

THE NARS ARRAY¹BERNARD DOST², ARIE VAN WETTUM² & GUUST NOLET²

ABSTRACT

Dost, B., A. van Wettum & G. Nolet 1984 The NARS array – Geol. Mijnbouw 63: 381-386.

We present a detailed description of the instrumentation and design of the Network of Autonomously Registrating Stations (NARS). The instrumentation of each station consists of three Teledyne Geotech SL 210/220 long period seismometers and a Kinometrics PDR-2 digital event recorder. This off-the-shelf technology was supplemented by specially designed pre-amplifiers, response shaping filters and time receivers which calibrate the PDR-2 clock in an automatic fashion. Expressions for the full system response are derived, and station locations are given.

INTRODUCTION

In the past 80 years, seismic waves have been vital in our efforts to build up a detailed picture of the Earth's internal structure. Refracted body waves (P and S waves) were used in the first half of this century to identify the major shells of the Earth. In the past two decades, seismic surface waves (Rayleigh and Love waves) established the existence of a low velocity channel in the upper mantle under oceans and continents (with the possible exception of the oldest shields). Surface waves and body waves generated by earthquakes were used to decipher lithospheric structure with increasing precision. These developments coincided with the rise of plate tectonics and with very significant advances in our understanding of the spreading, cooling and subsidence of oceanic lithosphere (e.g. WORTEL, 1980). With respect to continental evolution, however, the theory of plate tectonics seemed to raise as many problems as it solved.

A more detailed determination of the structure of the upper mantle is vital to a better understanding of the evolution of the continents. Today, seismic data from many different sources seem to indicate a very complicated upper mantle, with lateral heterogeneities extending to 300 km or more. Early higher mode surface wave analyses by NOLET (1975, 1976, 1977) seemed to indicate the presence of a low density layer at the bottom of the low velocity zone beneath Western Europe, and a much stronger layering of the upper mantle than hitherto assumed. The discovery of the low density channel still needs confirmation and that can only be achieved by more and better higher mode measurements. The opinion that the upper mantle exhibits a strong layering is gaining widespread acceptance at this moment.

A model for continental evolution that favours a layered,

laterally heterogeneous upper mantle was recently developed by VLAAR (1982, 1983), who proposed that continental lithosphere is frequently doubled by subduction of young oceanic slabs. That young slabs are more likely to start subducting than old, heavy but strong ocean floor, was a surprising result from numerical modelling experiments by CLOETINGH ET AL. (1982).

Existing seismic networks, such as the World Wide Standardized Seismograph Network (WWSSN) lack the high station density which is needed to study the dynamics of the upper mantle at a regional scale. Upgrading of the WWSSN equipment to broad-band, digital recording with large dynamic range, which is being discussed at the moment, will not help either, since improvements are sought in the frequency domain, whereas improvements in the wave number domain (i.e. a closer spacing of stations) is most needed for upper mantle studies.

The department of Theoretical Geophysics of Utrecht University realised this problem several years ago and decided to develop a portable network of 14 broad-band, digital seismic stations (NARS – Network of Autonomously Registrating Seismographs). The primary purpose of the network is to provide a flexible instrument to record higher and fundamental mode surface waves with a dense spatial sampling. Initially, the network has been installed on the West-European platform (Fig. 1). The technique of measuring higher modes has been described by NOLET & PANZA (1976), and some recent improvements are given in DOST (1984). A more extended report on the scientific aims of NARS can be found in NOLET & VLAAR (1982). The purpose of this paper is to describe the instrumentation, the response, and the calibration procedure in detail, and to provide all information needed by users of NARS data to convert the digital data to true Earth displacement.

For many years seismological observatories have been equipped with non-mobile seismometers and analogue recording. Maintenance could only be done by qualified personnel. A common seismic station consists of a seismometer-galvanometer system, producing an output on photo-

¹ Manuscript received: 1984-07-14.

Revised manuscript accepted: 1984-10-15.

² Department of Theoretical Geophysics, Instituut voor Aardwetenschappen, Rijksuniversiteit Utrecht, P. O. Box 80 021, 3508 TA Utrecht, The Netherlands.

