The KTB Seismological Network

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ABSTRACT. A local broad-band seismological network has been installed around the German Continental Deep Drilling Site (KTB).

The most prominent seismic activity in the KTB surrounding takes place in the Vogtland area and the Cheb (Eger) basin. Macro- and microseismic events in the close vicinity have been also reported in the past. The KTB program provides the opportunity to record crucial seismic data for the investigation of intra-plate seismicity and crustal state of stress, accompanied by various other projects for determining the stress and strain in the earth's crust. Additionally it was considered to be important to monitor the seismic activity during the drilling operation in the near-field of the drill site. The network is designed to provide information for source parameter determination for all events with ML > 0.1 within 20 km of the KTB site.

The network consists of 4 seismic stations, one near the drill site and 3 remote-stations, azimuthally distributed in 10 km distance. Special seismic vaults have been constructed in left-open quarries with direct coupling to basement rocks. All stations are equipped with a 3-component broad-band seismometer Streckeisen STS-2, bandwidth 50 Hz - 360 sec, and an on-site 20 bit (nominal 120 db) data acquisition system, Lennartz MARS-88. Each analog channel input is sampled with 8 kHz and decimated to 125 Hz final sampling rate.

A central data center in the KTB field laboratory, using a Sun Sparcstation 1, communicates with each site via optical cable or telephone lines. The data recording is based on event detection at each station, using a standard STA/LTA algorithm including a minimum detection level. Trigger status information of the individual stations is transmitted once per hour to the data center, where coincidence is automatically checked. Full waveform data are transferred only, if the events have been detected at least at a given number of stations, presently 2.

Examples from the broad range of application demonstrate the excellent data quality and performance of the network. Differences in waveforms, amplitudes and frequency content are observed, even for teleseismic recording, where the aperture is small. The average seismic noise level at all stations is below 10 nm/s.

INTRODUCTION

The KTB-drill site is located in NE Bavaria at the SW extension of the cenozoic Ohre (Eger) rift, adjacent to areas with seismotectonic activity. The highest activity occurs predominantly in the form of earthquake swarms in the northern part of the Cheb (Eger) basin and the southern Vogtland and has been widely reported (Neunhöfer and Tittel, 1981; Procházková et al, 1987; Schmedes, 1987 and Antonini, 1987). The maximum macroseismic intensity I=V historically observed in the closer surrounding of the drill site, has it's cause in the strongest earthquakes from these areas. But also documented macroseismic observations from the past (Brunhuber, 1912; Gebrande and Schmedes, 1982) provide prove for a local seismic activity in the closer KTB surrounding proper. During seismometric pre-site surveys in the last ten years, using mobile stations, several local earthquakes with magnitudes ML=0.3-3.1 have been detected and localized within 20 km of the KTB site. The majority has its epicenters between Marktredwitz and Waldsassen, north of KTB. Therefore, the installation of a local seismic network around KTB was considered to be necessary, both for technical and scientific reasons.

The **technical aspects** are seismic risk, the safety of the drilling operation against seismic effects and the possibility of drilling induced seismic events. Environmental and forensic aspects may also be of concern. The present-day public sensitivity in environmental issues, could lead easily to an interpretation, that local seismic events might been caused or triggered by the deep drilling operation. Continuous monitoring and accurate hypocenter determinations of local events will be an indispensable prerequesite for a clear distinction between natural and man-made events.

A local seismological network provides important contributions to the **scientific objectives** of the KTB project, which is devoted to the 'Fundamental investigations of the physical and chemical conditions and processes in the continental crust to achieve a better understanding of the structure, composition, dynamics and evolution of intracontinental crustal regions' (Emmermann and Wohlenberg, 1989). Systematic investigations of the local and nearby seismic activity will address the general problems of intra-plate seismicity, crustal stress fields, physics of earthquakes, and the brittle-to-ductile transition in the earth's crust. Additionally, a seismic network around KTB, equipped with true broad-band 3-component seismometers gives the opportunity to study fundamentals effects of local and teleseismic wave fields in a heterogeneous , and presumable anisotropic crystalline environment. All investigations can take great advantages from the interdisciplinary research in and around the KTB borehole applying other methods, e.g. 3-D steep and wide-angle seismics, borehole logging and stress measurements.

In this paper we report, after a general geological description, on the design, installation, instrumentation and operation of the KTB Seismological Network. In the final chapter, we present selected examples of the broad spectrum of seismic recordings, like noise measurements, local and teleseismic events and an event caused by the drilling operation.

Geological and Tectonic Setting

The KTB drill site is located at the western margin of the Bohemian Massif, at the contact zone of the two southern units of the Variscan belt of Europe (Fig. 1): the Saxothuringian and the Moldanubian. A cryptic suture zone, resulting from the col-

