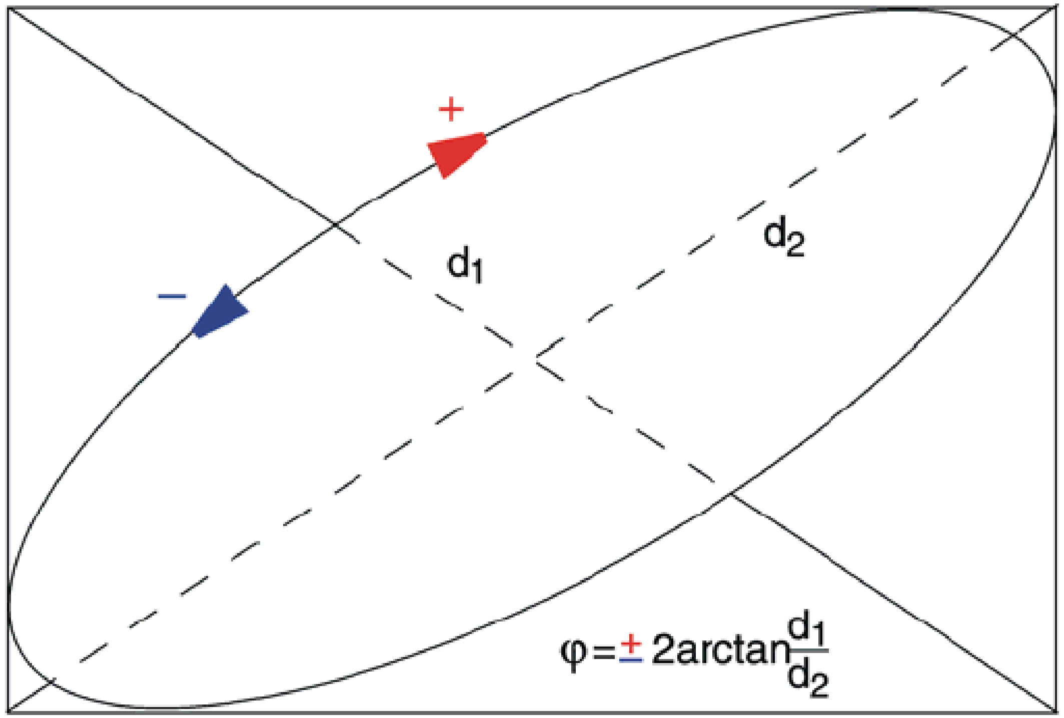
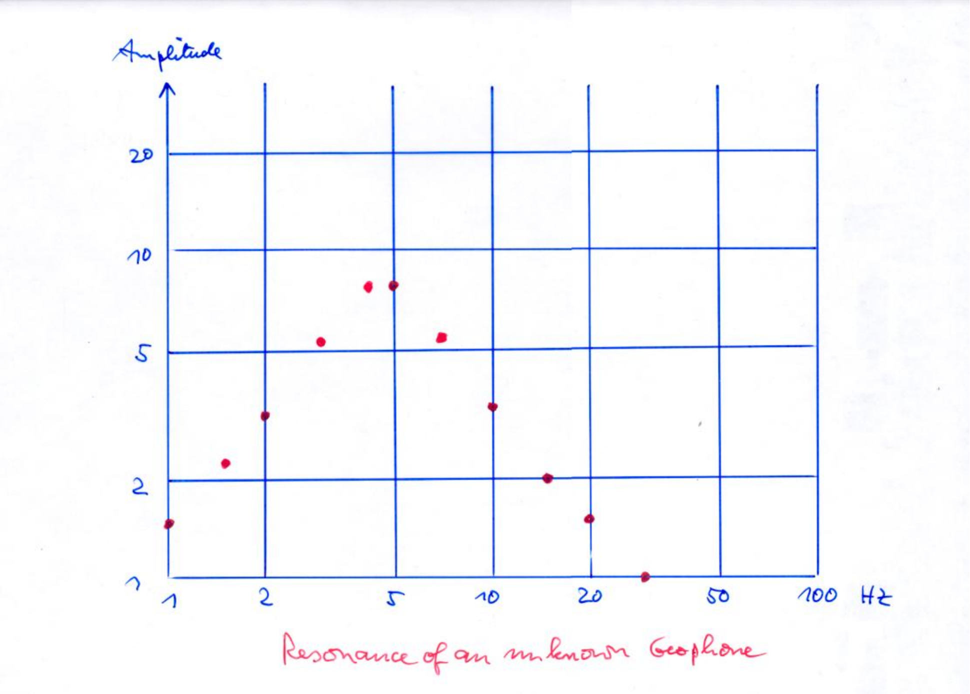


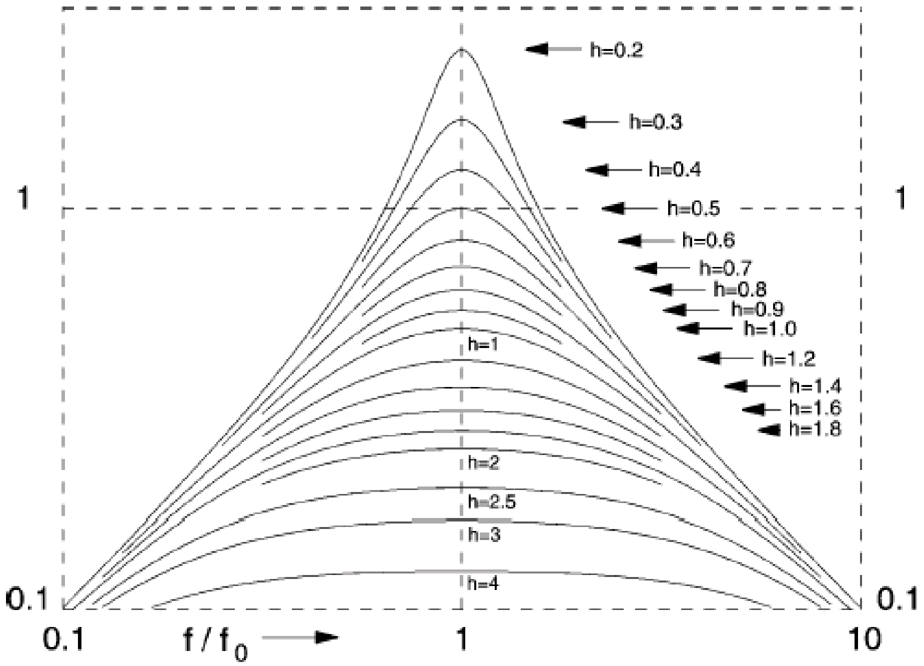
Figure 10.11 Lissajous figures. Upper: To the right is shown the cases of phase shift 90, -90, 0 and 180 degrees. To the left the figure shows how to measure the phase shift φ. The phase shift is positive if the motion is clockwise and negative if the motion is anti clockwise (left). Lower: Two signals with a phase shift of –90 degrees are shown as they appear on the oscilloscope screen. These figures assume that only the phase is different for input and output signals. If also the amplitude is different, the length of the x and y-axis will scale with the input and output amplitudes respectively.



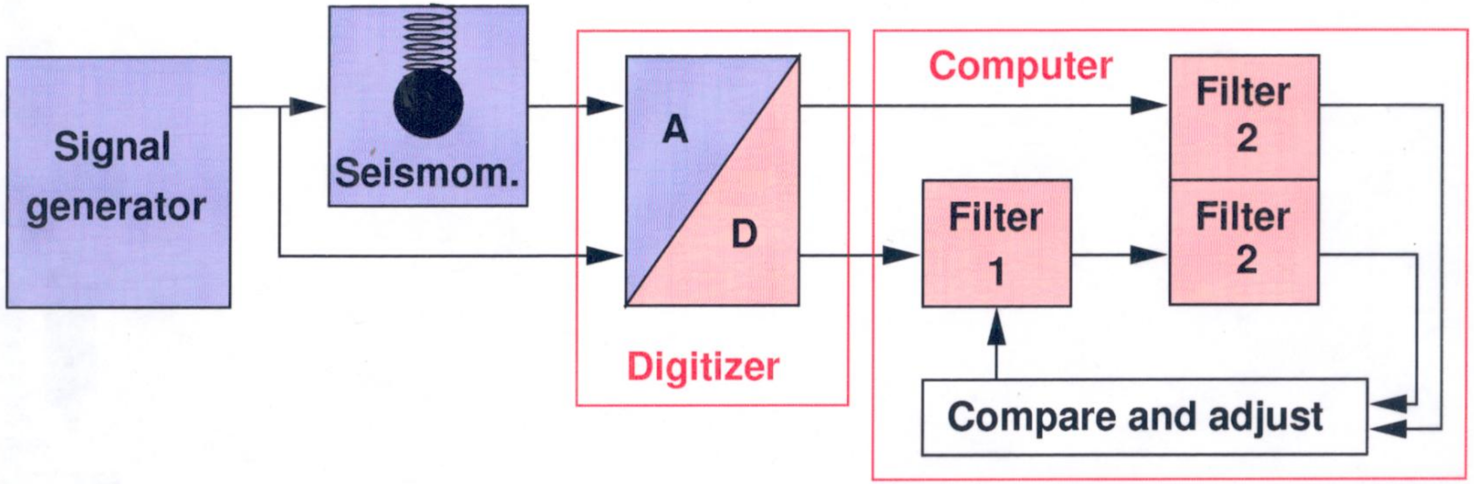
Misura della fase tra due onde sinusoidali con un'ellisse di Lissajous

The eigenfrequency f_0 and damping h of electromagnetic seismometers and most other seismometers can be determined graphically with a series of standard resonance curves on double logarithmic paper. The measured amplitude ratios are plotted as a function of frequency f on the same type of paper and superimposed on the standard curves. The desired quantities can be read directly. The method is simple but not very accurate.