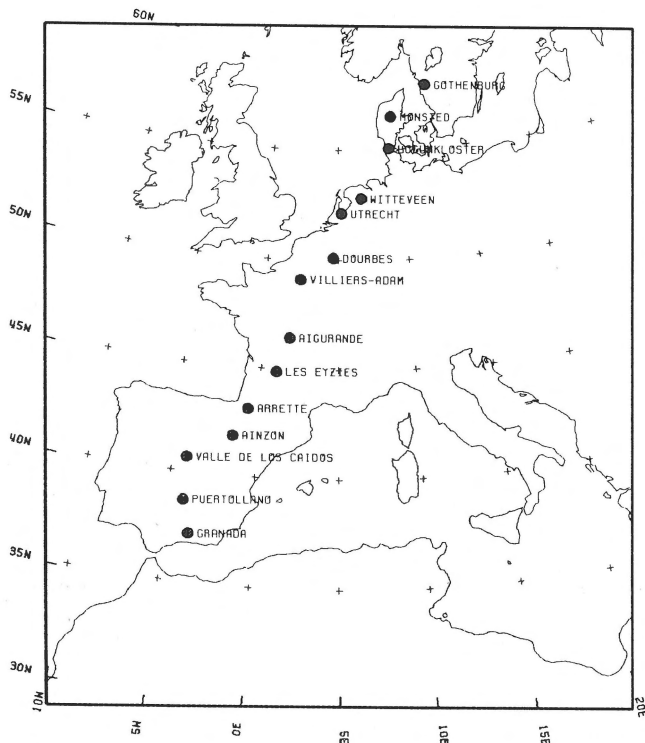


Fig. 1
NARS station locations

graphic paper or ink-recorders. Since 1948 an effort has been made to simplify the seismographic instruments, resulting in the sixties in portable long period seismometers (see MELTON, 1981). Recently, due to a great advance in (micro)electronic component development, the galvanometer could be replaced by an electronic amplifier-filter system (WIELANDT & MITRONOVAS, 1976) and digital recording. During the last few years digital event recorders have appeared on the market, and these instruments include the possibility of triggered recording.

Table I

STATION LOCATIONS

Station	Longitude	Latitude
NE01 Gothenburg	12.13 E	57.80 N
NE02 Monsted	9.17 E	56.46 N
NE03 Logumkloster	8.90 E	55.04 N
NE04 Witteveen	6.67 E	52.81 N
NE05 Utrecht ³	5.17 E	52.13 N
NE06 Dourbes	4.60 E	50.10 N
NE07 Villiers-Adam	2.33 E	49.10 N
NE08 Aigurande	1.73 E	46.42 N
NE09 Les Eyzies	0.98 E	44.85 N
NE10 Arrette	0.70 W	43.09 N
NE11 Ainzon	1.73 W	41.48 N
NE12 Valle de los Caidos	4.16 W	40.64 N
NE13 Puertollano	4.09 W	38.69 N
NE14 Granada	3.60 W	37.19 N
NE15 Valkenburg	5.78 E	50.81 N

³ Since June 1984 replaced by the station Valkenburg.

NARS INSTRUMENTATION

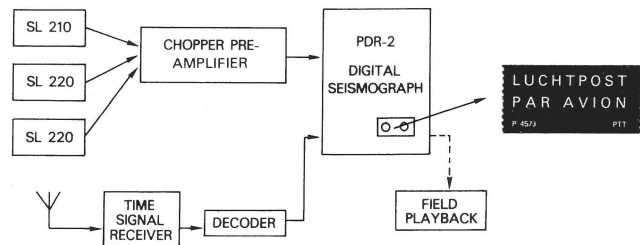


Fig. 2
NARS system configuration

NARS SYSTEM DESIGN

The NARS instrumentation was selected with the following requirements in mind:

- The network should record large earthquakes with a good signal to noise ratio. Since the aim of the network is to study Earth structure, not seismicity, we are not interested in small magnitude ($m < 6$) events;
- The frequency band should include surface waves between 5 and 100 seconds;
- Digital registration and a large dynamic range is necessary to allow for sophisticated data analysis techniques;
- Mobility and ease in maintenance is required to make the network multi-purpose and low-cost.