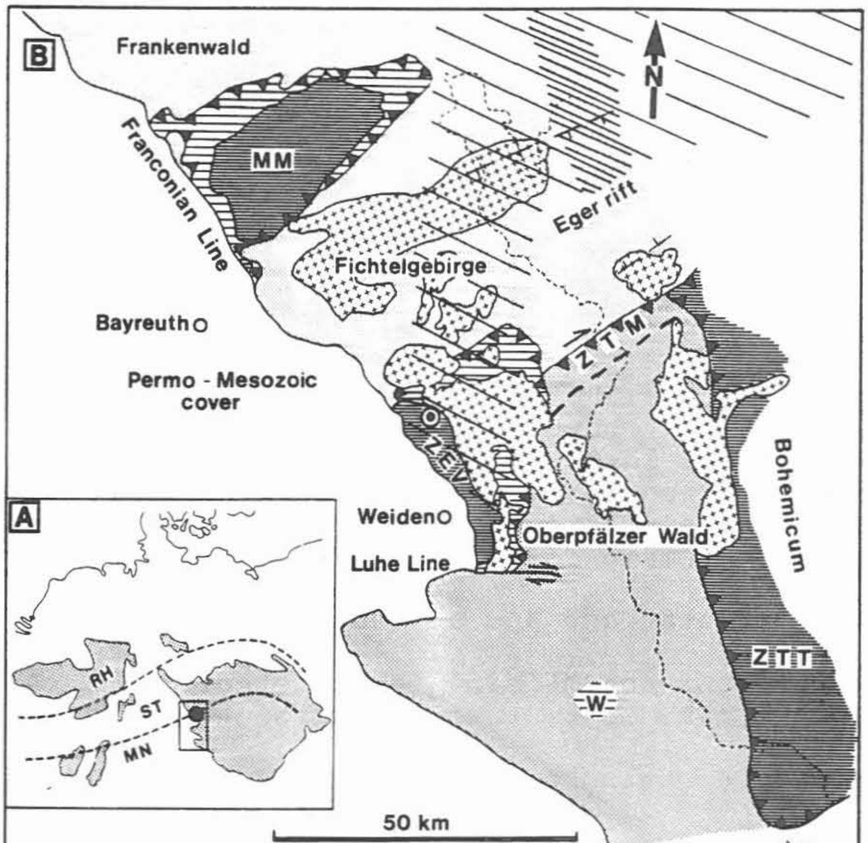


Fig. 1 Geological sketch map of the western rim of the Bohemian Massif in NE Bavaria from Weber (1990) with areas of low (I) and moderate (II) seismic activity superimposed.

A: Variscian basement outcrops in Middle Europe with zones according to Kossmat (1827). RH: Rhenoherzynian Zone; ST: Saxothuringian Zone; MN: Moldanubian Region. B: Geological map with the tectonometamorphic units. 1: crystalline nappe complexes; 2: basal units of the nappe complexes; MM: Münchberg nappe complex; ZEV: nappe complex of the Zone of Erbendorf-Vohenstrauß; ZTT: Zone of Tepla-Taus, forming the western part of the Bohemian terrane (Bohemicum); 3: Saxothuringian; 4: Moldanubian of the Oberpfälzer Wald; 5: late- to post-tectonic granites; 6: KTB drilling site. 7: overthrust; ZTM: Zone of Tirschenreuth-Mähring; W: Winklarn.

lision of the Saxothuringian plate in the northwest and the Moldanubian plate in the southeast about 320 million years ago, is overlaid by a sequence of paragneisses and metabasic units of more than 5,000 m thickness at the drill site (Emmermann et al., 1991). This overlay was last metamorphosed ca. 380 Ma ago and is called the Zone-Erbendorf-Vohenstrauß (ZEV).

The Saxothuringian/Moldanubian boundary is represented east of the KTB drill-site by the Zone-Tirschenreuth-Mähring (ZTM). In other parts it is covered by sediments of the Ohre rift and by Late Variscan granites (Franke, 1989). NW-SE crustal shortening and block-faulting had been predominant 340-320 Ma ago. Between 320 and 280 Ma ago post-tectonic granites intruded, as for example the Fichtelgebirge granites. Some intrusions follow the NW/SE-directed fracture zones, reflecting a system of block faults from Upper Carboniferous/Permian time. Some faults have been repeatedly reactivated, e.g. the Franconian Line. The youngest tectonic element is the Ohre rift of Oligocene to Early Quaternary age (Kopecky, 1986). Related Miocene sediments, basaltic pipes and lava flows are traced across the Franconian line into the Mesozoic foreland.

DESIGN and SITE SELECTION

The objectives of the KTB Seismological Network, generally described in the introduction, involve special requirements on its geometrical and instrumental design, which are specified by network density, frequency response and dynamic range (Willmore 1979). It also has to be capable to monitor continuously 24 hours per day. The main design parameters are:

1. the number of stations and appropriate geometry

2. the lowest magnitude ML(min) to be detected and the maximum magnitude ML(max) to be recorded without clipping

3. to solve for earthquake focal mechanism

Design parameter 1 was specified by the condition to obtain reliable hypocenter locations down to 15 km at the KTB site, the original target depth. Although a larger number of stations would have been necessary, a 4 station network was chosen as a compromise with the central station (NOTT) at KTB and 3 remote stations (FALK, NAPF, ROTZ) in 8-10 km distance (Fig. 2). The central station, 650 m south of the drill site is near enough to record even very small events, e.g. related to drilling, but already far enough to avoid severe disturbances by noise, generated by the drilling operation, like shakers, mud-pumps, generators, etc. (Schmedes, 1988). A description and the geographic coordinates are listed in Table 1a and Table 1b.

Considering the generally weak seismicity of the area and the number of seismic events in the past, an event of magnitude ML=0.1 up to a distance of 20 km from KTB ought to be detectable. For the same epicenter distance (Marktredwitz/Waldsassen) a magnitude ML=3.1 event should not cause saturation. These are conditions on acceptable ground noise, system gain, frequency response and dynamic range. To obtain a signal-to-noise ratio of at least 10 for a magnitude 0.1 event at 20 km distance, standard magnitude relations require, that the short period RMS-noise should not exceed 40 nm/s. The final sites fulfill this demand and were selected after an extensive site survey during Oct/Nov 87 for the central site and Jan-Sep 89 for the remote sites. We used 4 digital Lennartz PCM 5800 Data Acquisition Systems of the DEKORP Group; see also Table 3 below. A total of 18 sites (Fig. 2) has been tested.