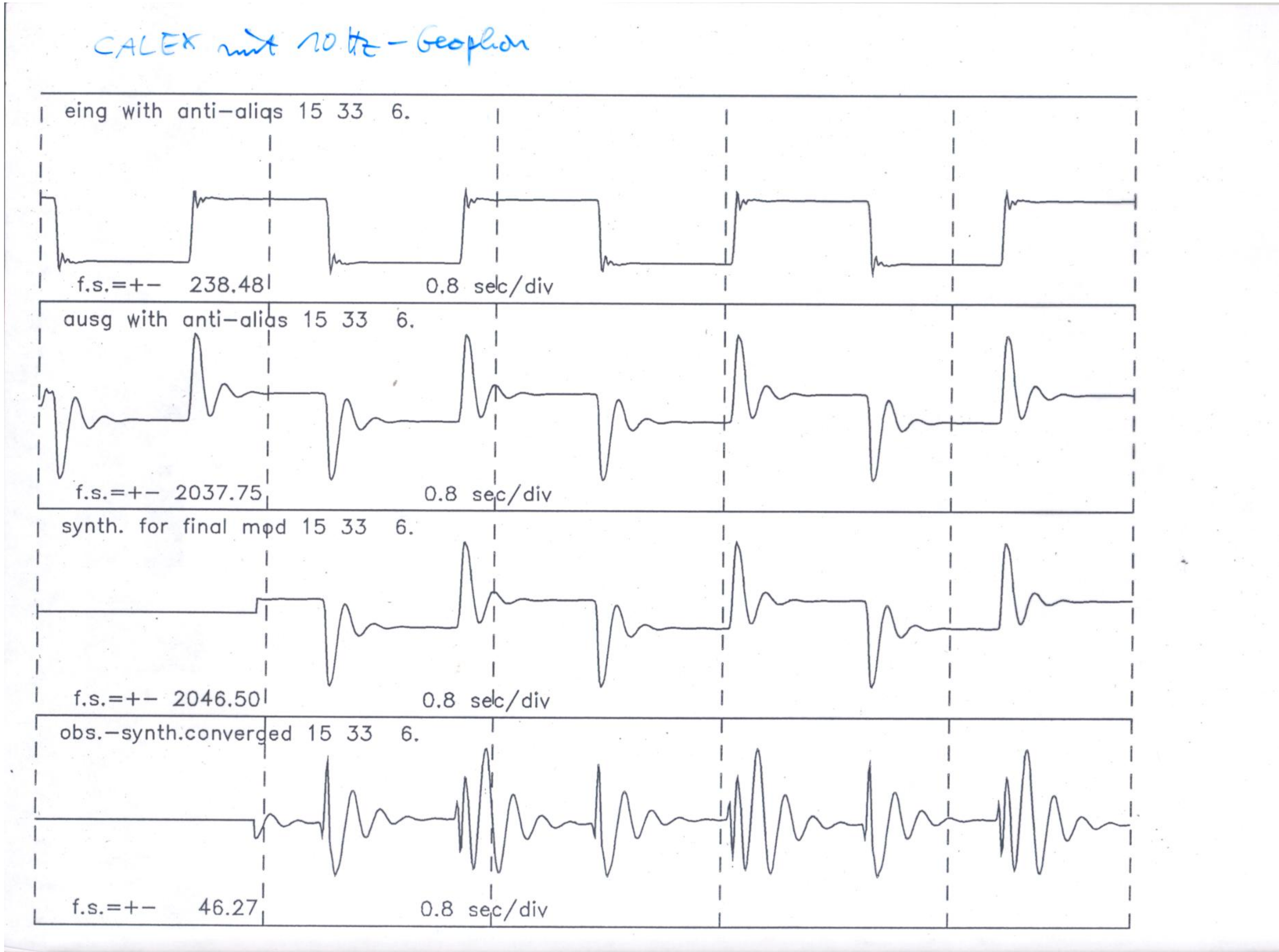


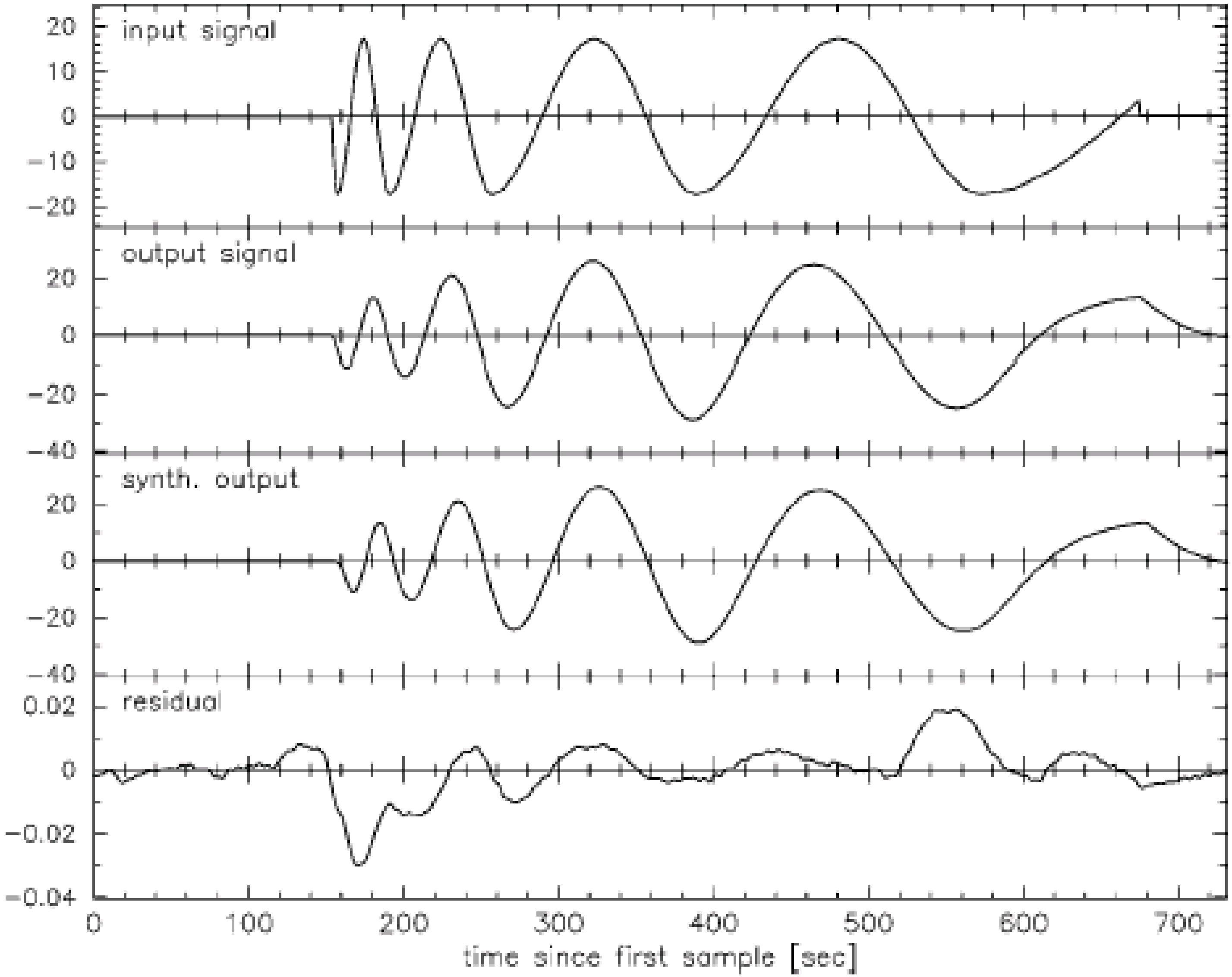


Calibration with arbitrary signals

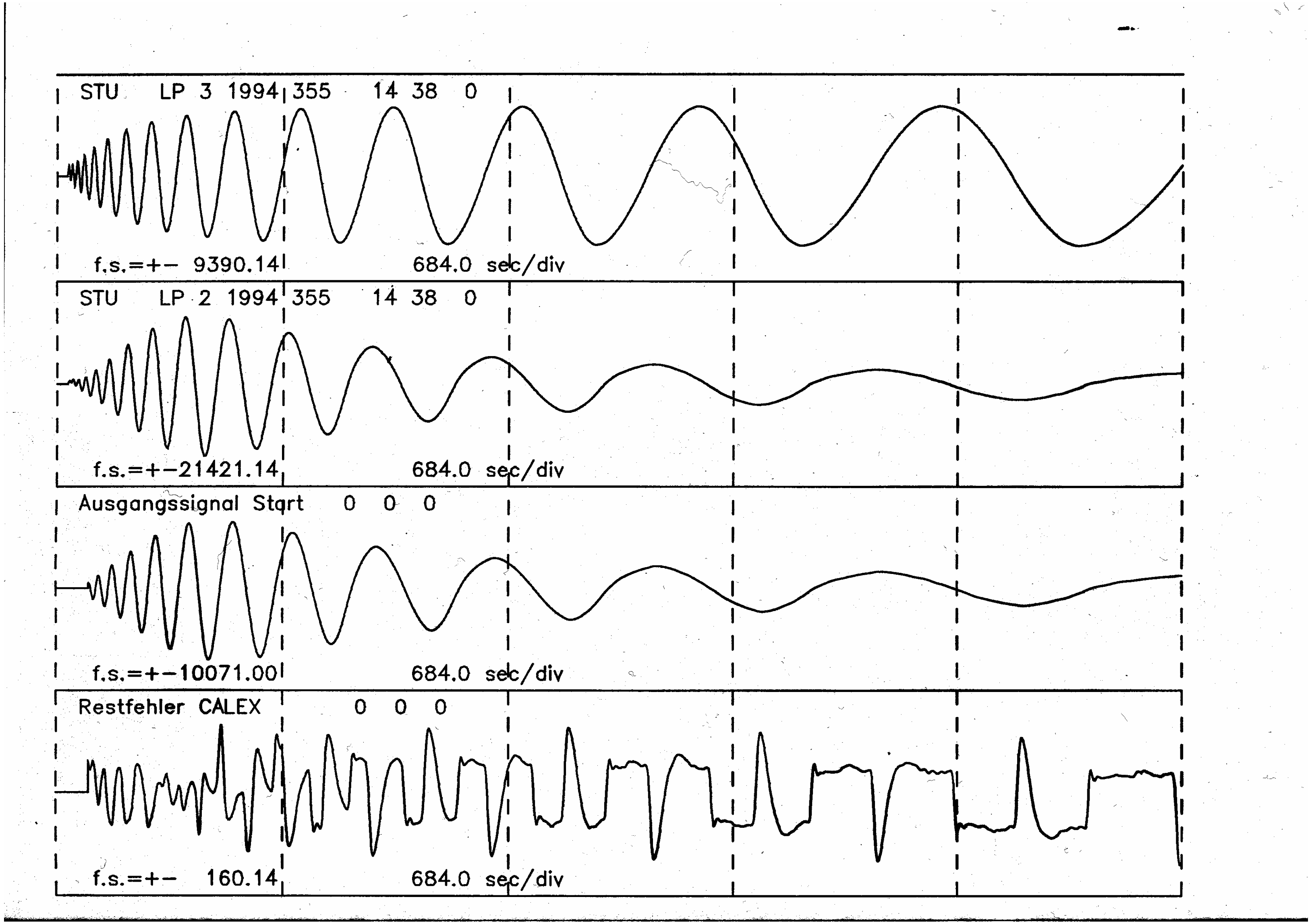


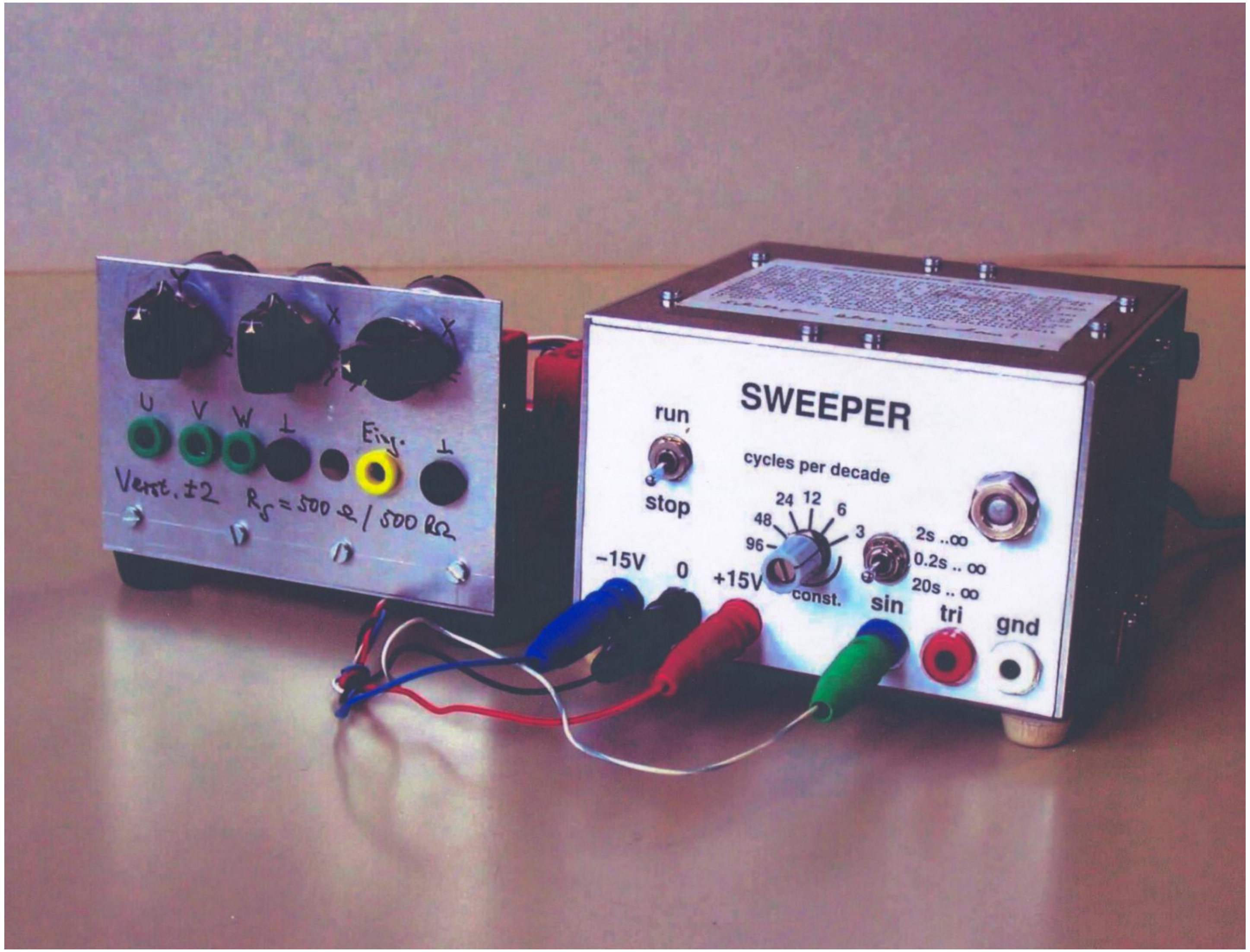
For a perfect fit, filter 1 must be an exact digital representation of the seismometer.
This is only possible when the passband is limited with the anti-alias-filter 2.

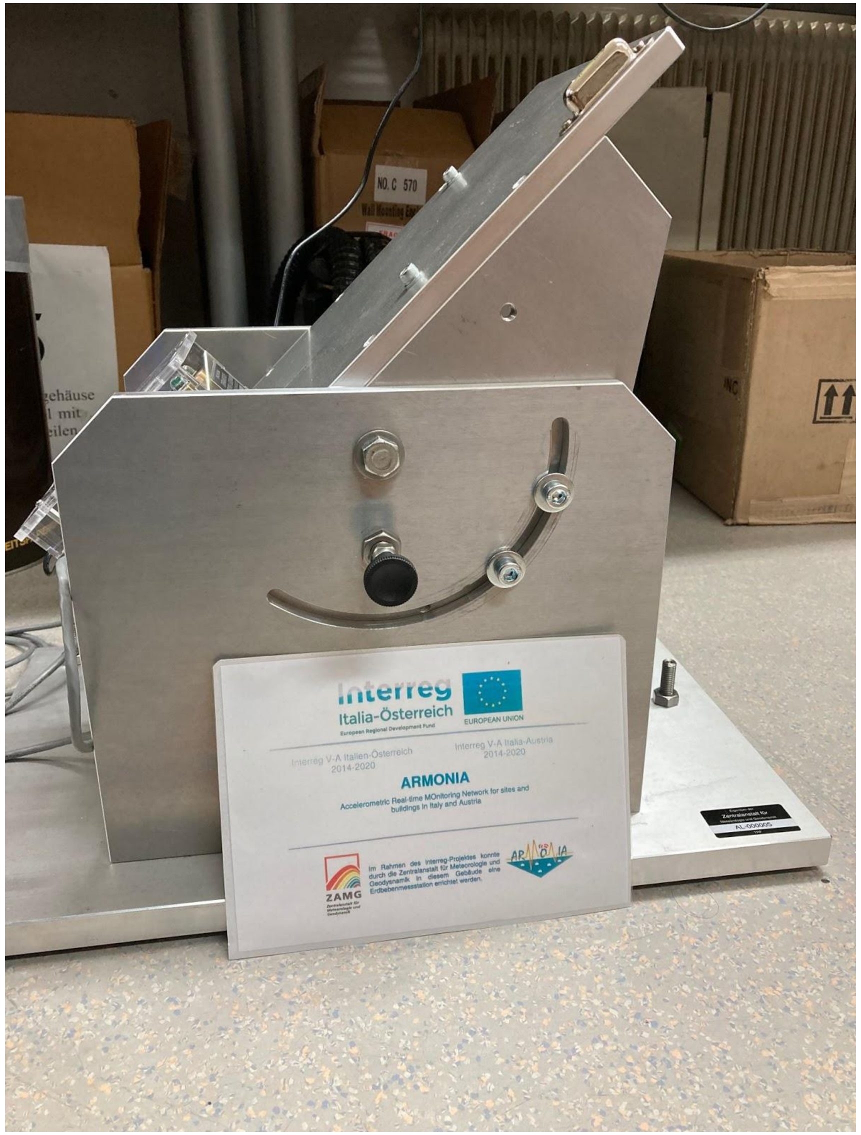

CALEX mit 10 Hz – Geophon
eing with anti-alias 15 33 6.
f.s.=+- 238.48
0.8 sec/div
ausg with anti-alias 15 33 6.
f.s.=+- 2037.75
0.8 sec/div
synth. for final mod 15 33 6.
f.s.=+- 2046.50
0.8 sec/div
obs.-synth.converged 15 33 6.
f.s.=+- 46.27
0.8 sec/div



input signal
output signal
synth. output
residual
20
10
0
−10
−20
−40
0.02
−0.02
−0.04
0
100
200
300
400
500
600
700
time since first sample [sec]


STU LP 3 1994 355 14 38 0
f.s.=+- 9390.14
684.0 sec/div
STU LP 2 1994 355 14 38 0
f.s.=+-21421.14
684.0 sec/div
Ausgangssignal Start 0 0 0
f.s.=+-10071.00
684.0 sec/div
Restfehler CALEX 0 0 0
f.s.=+- 160.14
684.0 sec/div


SWEEPER
run
stop
cycles per decade
24
12
6
48
96
3
const.
2s ..∞
0.2s .. ∞
20s .. ∞
-15V
0
+15V
sin
tri
gnd
U
V
W
Eing.
Verst. ±2
Rs = 500 Ω / 500 kΩ


Interreg
Italia-Österreich
European Regional Development Fund
EUROPEAN UNION
Interreg V-A Italien-Österreich 2014-2020
Interreg V-A Italia-Austria 2014-2020
ARMONIA
Accelerometric Real-time MOnitoring Network for sites and buildings in Italy and Austria
Im Rahmen des Interreg-Projektes konnte durch die Zentralanstalt für Meteorologie und Geodynamik in diesem Gebäude eine Erdbebenmessstation errichtet werden.
ZAMG