In view of this we opted for triggered recording and selected the Kinometrics PDR-2 digital event recorder. The PDR-2 can be used with long period seismometers. As portable long period seismometers we chose the Teledyne Geotech SL 210 (vertical) and SL 220 (horizontal) instruments. Matching the output of these seismometers to the PDR-2 necessitated the introduction of a pre-amplifier to take full advantage of the large dynamic range of the PDR-2. The seismometers can be tuned to an eigenperiod of 10 to 30 seconds, but become increasingly unstable at longer periods. This made us decide to tune the seismometers to 12 seconds eigenperiod and to introduce a response shaping filter after the pre-amplifier to widen the frequency band towards low frequencies. Finally a time receiver has been built for regular calibration of the internal PDR-2 quartz clock.

NARS INSTRUMENTATION

Seismometers

Each station is equipped with one vertical and two horizontal seismometers. The history of the development of portable long period seismometers shows a large effort to diminish the length of the spring and weight of the mass.

With the introduction of the zero-initial length spring (see AKI & RICHARDS, 1980, pp 482-484) the seismometer could be realised. The relation between period and mathematical spring length being

$$T = 2\pi/[l/g]^{1/2} \quad (1)$$

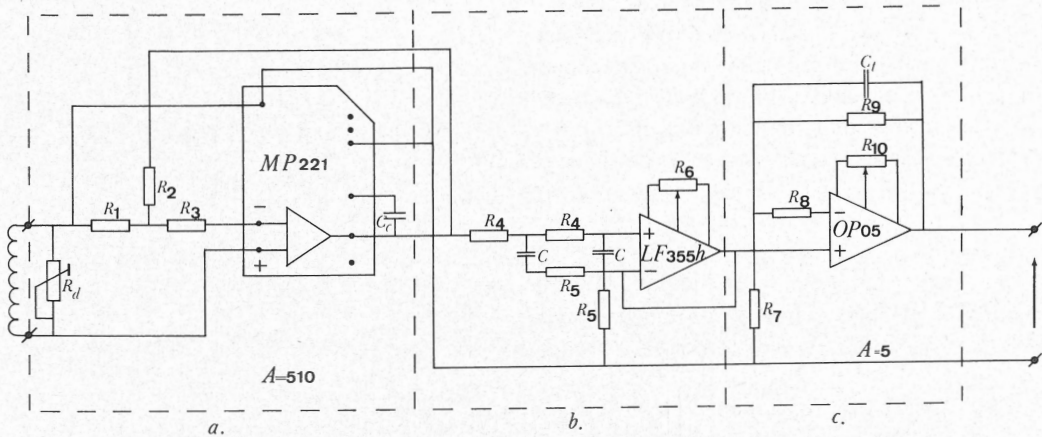


Fig. 3 Pre-amplifier/filter circuit diagram.

where l denotes spring length, g gravity constant and T the period. At 10 seconds the equivalent spring length $l = 25$ m, but at 30 seconds $l = 225$ m. The seismometer reacts to tilts of the base and extension of the spring as if the dimensions of the instrument are equal to the mathematical equivalent lengths (WILLMORE, 1979). The seismometer transferfunction (in V/m as a function of circle frequency w), defined as response to a signal $\exp(+iwt)$ is given by:

$$T(w) = i w^3 S / (-w^2 + 2i w w_0 h_0 + w_0^2) \quad (2)$$

where S denotes the coil constant in Vsm^{-1} , w cornerfrequency in rad/s, w_0 the eigenfrequency in rad/s and h_0 the damping of the seismometer. The seismometers used have $S = 90 \pm 4 Vsm^{-1}$ (SL 210) and $S = 93 \pm 4 Vsm^{-1}$ (SL220), and are tuned to $w_0 = 0.5236$ rad/s and $h_0 = 1$.

Pre-Amplifier-filter

The pre-amplifier-filter is divided into three parts (see Fig. 3):
 a. Pre-amplifier, with a gain setting of 510,
 b. Response shaping filter,
 c. Additional amplification, gain 5.