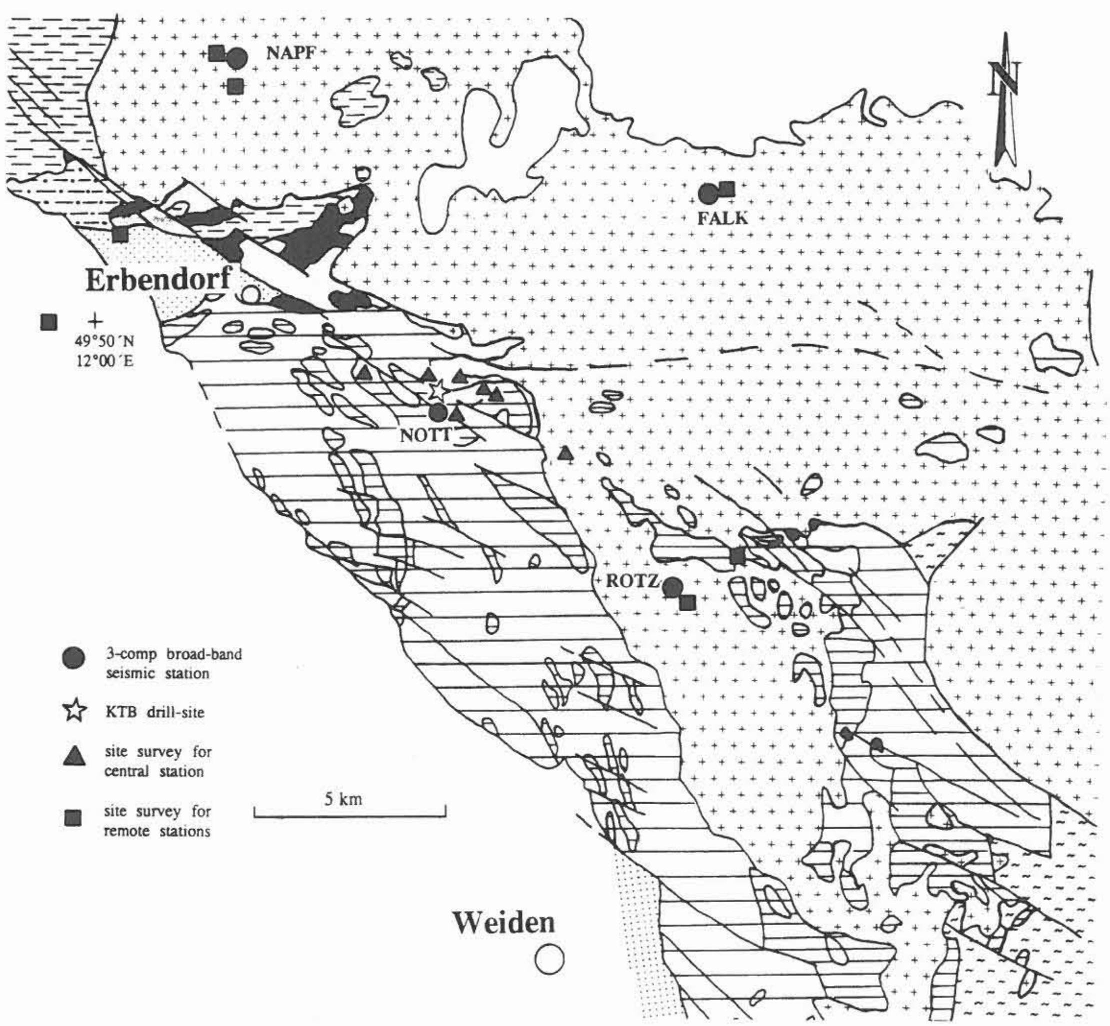


Fig. 2 Station locations of the KTB Seismological Network and the site survey.

The system gain has been selected to resolve the minimum design event of magnitude ML=0.1 with 10 bits. Another 60 db (10 bits), resulting in a total of 20 bit dynamic range, are required to record the maximium design event ML=3.1 without saturation (see design parameter 2). This can be provided by the Lennartz MARS-88 in combination with the Streckeisen STS-2 seismometer, therefore chosen.

Tab. 1a Description of the seismic sites of the KTB Seismological Network.

Geographic Location	Station Code	ID[1]	Geological Setting[2]	Remarks
Nottersdorf	NOTT	83	calc-silicate bearing amphibolite with small intercalations of marble	650 m S of KTB; left-open quarry at small settlement; neighboring road; farming noise during the day; quiet site during the night
Rotzenmühle	ROTZ	84	granodiorite to diorite	8.5 km SE of KTB; left-open quarry; near small old mill randomly in operation; very quiet site
Falkenberg	FALK	86	Falkenberg granite	9 km NE of KTB; man-caved cellar of old farm house in small village; local noise during the day
Napfberg	NAPF	87	Steinwald granite	10 km NW of KTB; left-open quarry in forest state park; very quiet site

[1] manufacturer identification number of the data acquisition system recorded in the header of the data blocks

[2] Stettner, 1990

Tab. 1b Coordinates of the stations of the KTB Seismological Network and the KTB drill sites.

Station Code	Latitude	Longitude	Heights N.N.	Comments
NOTT	49° 48.659′	12° 7.338′	490 m	
ROTZ	49° 46.068′	12° 12.502′	430 m	
FALK	49° 51.635′	12° 13.490′	465 m	
NAPF	49° 53.324′	12° 3.104′	695 m	
KTB-VB	49° 48.980′	12° 7.160′	513.418 m	pilot hole
KTB-HB	49° 48.980′	12° 7.320′	513.753 m	main hole

For the study of focal mechanism (design parameter 3) the network fulfills only the minimum requirements by the number of stations and their azimuthal distribution. This is, however, partially compensated by the consequent 3-component recording of the wave field. From the theoretical point of view it would be ideal to record frequencies as high as possible, especially for the weak events, as observed here. Due to limitations of the seismometers and the data transmission the frequency band has been bound to 50 Hz.