BASALT
Accelerograph

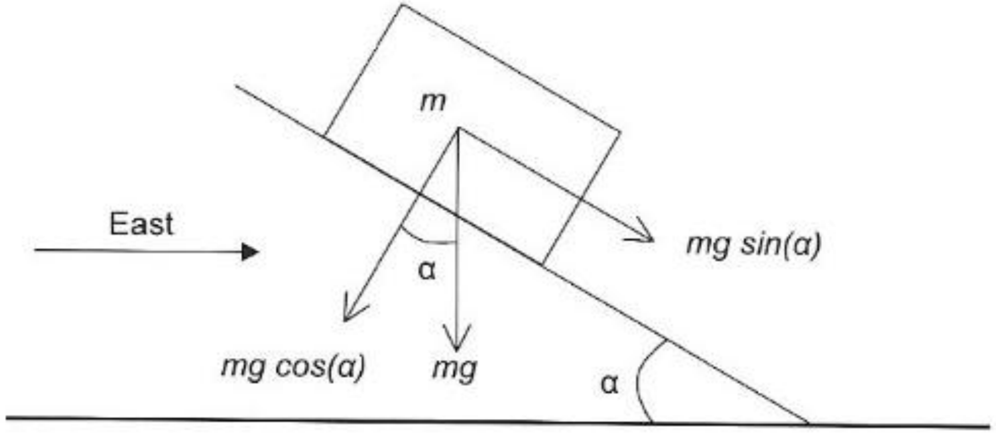
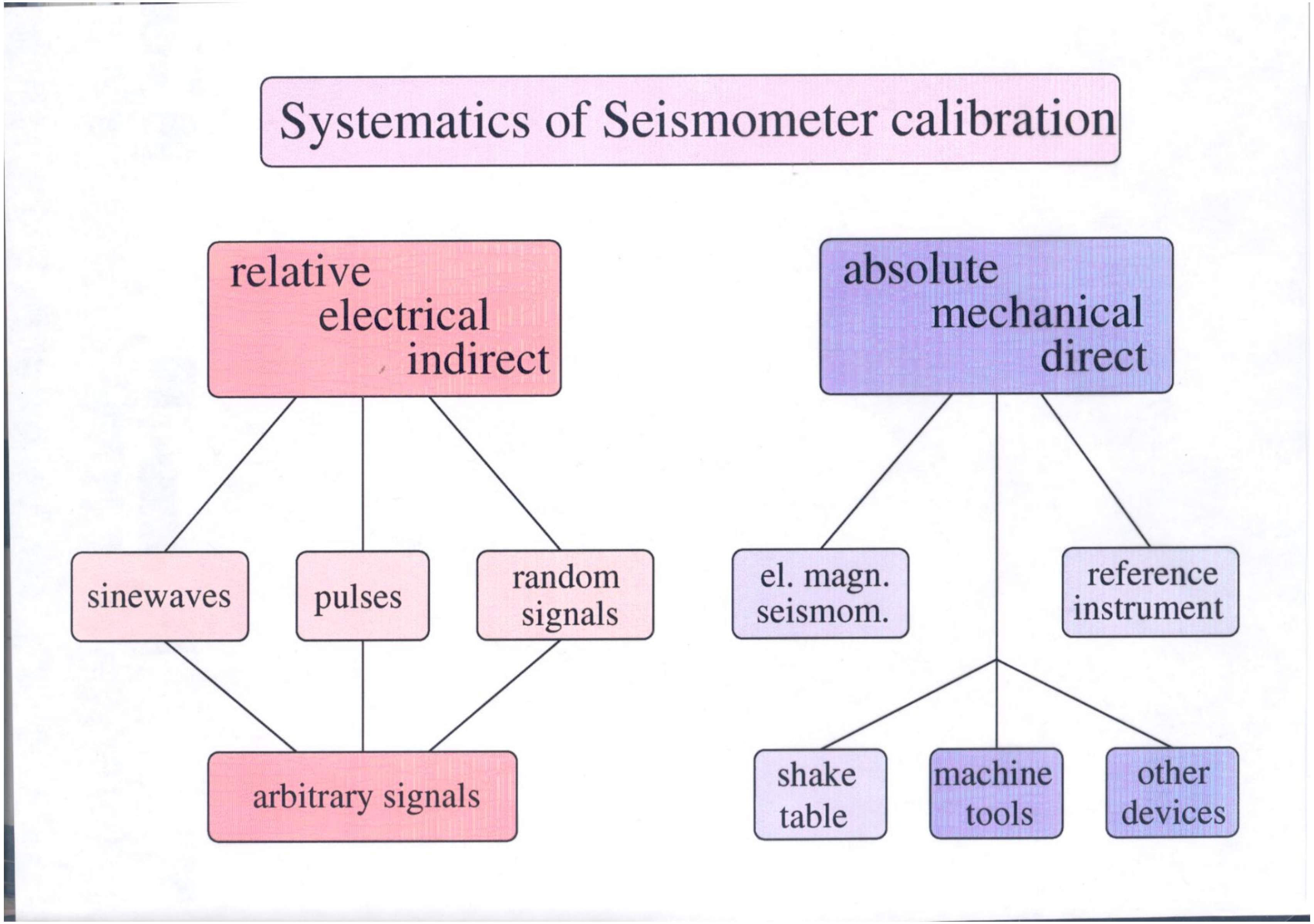
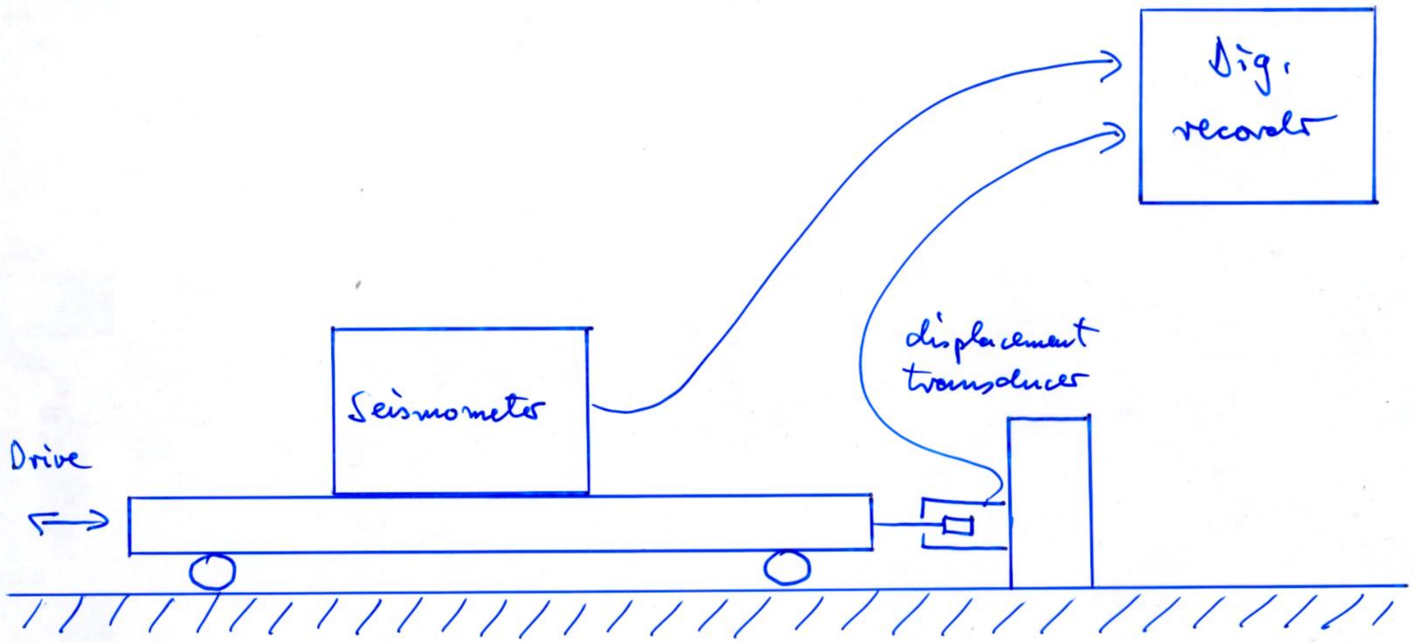
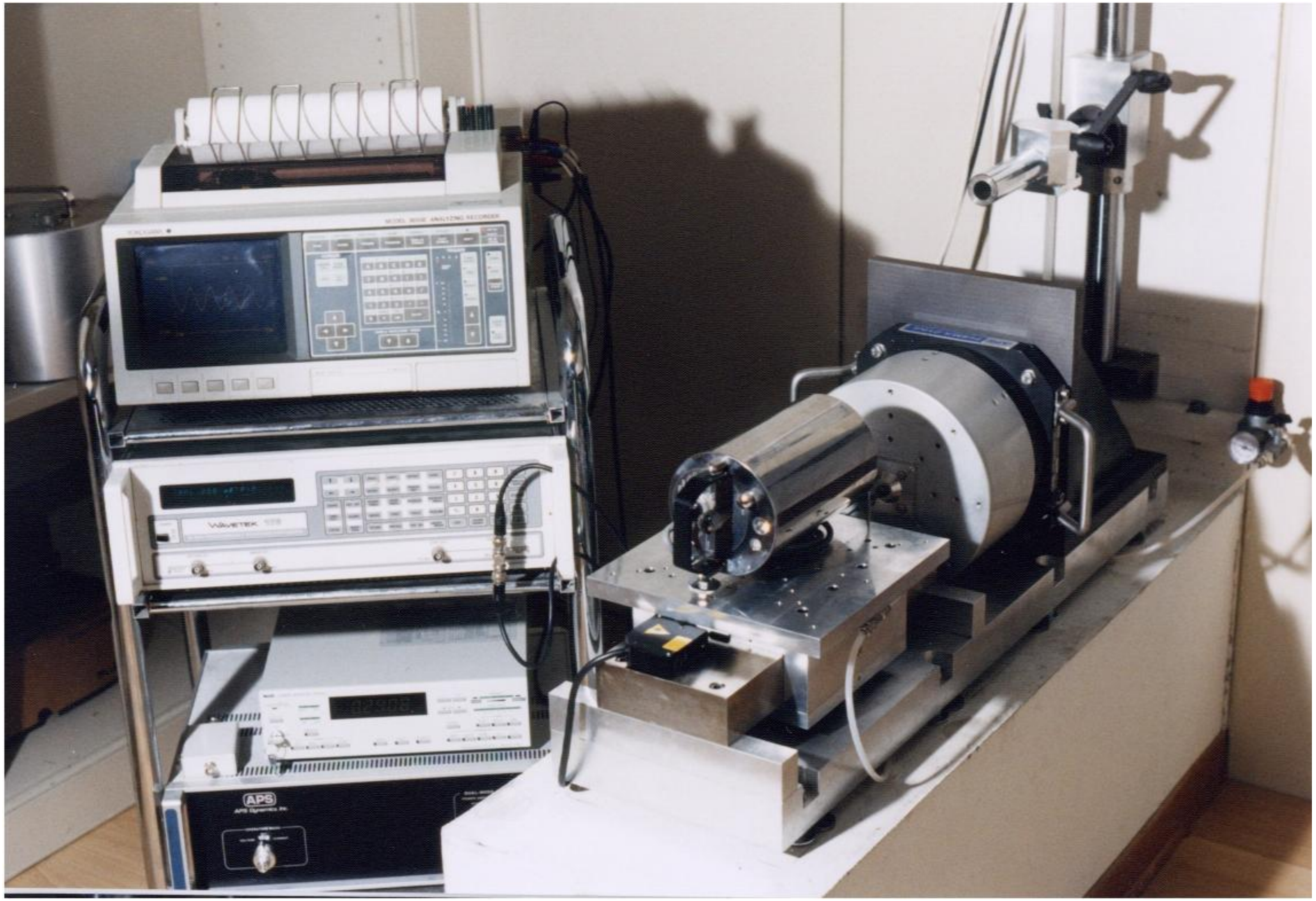


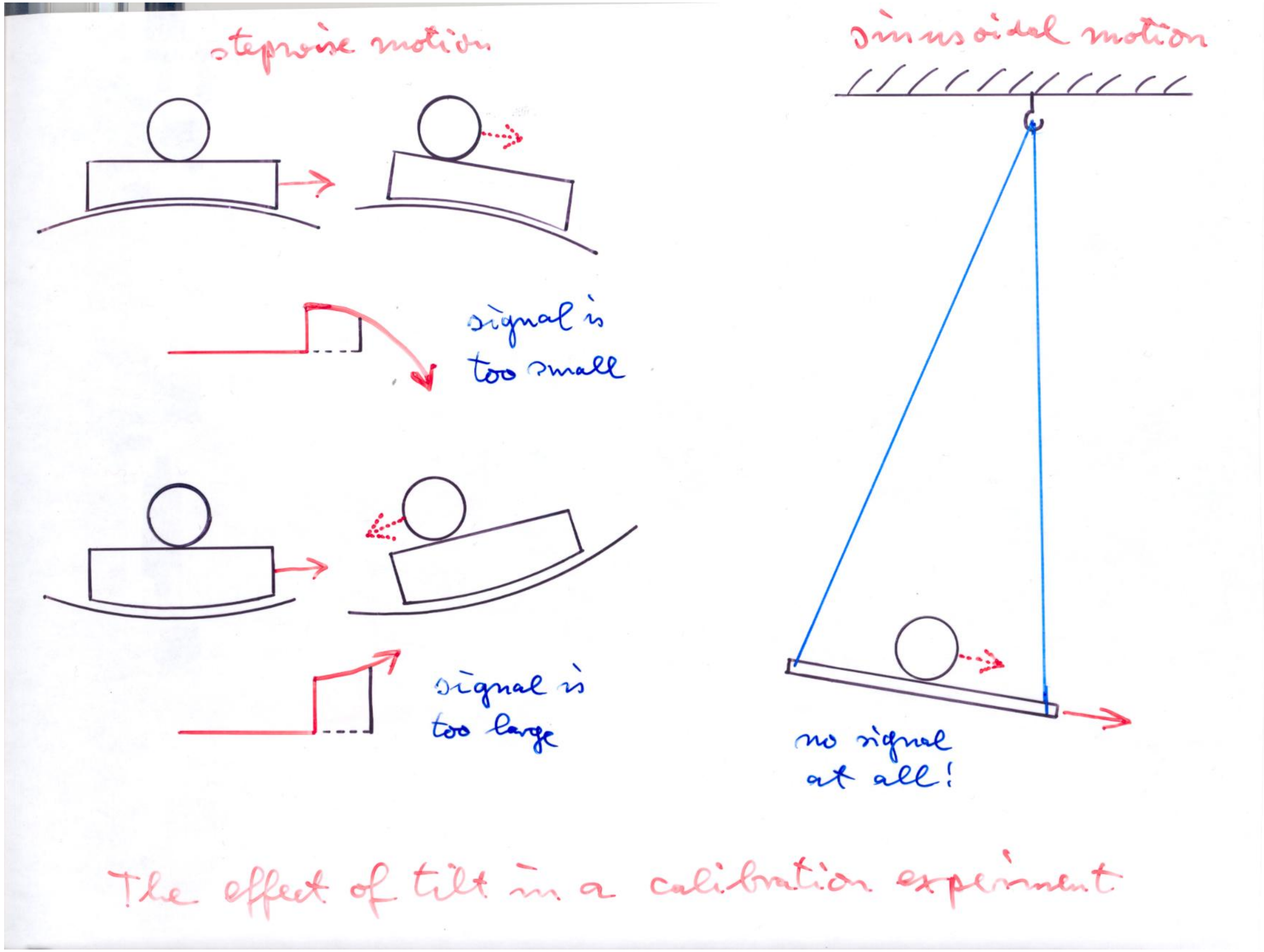
Figure 10.15 Tilting an accelerometer to determine generator constant. It is assumed that the sensor horizontal direction is towards East.