Long period digital recording can only be accomplished by using low noise chopper amplifiers, the input being nearly a DC signal. To match the seismometer output to the PDR-2 a gain factor of only 40 is needed. Introduction of the shape response filter, however, (see Fig. 6) decreases the signal level near the short end of the pass-band with a factor of about 65, so a total gain should be applied of approximately 2600. If we apply this gain before filtering, the voltage after amplification can exceed the alimentation voltage of the chopper amplifier, introducing distortion of the signal. For this reason we restricted the amplifier gain to 500 before filtering and to 5 afterwards. A detailed description of the three components, illustrated by Figure 3, is as follows;

a. *Pre-amplifier.* R_d takes care of the critical damping of the seismometer. R_1 and R_2 determine the gain and R_3 is used to diminish the DC offset. An offset error voltage is generated by the bias current flowing through the summing impedance

of R_1 and R_2 . If we choose $R_3 = R_1 \cdot R_2 / (R_1 + R_2)$ – provided the source impedance is much less than R_1 – it compensates the offset. A central position is taken by the Analogic MP 221 chopper amplifier, with a specified noise level from DC to 1 Hz of less than 100 nV peak-to-peak and a drift less than 50 nV/°C. C_c is a compensation capacity, dependent on the gain.

b. *Response shaping filter.* One can easily show that the transfer function of the second order filter, as illustrated by Figure 4, is equal to:

$$U_u / U_i = Y_1 \cdot Y_2 / (Y_1 \cdot Y_2 + Y_4 \cdot (Y_1 + Y_2 + Y_3)) \quad (3)$$

U_u and U_i denote respectively the output and input voltage and Y_i the admittance. Taking $Y_1 = Y_2 = 1/R_4$ and $Y_3 = Y_4 = iwC$ one achieves the well-known formula of a Biquadratic low-pass filter. Addition of a resistance R_5 after C gives us an additional high pass part. The total transferfunction for the response shaping filter now becomes:

$$U_u / U_i = \frac{(-w^2 + 2 i w w_0 h_0 + w_0^2) w_1^2}{(-w^2 + 2 i w w_1 h_1 + w_1^2) w_0^2} \quad (4)$$

where $w_1 = ((R_4 + R_5) \cdot C)^{-1}$, $h_1 = 1$, $w_0 = (R_5 \cdot C)^{-1}$, $h_0 = 1$.
 When w_0 and h_0 are chosen to be identical to the eigenfrequency and damping of the seismometer, we can change the eigenfrequency of the seismometer from w_0 to w_1 . R_6 and R_9 are used to handle the offset.

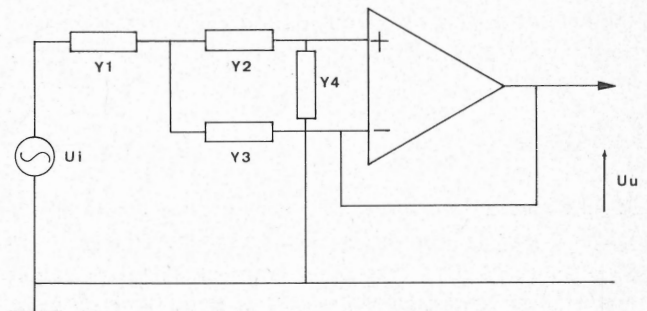


Fig. 4 Schematic second order filter circuit

c. *Additional amplification.* Instead of a chopper amplifier we use for the second amplifying stage an OP05 operational amplifier. The offset problem is handled in the same manner as in a., the only difference being the fact that the operational amplifier is used in an inverting configuration. It is introduced to cut off high frequencies, far outside the passband of the rest of the system.

Digital Event Recorder

The PDR-2 digital event recorder is a low power multi-microcomputer. The most important settings are:

a. *Sampling rate and triggering.* A sampling rate of 125 ms is chosen. This value combines long recording capacity (10 hours of data for the three channel system) with a broad frequency band (Nyquist frequency at 4 Hz). To avoid aliasing problems a second order low-pass Butterworth filter is applied with a cornerfrequency at 1 Hz.