By the chosen station spacing of ca. 10 km, the network acts at the same time as a teleseimic array with almost optimal suppression of the microseismic noise. Using a period of 6s (see Fig. 9 below) and a wave velocity of 3 km/s, the wavelength would be 18 km. Henger (1975) determined for the nearby (50 km SW) Gräfenberg Array (GRF), but located in the sediments of the Franconian Jura, an optimal station spacing of 10 - 12 km for a triangular teleseismic subarray. Therefore the KTB Seismological Network can be regarded with its installation on basement rock, as an excellent supplement to the Gräfenberg Array.

INSTALLATION

Three of the four sites (NOTT, NAPF, ROTZ) have been selected in open quarries no longer in use.

A construction company broke a niche into a side-wall of the quarry. After constructing a small building of approximately 3 by 4 meters, the niche has been refilled with loose material (gravel, soil) on the sides, the back and the top to isolate against external temperature variations. The longitudinal section of a station is shown in Figure 3. The inside of the building is divided by an internal wall into two chambers, the electronic chamber in front with the outside door, and the seismic vault in the back. In the latter the seismometer and the so-called host-box are installed on a pier with 70 cm in diameter and ca. 50 cm in height. To avoid coupling of the seismic pier with the building, the bedrock in the seismic vault has been left exposed. The seismometer is shielded by two Styrofoam boxes against temparture fluctuations.

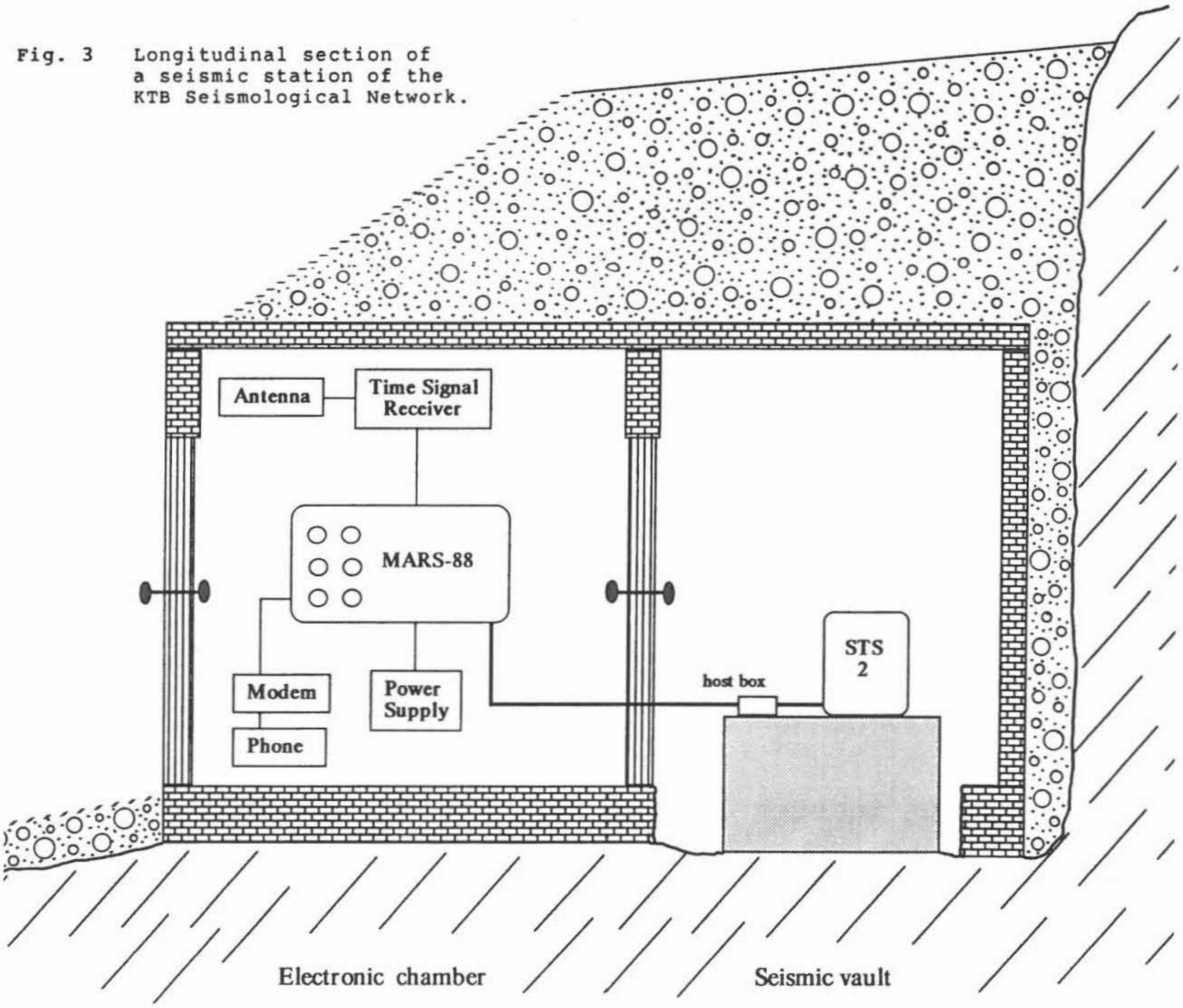
The electronic chamber houses the on-site data-acquisition system, the time signal receiver, communication devices (modems, phone or optical-cable connection), power supply system and power back-up devices. During a station visit usually only the electronic chamber needs to be entered. Only in cases of manual initiated recentering of the mass position of the seismometer it is required to open the door to the seismic vault. For fresh-air circulation, there are two air-holes in the front-wall of the building. A timer controlled ventilator has been installed, to reduce humidity in the electronic chamber, if needed.