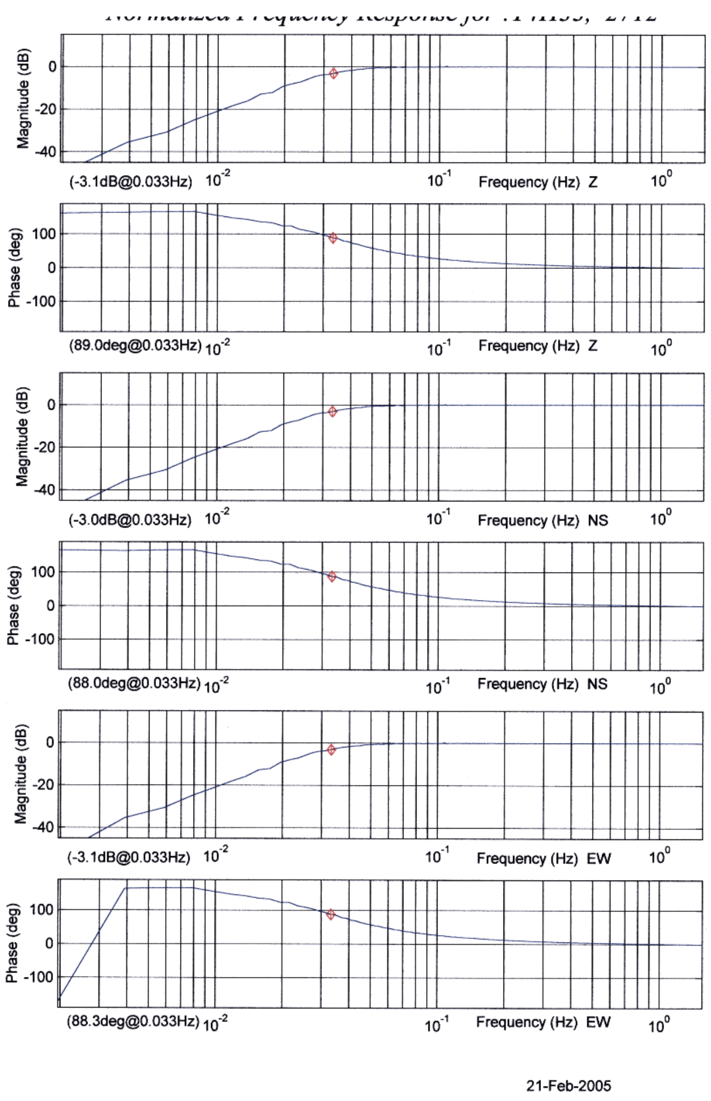

Systematics of Seismometer calibration
relative electrical indirect
absolute mechanical direct
sinewaves
pulses
random signals
el. magn. seismom.
reference instrument
arbitrary signals
shake table
machine tools
other devices



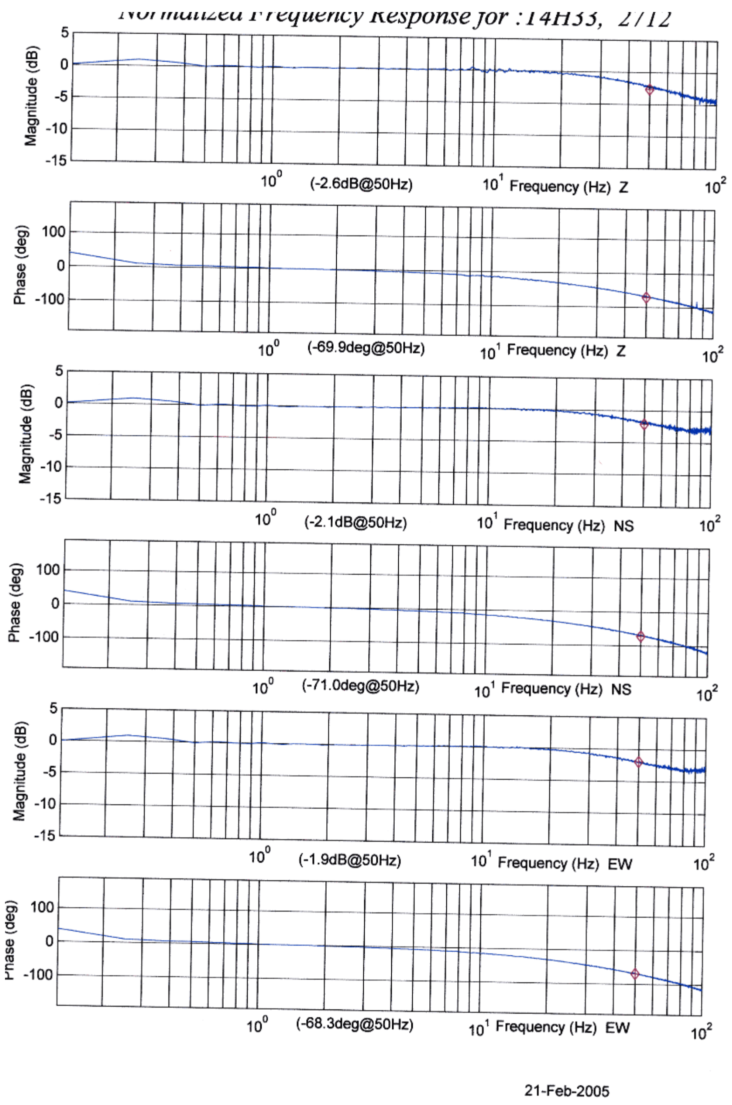
Shake table



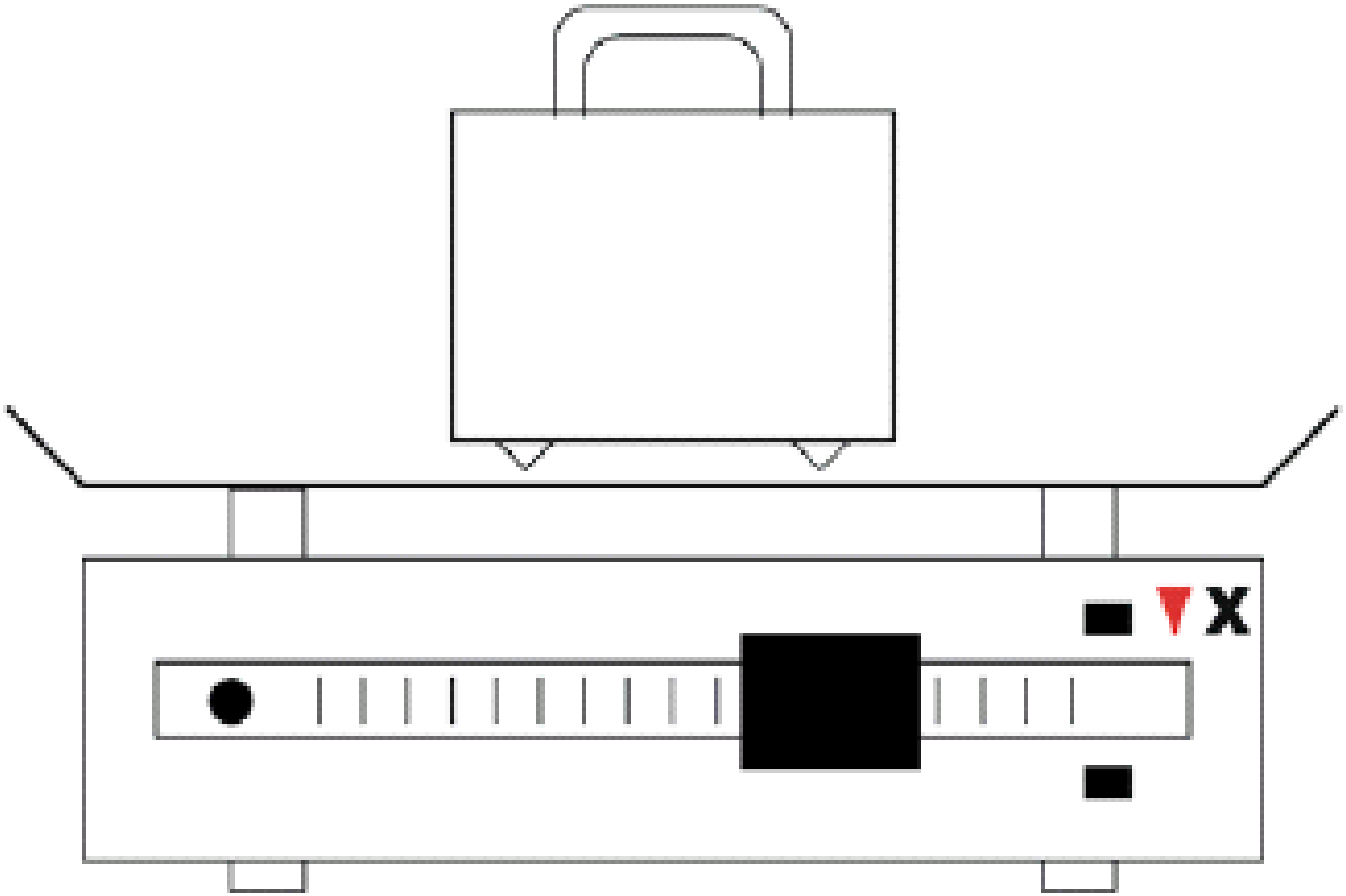

stepwise motion
signal is
too small
signal is
too large
sinusoidal motion
no signal
at all!
The effect of tilt in a calibration experiment