The PDR-2 is provided with a triggering mechanism, based on Short Term Average (STA) and Long Term Average (LTA) calculations. Of crucial importance to the system is the parameter setting. In our case, for detection of earthquakes with magnitude $m > 6$, an STA length of 4 s is used and an LTA of 128 s; A trigger is effected whenever the ratio STA/LTA exceeds 4.

b. *Data Format.* The seismic sample consists of 2 bytes (16 bits) and is divided into a 12 bit mantisse and 3 bit for the binary gain code. This results in a dynamic range of 114 dB. Data are recorded in blocks of 3072 samples on standard 300 ft, 1667 bpi digital cassettes. Four track recording results in a capacity of 900,000 samples per cassette, or 10 hours of data. To each group a header consisting of 114 bytes is added, which contains information on parameter setting as well as the time contained in the internal PDR-2 quartz clock, and certain system status information. In the data-centre in Utrecht, cassettes are read out and stored on 9 track, 1600 bpi computer tape.

Play-back

A Kinematics CTU-1 play-back unit is used for station servicing in the field and for a first impression on paper of the data on cassette tapes that arrive in Utrecht. To inspect data in the field for e.g. parity errors a Tandy TRS-80 model 100 is used. Data can be transmitted at 9600 baud if a time delay is set at the PDR-2.

Time receiver

A time receiver has been build using a design, published in ELEKTUUR (1981). The role of this instrument in the system is shown in Fig. 5. By means of an active antenna a coded time signal emitted by the DCF-77 station in Frankfurt is received. At stations far away from Frankfurt an extra loop antenna is used, consisting of a coil tuned to 77 kHz. This dramatically

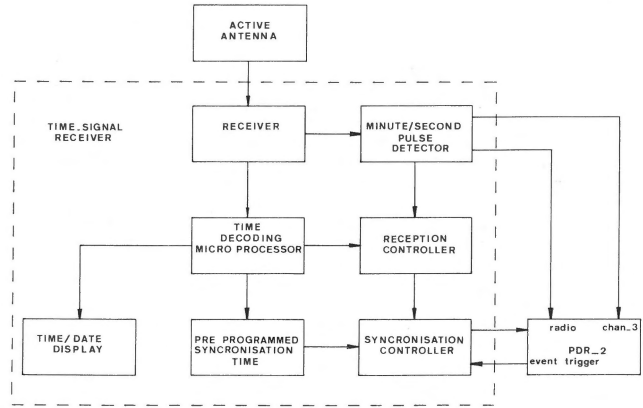


Fig. 5
Block diagram of the functioning of the time receiver in connection with the PDR-2.

enlarges the signal to noise ratio. The signal is decoded in a microprocessor unit and time is shown on a display. Manual time calibration is needed when starting up the system. To accomplish this a minutepulse is sent to the PDR-2. With a slight modification of the PDR-2 we succeeded in an automatic adjustment of the PDR-2 clock at pre-programmed time intervals. This procedure synchronizes the clock to the nearest second; in consequence the clock drift can not be more than 0.5 s. To check this procedure a minutemark is superposed on the seismic signal, on the third channel (EW), during the first two minutes before each triggering. Since the first two minutes of each event consist of microseismic noise, no signal of interest is disturbed by this procedure. Automatic time calibration is only done if the reception is good, at the pre-programmed time and if no earthquake is being recorded.

SYSTEM RESPONSE

The total system response is equal to the product of the individual responses of the seismometer, pre-amplifier and the anti-aliasing filter of the PDR-2. The total transfer function $T(w)$ for the displacement becomes:

$$T_d(w) = \frac{A D_{\max} (i w^3 w_2^2)}{(-w^2 + 2i w w_1 h_1 + w_1^2)(-w^2 + 2i w w_2 h_2 + w_2^2)} \quad (5)$$

A denotes the gain factor in $V s m^{-1}$, D_{\max} the maximum sample value (2048.0 in our standard storage in floating point format of 262144 in some distributed data in integer format) divided by the maximum voltage the PDR-2 can handle (2.5 V), w_1 and h_1 eigenfrequency and damping of the seismometer/filter system, w_2 and h_2 eigenfrequency and damping of the anti-alias filter. $T_d(w)$ is then given in Digital Units (DU) per meter.