The forth station (FALK) is set up in an old cellar, dug horizontally 15 m into the granite. The cellar belongs to an old farm house constructed against the hillside and no longer in use. Therefore the electronic equipment has been set up in a cabinet in the farm house appr. 20 m from the seismic vault to avoid problems caused by humidity. To insure good coupling to the basement rock the top of the granite (5-10 cm) has been removed before cementing the seismometer pier. The pier is located at the end of the cellar being inclosed by a front- and side-wall to avoid thermal convection. The exposed granite ceiling has been cemented to prevent intrusion of water.

Also at station NAPF, the electronic equipment has been set up ca. 20 m from the seismic vault in a refurbished quarry building, still having the same station layout as NOTT and ROTZ.

The principle layout of the seismic vault and the electronic chamber is for all stations identical. Only the electrical power supply differs for station NAPF, where a solar system with 12 V DC has been installed (APPENDIX 1a). All other stations are supplied by 220 V AC by the public electricity system (see APPENDIX 1b).

Fig. 3 Longitudinal section of a seismic station of the KTB Seismological Network.



SEISMOMETER

The seismic sensor used is a 'Portable very-broad-band triaxial Seismometer' STS-2 by Streckeisen AG Messgeraete.

All 3 sensors are identical and housed in a single sealed, cylindrical, vacuum-tide package including the electronics and power conditioning. The 3 sensors (Fig. 4) are obliquely inclined to the base plate with the azimuthal differences being 120 degrees. The orientation of the sensors is factory-adjusted.

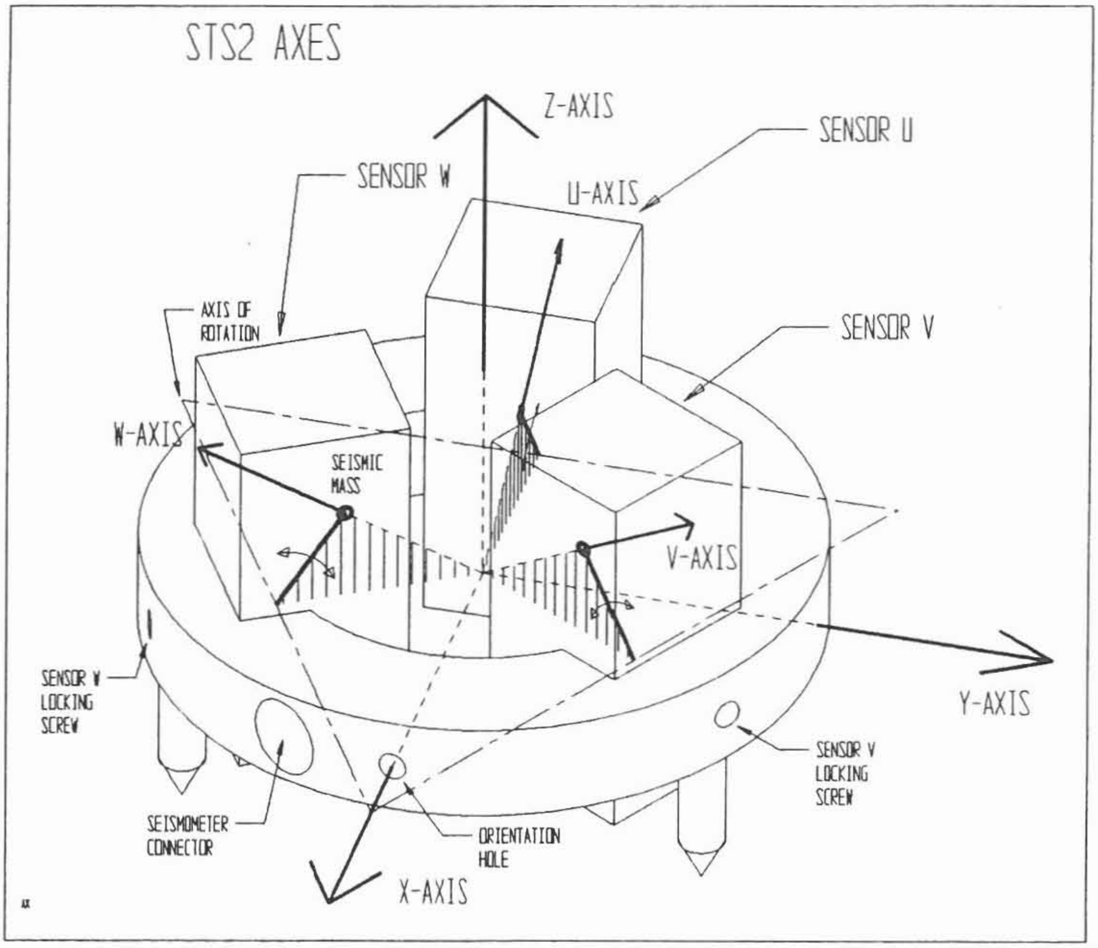


Fig. 4 Schematic of the STS-2 very-broad-band seismic sensor. (from Streckeisen AG Messgeraete)

The raw signal output of the sensors are electrically summed by the seismometer electronics providing standard vertical and horizontal seismic signals. By having no precise information of the geometrical specifications, the sensors can not be calibrated by the user.