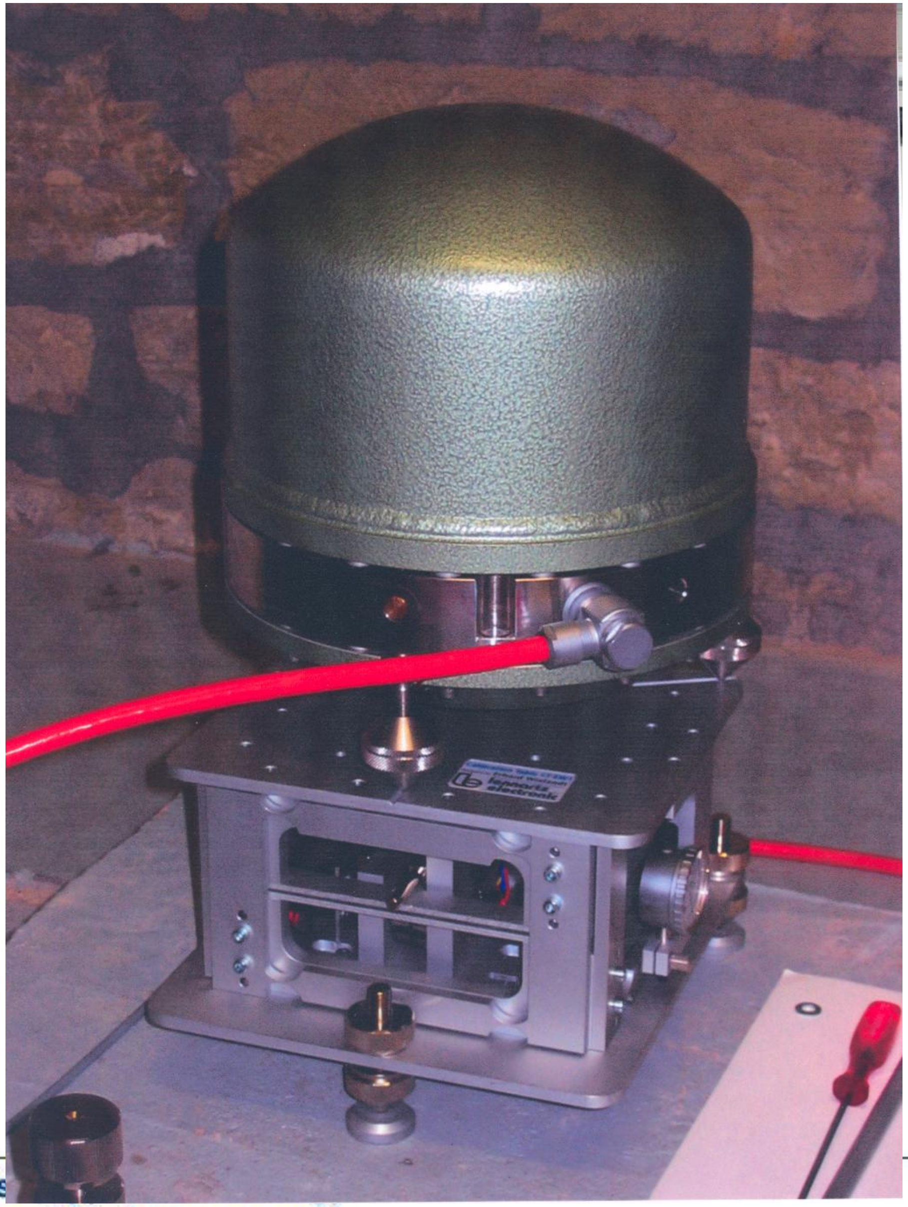


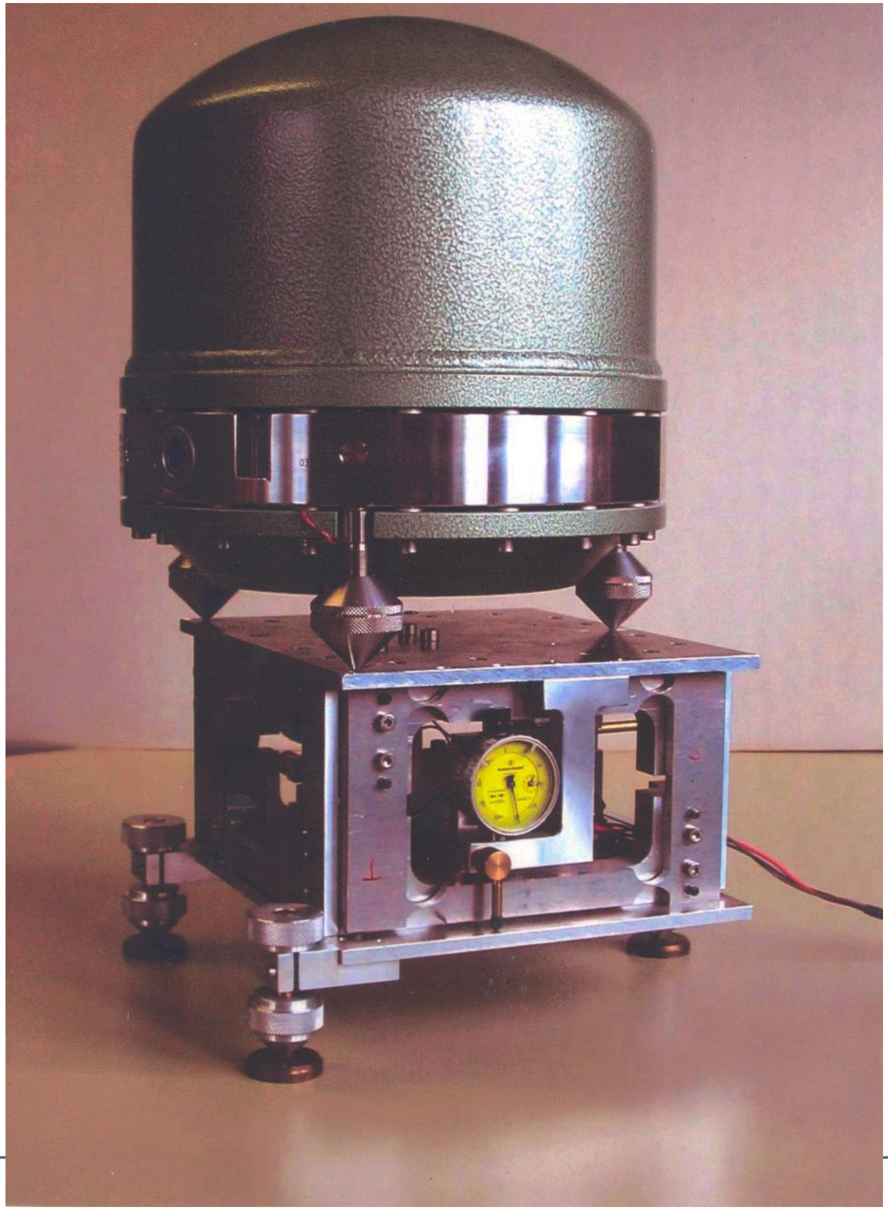
Magnitude (dB)
(-3.1dB@0.033Hz)
Frequency (Hz) Z
Phase (deg)
(89.0deg@0.033Hz)
Frequency (Hz) Z
Magnitude (dB)
(-3.0dB@0.033Hz)
Frequency (Hz) NS
Phase (deg)
(88.0deg@0.033Hz)
Frequency (Hz) NS
Magnitude (dB)
(-3.1dB@0.033Hz)
Frequency (Hz) EW
Phase (deg)
(88.3deg@0.033Hz)
Frequency (Hz) EW
21-Feb-2005



Normalized Frequency Response for :14H33, 2/12
Magnitude (dB)
(-2.6dB@50Hz)
Frequency (Hz) Z
Phase (deg)
(-69.9deg@50Hz)
Frequency (Hz) Z
Magnitude (dB)
(-2.1dB@50Hz)
Frequency (Hz) NS
Phase (deg)
(-71.0deg@50Hz)
Frequency (Hz) NS
Magnitude (dB)
(-1.9dB@50Hz)
Frequency (Hz) EW
Phase (deg)
(-68.3deg@50Hz)
Frequency (Hz) EW
21-Feb-2005