Typical values of the different parameters are:

$$\begin{aligned} A &= 2570. \text{ Vsm}^{-1} & w_2 &= 6.283 \text{ rad s}^{-1} & h_2 &= 0.707 \\ D_{\max} &= 819.2 \text{ DU V}^{-1} & w_1 &= 0.063 \text{ rad s}^{-1} & h_1 &= 1.0 \end{aligned}$$

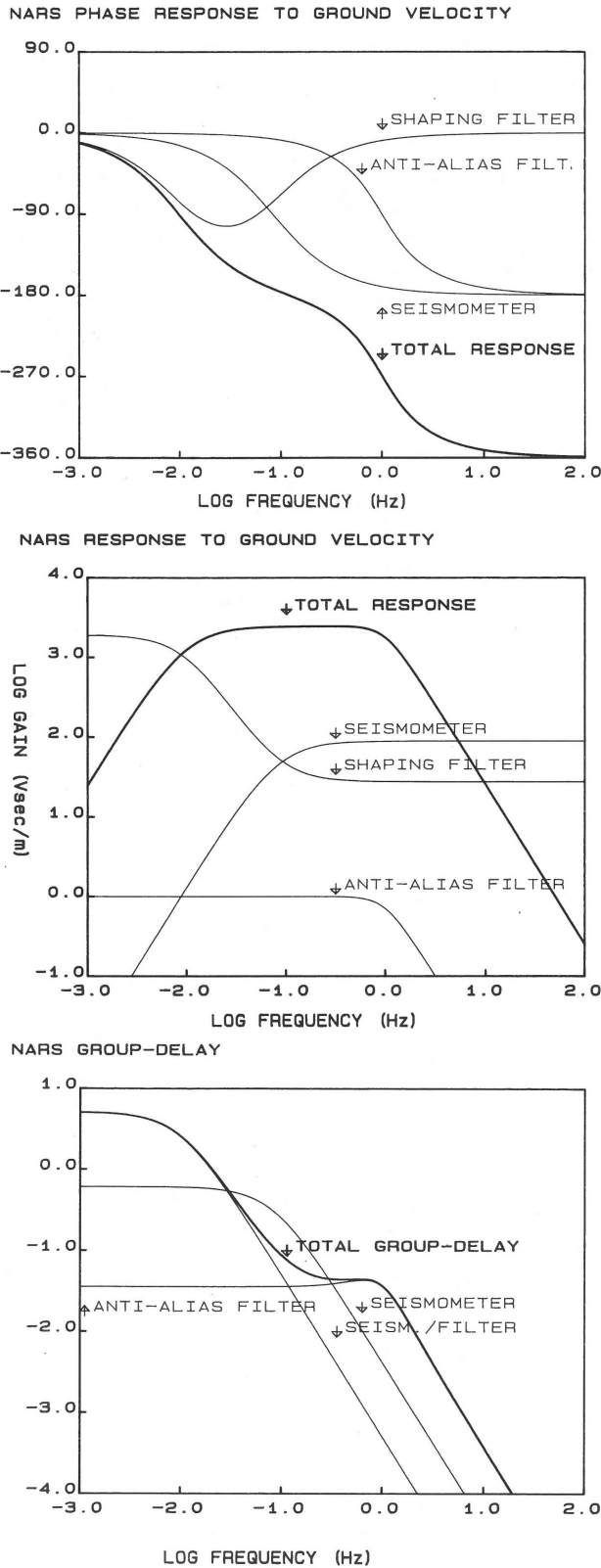


Fig. 6
 individual instrument responses and total system response, showing
 from top to bottom:
 Amplitude of the transfer functions in volts per meter per second
 as a function of frequency.
 Phase-shift in degrees as a function of frequency.
 Group delay in seconds as a function of frequency.