The installation is quite simple and only two steps are required: the azimuthal orientation and horizontal leveling. To obtain standard output signals the X-axis has to be aligned towards east by using a manufacturer supplied rod. There is no external pressure shielding required.

The STS-2 uses the force-feedback principle, like the STS-1 (Wielandt and Streckeisen, 1982), with the broad-band signal output being proportional to ground velocity with a nearly flat velocity response between 120 sec and 50 Hz (Fig. 5a,b). For frequencies below 1 Hz the transfer function for the seismometer response to ground displacement at frequency f is given by the manufacturer as

$$T(f) = 2*pi*i*f*S / (1-2*i*fo*h/f - (fo/f)**2)$$

with

S = generator constant, 1500 Vs/m
fo = corner frequency, 1/120s
h = fraction of critical damping, 0.707

Between 1 and 10 Hz and above 10 Hz the velocity response is specified being flat within ±0.15 db and ±1.5 db (±1.5% and ±15% in amplitude) respectively. The manufacturer-given specifications are listed in APPENDIX 2a,b.

The output, calibration, control signals and power are accessible through 2 connectors of a so-called host-box for monitoring purpose and remote control. It houses also a DC/DC converter. The required DC voltages are derived from 10 - 30 V DC external supply, here provided as stabilized 12 V DC from the MARS-88 Data Acquisition System, described below.

Automatic recentering of the mass can be initiated manually by pressing a pushbutton at the host-box or remotely by an autozero command. To avoid a long impulse response decay of the seismometer the low-corner frequency of 1/120 Hz is changed automatically to 1 Hz during the autozero cycle. All 3 sensors are being recentered during the cycle one after the other.

Fig. 5a STS-2 Velocity Response (from Streckeisen AG Messgeraete).

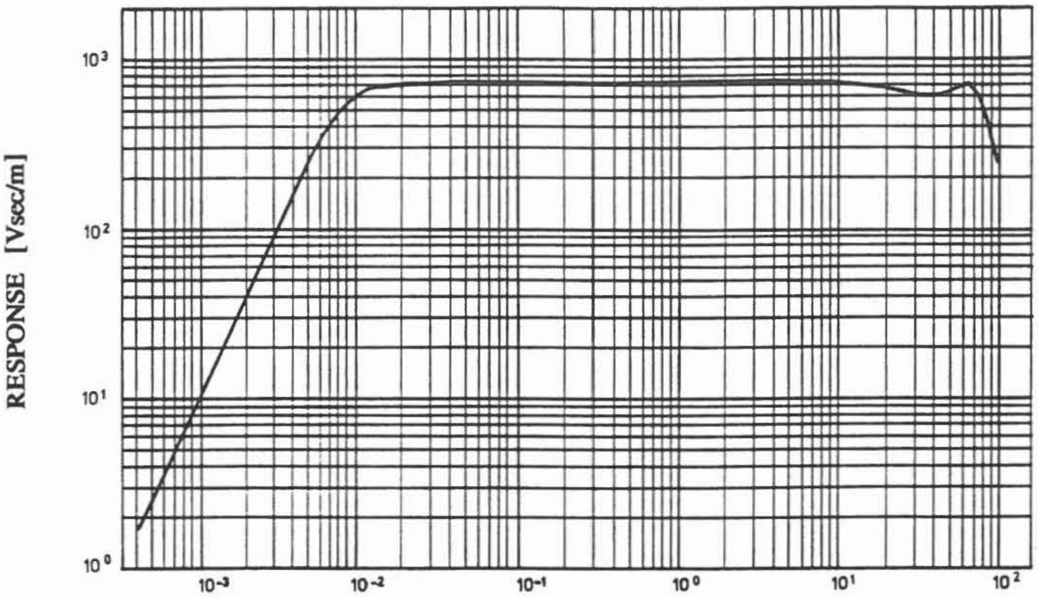
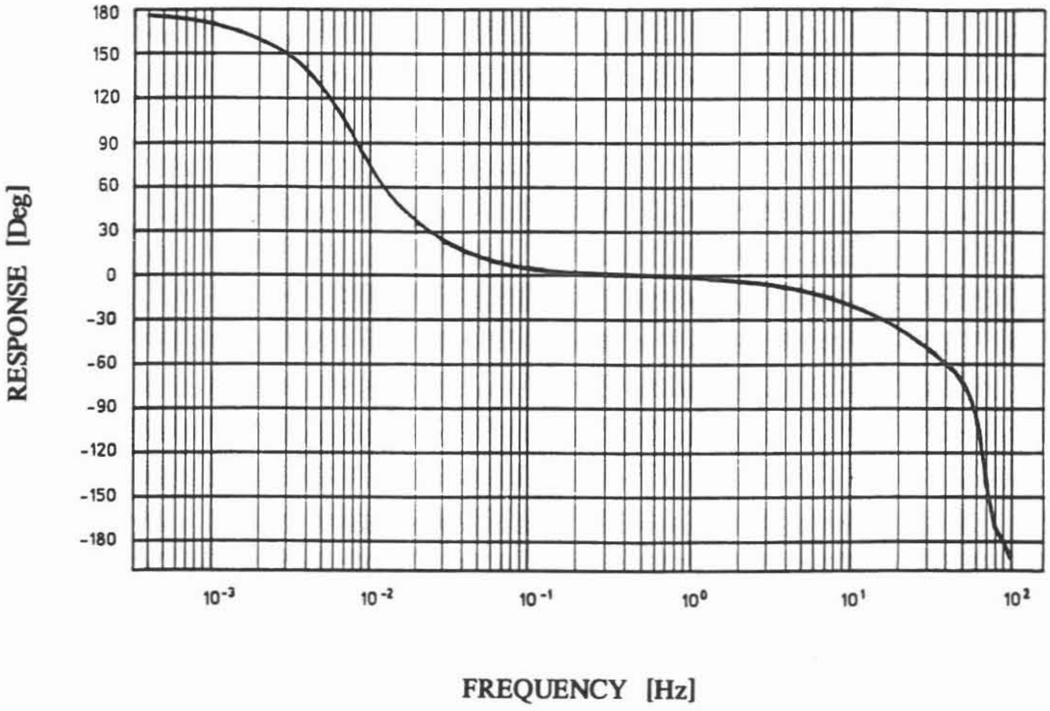


Fig. 5b STS-2 Phase Response (from Streckeisen AG Messgeraete).