X



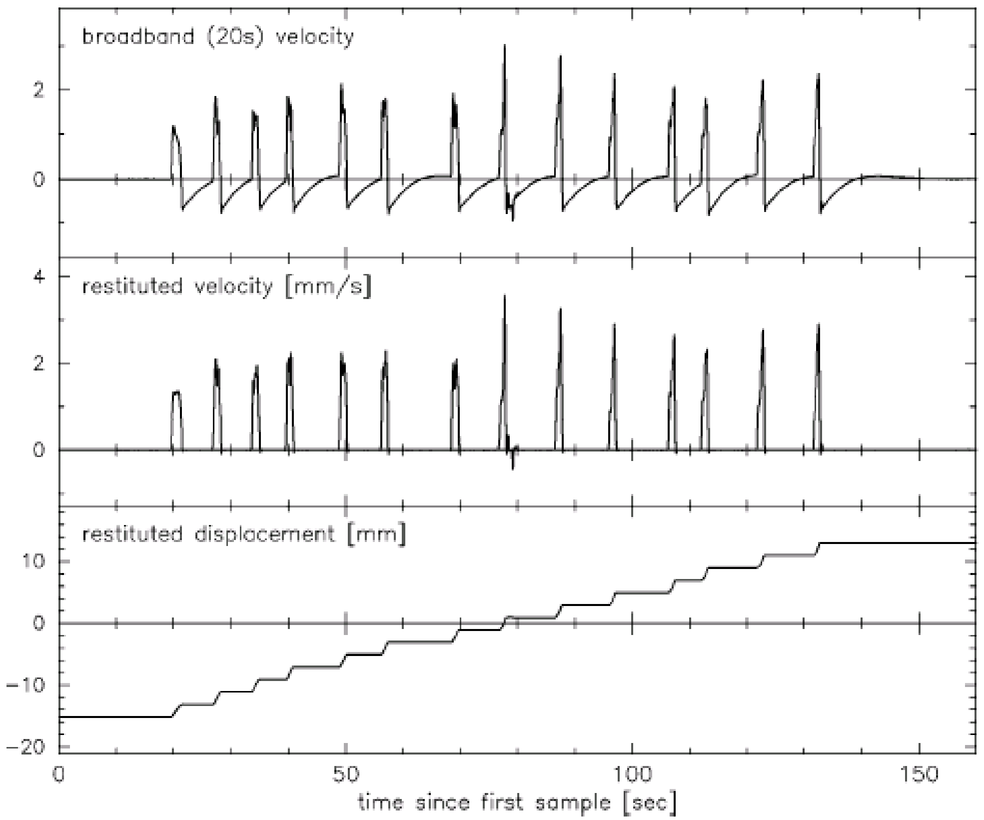


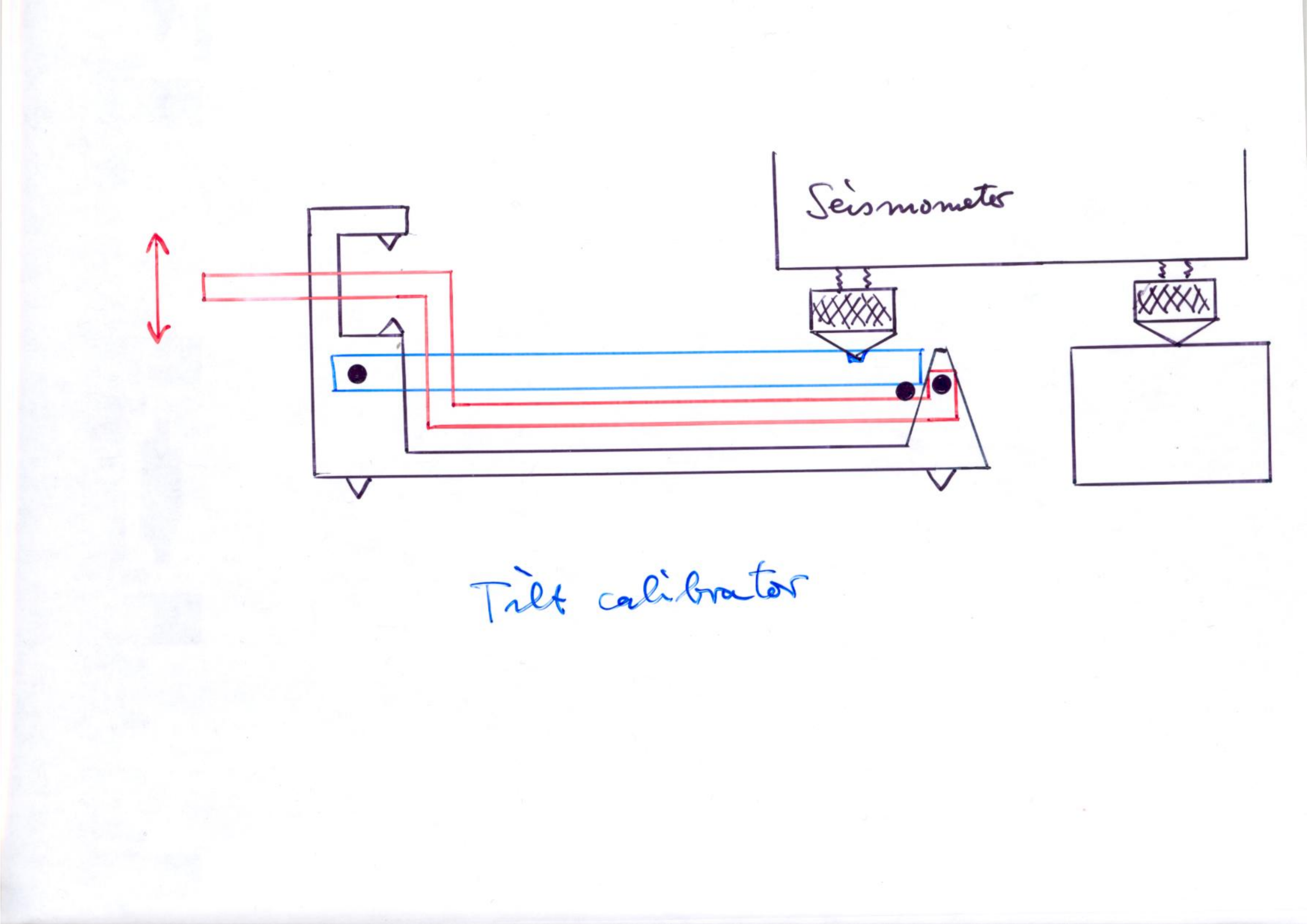
1 - The trace is deconvolved with the velocity transfer function of the seismometer.

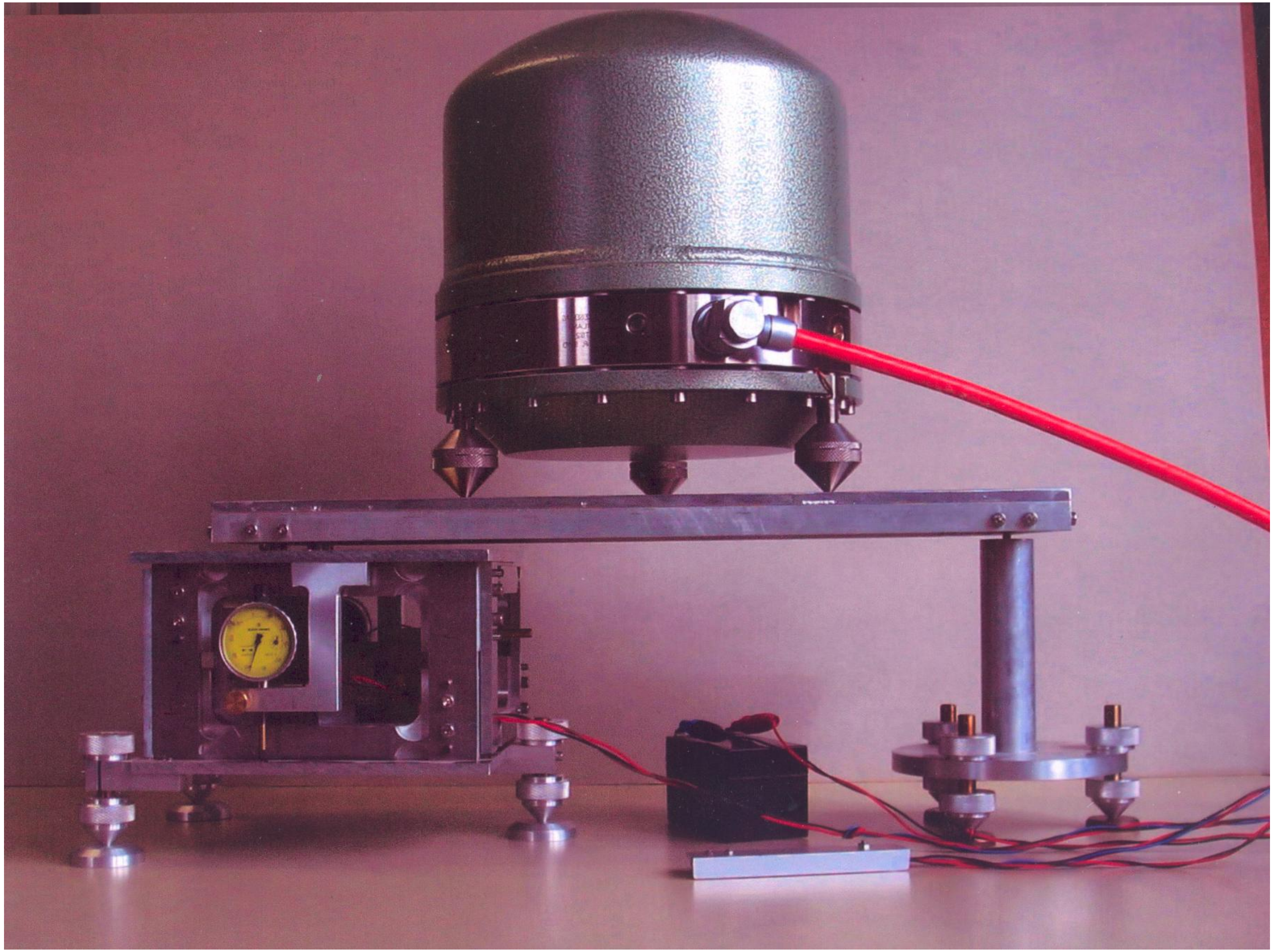
2 - The trace is piecewise detrended so that it is close to zero in the motion-free intervals; interpolated trends are removed from the interval of motion.

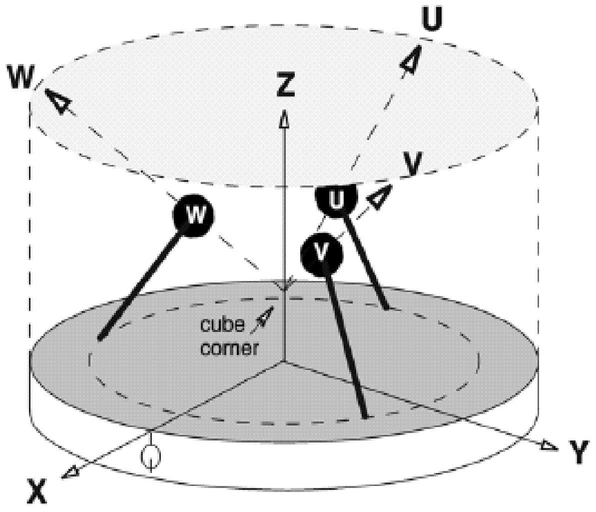
3 - The trace is integrated.

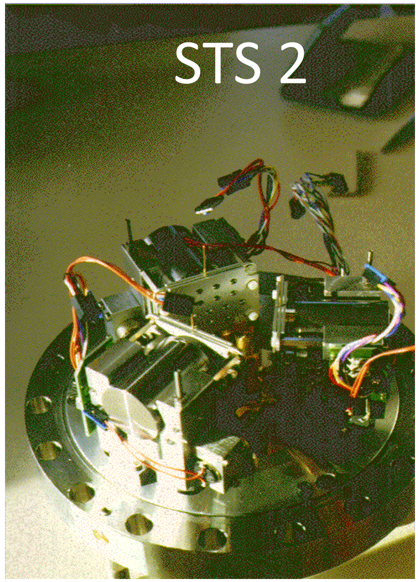
4 - The displacement steps are measured and compared to the actual motion.