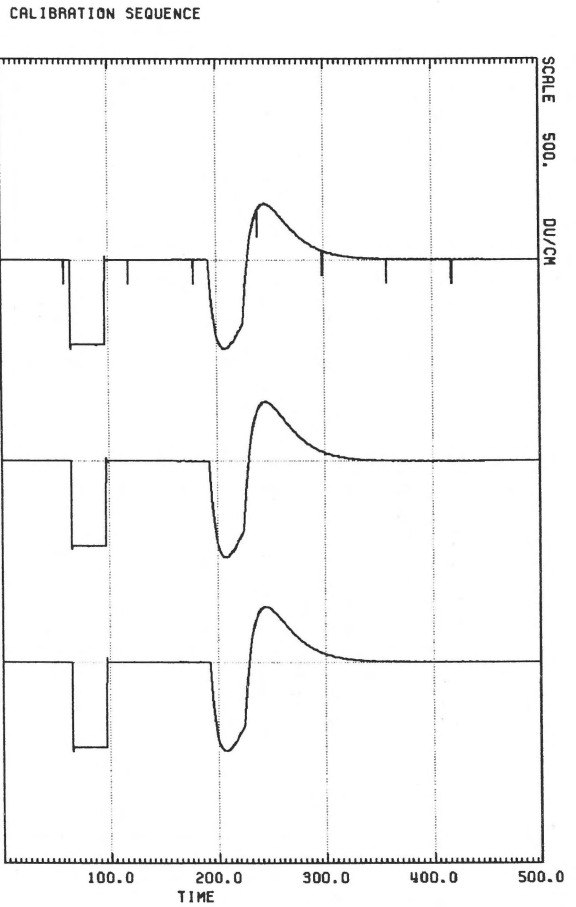


Fig. 7
 Registration of a system calibration. At the third component
 minutemarks are visible.

Comparison with other broad-band systems, e.g. the Graefenberg array (SEIDL & STAMMLER, 1984), is eased by showing the amplitude response to ground velocity in $Vs\ m^{-1}$ as well as the phase response in degrees and group delay in seconds. The transfer function $T_V(\omega)$ for the velocity then becomes:

$$T_V(\omega) = T_d(\omega)/(D_{max} i \omega) \tag{6}$$

Division by D_{max} translates DU to Volts. Results are shown in Figure 6.

SEIDL & STAMMLER (1984) show that the anti-aliasing filter determines mainly the leading edge of the onset of a phase on the seismogram. The use of a 7th order anti-aliasing filter may introduce an apparent delay in the arrival times of 0.1 second for a noise level of 10%. This can be a serious drawback, especially for a mobile array like NARS. In practice a 2nd order anti-aliasing filter has proved to be sufficient for NARS, and results in an apparent delay well below the sampling interval even for high noise levels.

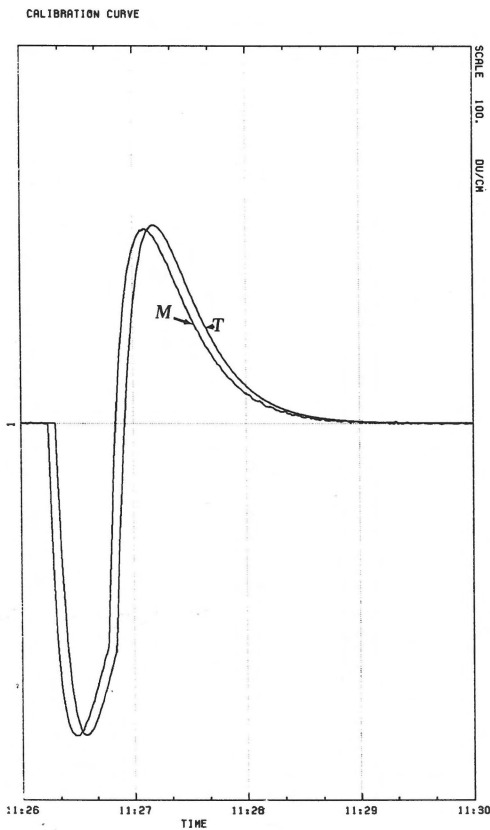


Fig. 8
A comparison between theoretical (T) and measured (M) calibration curves. Curves have been shifted in time to facilitate comparison.