DATA ACQUISITION SYSTEM and DATA CENTER

The network consists of 4 autonomous stations with a direct link to the data center in the KTB field laboratory (Fig. 6). The main data stream, processing and management during acquisition is done at the individual seismic sites using the MARS-88 Data Acquisition System (manufacturer specifications see APPENDIX 3). The MARS-88 includes the pre-amplification, a 16 bit analog-to-digital converter, decimation filter, event-detection, intermediate data storage and manages the data transfer on request by the data center.

The basic operations of the MARS-88 are shown in Figure 7. All channels are independently, but simultaneously sampled. The primary sample rate of 8 KHz per channel is decimated in a real time signal processor using a FIR filter algorithm (Heute, 1978). Thereby an enhanced resolution of 20 bit is obtained at the output sample rate of 125 Hz. The resulting bandwidth of the seismic signal is 50 Hz, that means, data are stored with an effective oversampling of 2.5 only. The sampling rate of 125 Hz has been chosen to fit the demands for high frequency resolution of the network.

Independently of the parameter setting of triggered or continuous recording, a continuous data stream is stored as a floating point 16 bit word (13 bit mantissa, 3 bit exponent) in a static CMOS-RAM of 4 MB. With the present sampling rate of 125 Hz this provides 88 min of continuous 3-component output data in the buffer at each site.

Parallel the data stream is checked for events by an event-detection algorithm (Fig. 8). After bandpass-filtering using two-pole butterworth filters, a short-term average STA is compared with a long-term average LTA multiplied by a given trigger RATio plus a minimum trigger LEVel (capital letters characterize the corresponding commands of the MARS-88).

The present trigger parameter settings for station NOTT are listed in Table 2 and are identical for all sites, except for station FALK, where the trigger RATio has been set to 4.0 on all channels. The parameter SCAle presents the pre-amplifier setting of 8 μV per LSB of the original 16 bit word or 500nV (0.332 nm/s) for the LSB of the 20 bit word. The LEVel has been set to 8 counts, equivalent to 16 μVolts (10.666 nm/s). The UPTime parameter defines for how many consecutive data samples the STA value must be above the threshold. In case of a detected event, the 'central monitoring program' will 'index' the data in form of a status log. After the 4 MB data buffer has been filled, all data not indexed, will be overwritten. The PRE- and POSt-event times are 32 and 100 sec respectively. The PRE-event time has been chosen to record even weak P-phases of local events, when the trigger conditions are fulfilled only by S-Phases.

Since all digital data acquisition and data management tasks are performed at each individual site, the main tasks of the data center are to communicate periodically with each network station, decide which data should be transmitted to the center, store the data in a data base and provide tools for data