Seismometer
Tilt calibrator

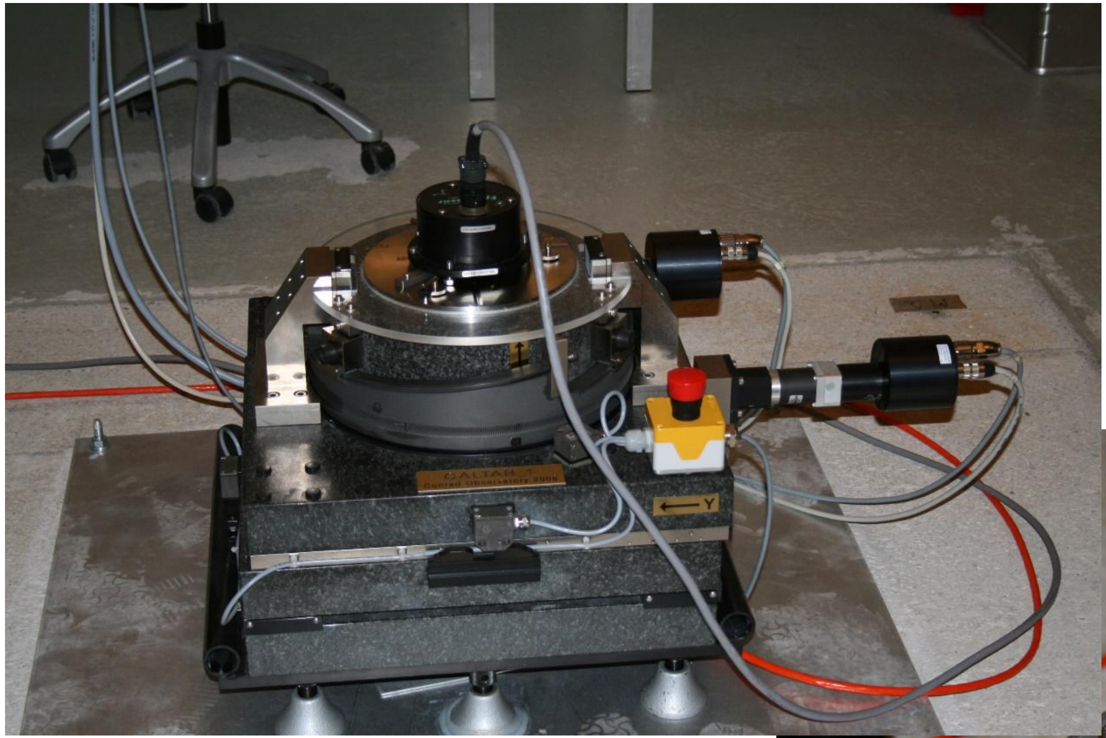


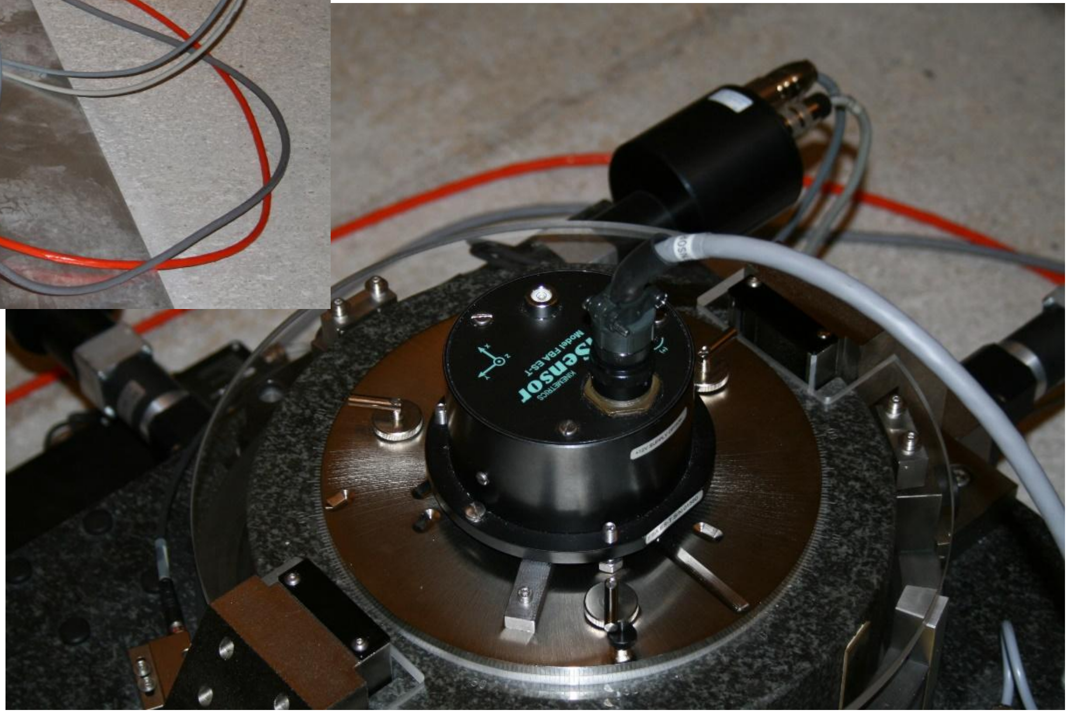




$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{\sqrt{6}} \begin{pmatrix} -2 & 1 & 1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{pmatrix} \begin{pmatrix} U \\ V \\ W \end{pmatrix}$$

$$\begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} = \frac{1}{6} \begin{pmatrix} 4 & 1 & 1 \\ 0 & 3 & 3 \\ 2 & 2 & 2 \end{pmatrix} \begin{pmatrix} T_U \\ T_V \\ T_W \end{pmatrix}$$




KINEMETRICS
Model FBA ES-T

CMG-40T CALIBRATION SHEET

WORKS ORDER:	2712	DATE:	22-Feb-2005
SERIAL No:	T4H33	TESTED BY:	P. Stott

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 399.6	19.6	0.004176
NORTH/SOUTH	2 x 400.4	20.8	0.004421
EAST/WEST	2 x 403.1	21.0	0.004466

Power Consumption: 62.8mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.

POLES AND ZEROS TABLE

WORKS ORDER No: 2712

SENSOR SERIAL No: T4H33

Velocity response output, Vertical Sensor:

POLES (HZ)	ZEROS HZ
$-23.56 \times 10^{-3} \pm j\, 23.56 \times 10^{-3}$	0
-180.0	0
-160	
-80	

Normalizing factor at 1 Hz: A = 2304000

Sensor Sensitivity: See Calibration Sheet.

Velocity response output, Horizontal Sensors:

POLES (HZ)	ZEROS (HZ)
$-23.56 \times 10^{-3} \pm j\, 23.56 \times 10^{-3}$	0
-180.0	0
-160	
-80	

Normalizing factor at 1 Hz: A = 2304000

Sensor Sensitivity: See Calibration Sheet.

NOTE: The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with 2π. The normalizing factor A should also be recalculated.

KINEMETRICS

EpiSensor
FBA ES-DECK
Calibration Data

Unit Serial Number	E 2877	
Oscillator Board Serial Number	4800268	
Current	+12V /mA	-12V /mA
	13	10.2
Sensor Output Voltage Level	2.5V	10V
	X	
Standard or Low Noise Output	Standard	Low Noise
	X	
Output Type	Single Ended	Differential
	X	
Sensitivity	1.25 V/g	
Final Setup Check by	AK	
Test Date	06/12/2001	

	Serial Number	Range Set
X Axis Module	6055	2G
Y Axis Module	6029	2G
Z Axis Module	6083	2G

This data sheet reflects the configuration of the EpiSensor set in the factory. If you wish to change this refer to the Operating Manual included with your EpiSensor ES-DH. The data for the individual modules is included on the following pages.

ES-T Calibration Sheet Version 1.0

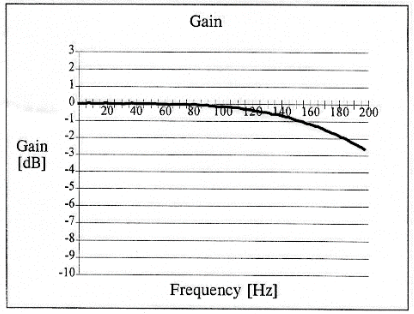
Kinemetrics Inc.
222 Vista Avenue
Pasadena
California 91107
USA

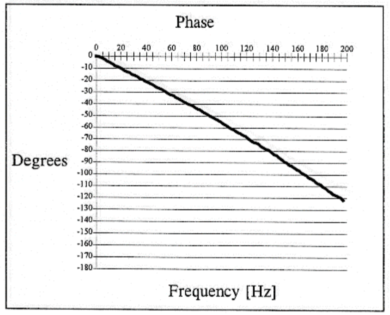
(626) 795 2220
www.kinemetrics.com

EpiSensor Module Data Sheet

Serial Number 6055 Date: 05/10/2001

Parameter	Value	Units
Span at 1/4g	10.0014	Volts/g
Span at 1/2g	5.0035	Volts/g
Span at 1g	2.5003	Volts/g
Span at 2g	1.2512	Volts/g
Span at 4g	0.6261	Volts/g
Bandwidth (-3dB) @ 1g	212	Hz
Gain Variation at 100Hz @ 1g	-0.14	dB
Phase at 100Hz @ 1g	-56.6	Degrees
Non-Linearity @ 1g	261	ug/g^2
Mechanical Alignment Error	0.1011	Degrees
Cal-Coil Sensitivity	0.0554	g/Volt
Poles and Zeros	See Manual	rad/sec



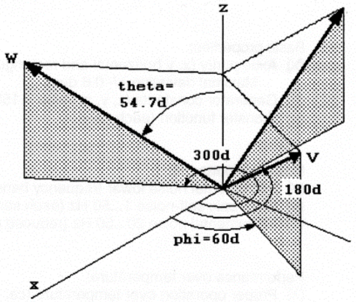


******* LABORATORY DATA OF THE SEISMOMETER NO. 40343 *******

1. Internal oscillator
Frequency: 22.41 kHz Amplitude: 5.643 Vrms

2. Generator constant and orientation of the axes U, V, and W relative to X, Y, Z
U, V, and W are the uncalibrated, oblique sensitivity axes ('cube corner' configuration)

-> Naming conventions: See sketch below! <-
Sensor U: G/G0 = 1.0749 theta = 55.158d phi = 179.82d
Sensor V: G/G0 = 1.0712 theta = 55.264d phi = 59.964d
Sensor W: G/G0 = 1.0683 theta = 54.966d phi = 299.85d
'G/G0' is the normalized generator constant (actual constant divided by 1500V*sec/m)



3. Model parameter optimization of the transfer function

a) High-frequency end (1 - 100 Hz)
Parameters partially optimized for best fitting measurement data. Model function: Linear filter function with discrete poles and zeroes at complex frequencies. Data points to be optimized:
96 complex values of the measured transfer function applying sweep signal at calibration inputs.

4 Zeroes [Hz]:
Sensor U: -73.50+/-68.29i -30.83** -2.411
Sensor V: -73.50+/-68.29i -30.17** -2.411
Sensor W: -73.50+/-68.29i -31.38** -2.411
9 Poles [Hz]:
Sensor U: -1629.7+/-433.7i -1514.0+/-1825.5i -72.34 -66.90* -15.01* +/-62.61i* -2.459*
Sensor V: -1629.7+/-433.7i -1514.0+/-1825.5i -72.34 -65.98* -15.47* +/-63.08i* -2.454*
Sensor W: -1629.7+/-433.7i -1514.0+/-1825.5i -72.34 -69.37* -14.71* +/-62.77i* -2.460*

* = optimized, ** = optimized and corrected for ground motion instead of calibration coil excitation.
Notes: Values without asterisk are standard values from the theoretical model function (no optimization).
Optimization performed with MATHSOFT MATHCAD V8.01, built-in inversion algorithm 'MINERR'

b) Low-frequency end (0.00586 - 0.10547 Hz)
Model: Linear 2nd order highpass filter. Data points to be optimized: 64 complex values of the measured transfer function applying sweep signal at calibration inputs.
Parameters: 1. 2nd order corner period [sec]. 2. 2nd order damping constant. 3. Standard dev. corner period [%]. 4. Standard dev. damping constant [%]. 5. Ampl. RMS Error. 6. Phase RMS Error.

	Parameter					
	1	2	3	4	5	6
Sensor U:	119.78	0.7056	0.0698	0.0882	00.54	00.36
Sensor V:	120.05	0.7082	0.0744	0.0938	00.56	00.35
Sensor W:	120.14	0.7056	0.0559	0.0706	00.59	00.20

Note: Optimization performed with MATHSOFT MATHCAD V8.01, built-in inversion algorithm 'MINERR'