SYSTEM CALIBRATION

The PDR-2 allows for automatic or semi automatic system calibration. In the automatic mode a calibration is done after each triggering and in the semi-automatic mode one can start the calibration from the keyboard. A blockpulse of -1.0 V, with a duration of 32 seconds, is applied to the calibration coil of the seismometers. Their responses to this pulse, together with the pulse itself are recorded on cassette tape. In practice at the beginning and at the end of a cassette tape a semi-automatic calibration is done, as the automatic mode is too tape consuming. An example of a recorded system calibration is given in Fig. 7.

At system calibration the calibration coil applies a step in acceleration (da) to the system, which can be calculated by:

$$da = G_{cal} I_{cal} / M \quad (7)$$

G_{cal} being the motor constant of the calibration coil ($.029 \pm .002$ N/A), I_{cal} the current through the calibration coil (-1.0 mA) and M the weight of the inertial mass of the seismometer (2.0 kg). The system response to da is:

$$A(w) = 2\pi \cdot da \cdot T_d(w) / (iw)^3 \quad (8)$$

and is given in DU s.

Figure 8 shows a comparison between the theoretical and recorded calibration curves. For sake of clarity an offset is introduced between the two curves. There are a number of methods already developed (see RASSON & DE MEYER, 1983 for references) to measure the instrument parameters from the recorded calibration pulse, so a check on instrument performance can be made. The peak to peak amplitude of the calibration curve however is poorly determined and may show variations up to 25%. This is due to station conditions, especially temperature fluctuations influencing the vertical seismometer and atmospheric variations working on the horizontal ones.

ACKNOWLEDGEMENTS

We like to thank Dr Wielandt for stimulating discussions and many helpful suggestions. The NARS project is financially supported by the Netherlands Organisation for the Advancement of Pure Research (Z.W.O.-A.W.O.N.)

REFERENCES

- Aki, K. & P. J. Richards 1980 Quantitative Seismology, theory and methods - Freeman (Town): 932 pp.
- Cloetingh, S. A. P. L., M. J. R. Wortel & N. J. Vlaar 1982 Evolution of passive continental margins and initiation of subduction zones - Nature 297: 139-142.
- Dost, B. 1984 Optimization of higher-mode surface-wave analysis with application to NARS-data-NARS progress rep 2: 1-15.
- Elektuur 1981 Universele tijdsein processor 215: 950-960.
- Melton, B. 1981 Earthquake Seismograph Development: A modern history - Part-1 - EOS (A.G.U. Trans.) 61: 505-511.
- Nolet, G. 1975 Higher Rayleigh modes in W. Europe - Geophys. Res. Lett., 2: 60-62.
- 1976 Higher modes and the determination of upper mantle structure - Ph. D. Thesis, Utrecht Univ.: 90 pp.
- 1977 The upper mantle under W. Europe inferred from the dispersion of Rayleigh modes - J. Geophys., 43: 265-286.
- Nolet, G. & G. F. Panza 1976 Array analysis of seismic surface waves: limits and possibilities - Pure Appl. Geophys. 114: 776-790.
- Nolet, G. & N. J. Vlaar 1982 The NARS project: Probing the Earth's interior with a large seismic antenna - Terra Cognita 2: 17-25.
- Rasson J. & F. De Meyer 1983 Calibration of long period seismic channels - Inst. Roy. Meteor. Belg., Publ. Ser. A 110: 49 pp.
- Seidl D. & W. Stammler 1984 Restoration of broad-band seismograms 1 - J. Geophys. 54: 114-122.
- Vlaar, N. J. 1982 Lithospheric doubling as a cause of intracontinental tectonics - Ned. Akad. Wet. Proc. Ser. B85: 469-483.
- 1983 Thermal anomalies and magmatism due to lithospheric doubling and shifting - Earth Planet. Sci. Lett. 65: 310-322.
- Wielandt, E. & W. Mitronovas 1976 An electronic long period seismograph for surfacewave dispersion studies - Seismol. Soc. Am. Bull. 66: 987-996.
- Willmore, P. L. 1979 Manual of Seismological Observatory Practice - World Data Centre A for Solid Earth Geophysics: 165 pp.
- Wortel, M. J. R. 1980 Age-dependent subduction of oceanic lithosphere - PhD Thesis, Utrecht: 147 pp.