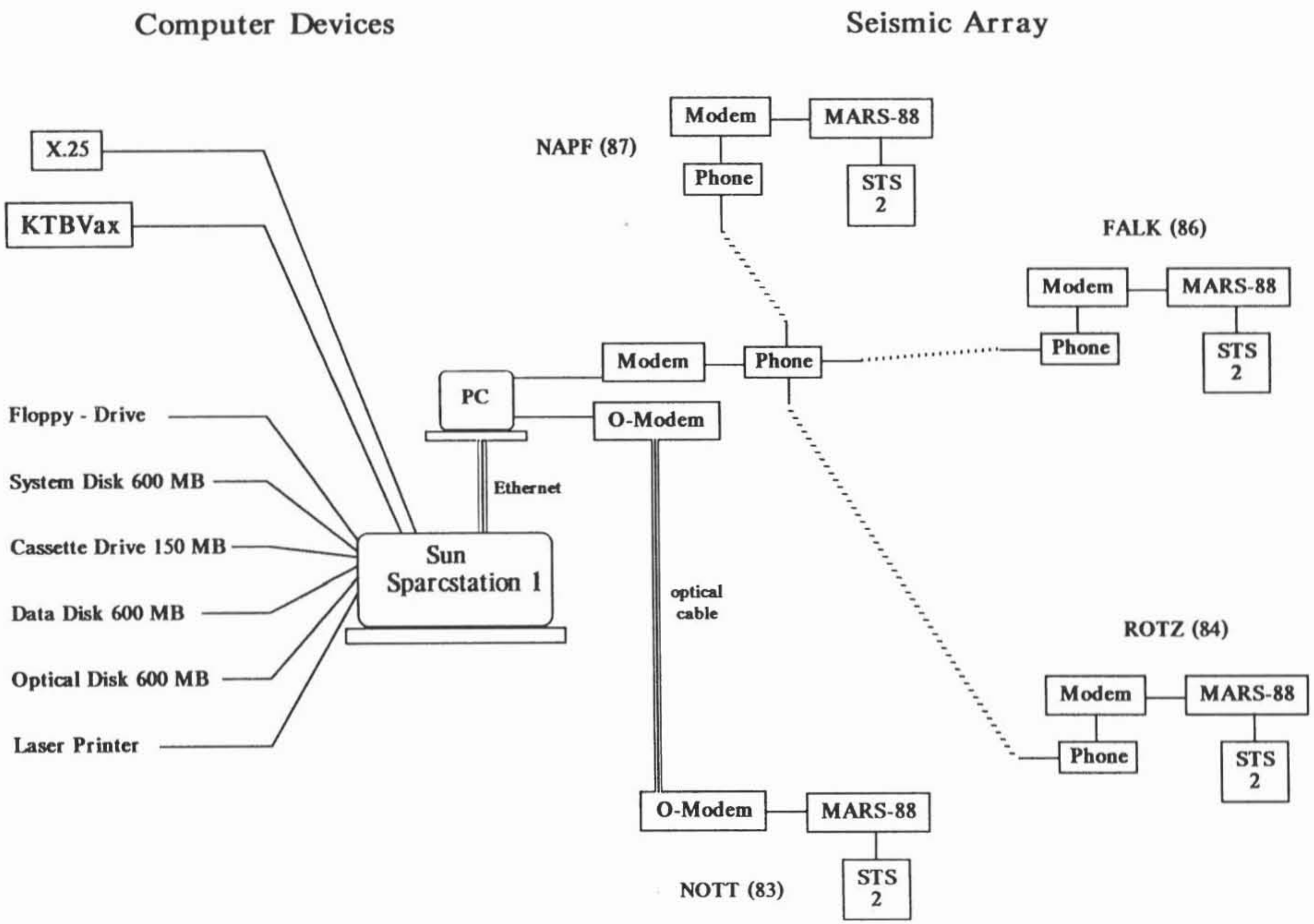


Fig. 6 Hardware and Instrumention of the KTB Seismological Network.

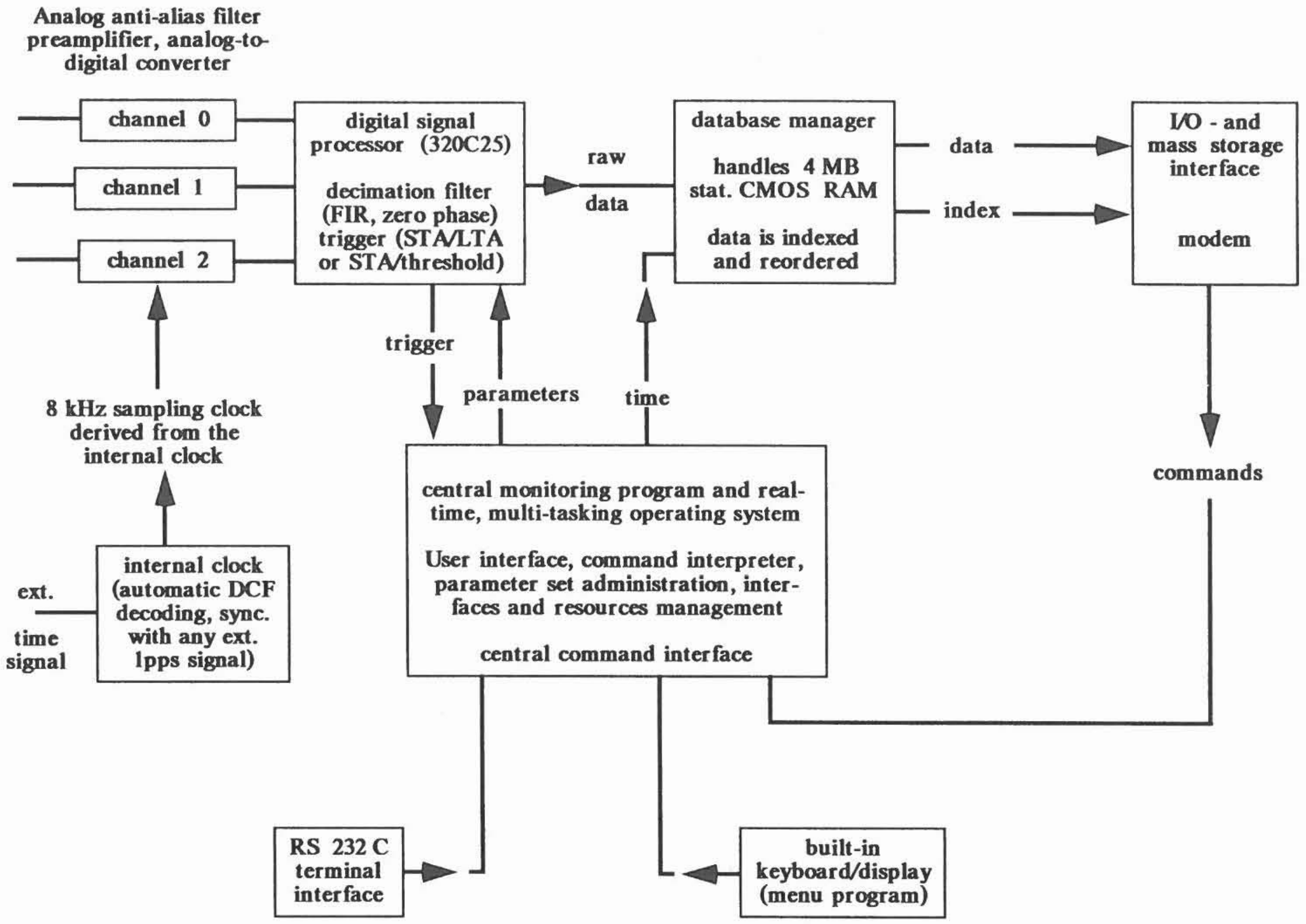


Fig. 7 Diagram of the MARS-88 main logical building blocks.
(from Lennartz electronic GmbH)

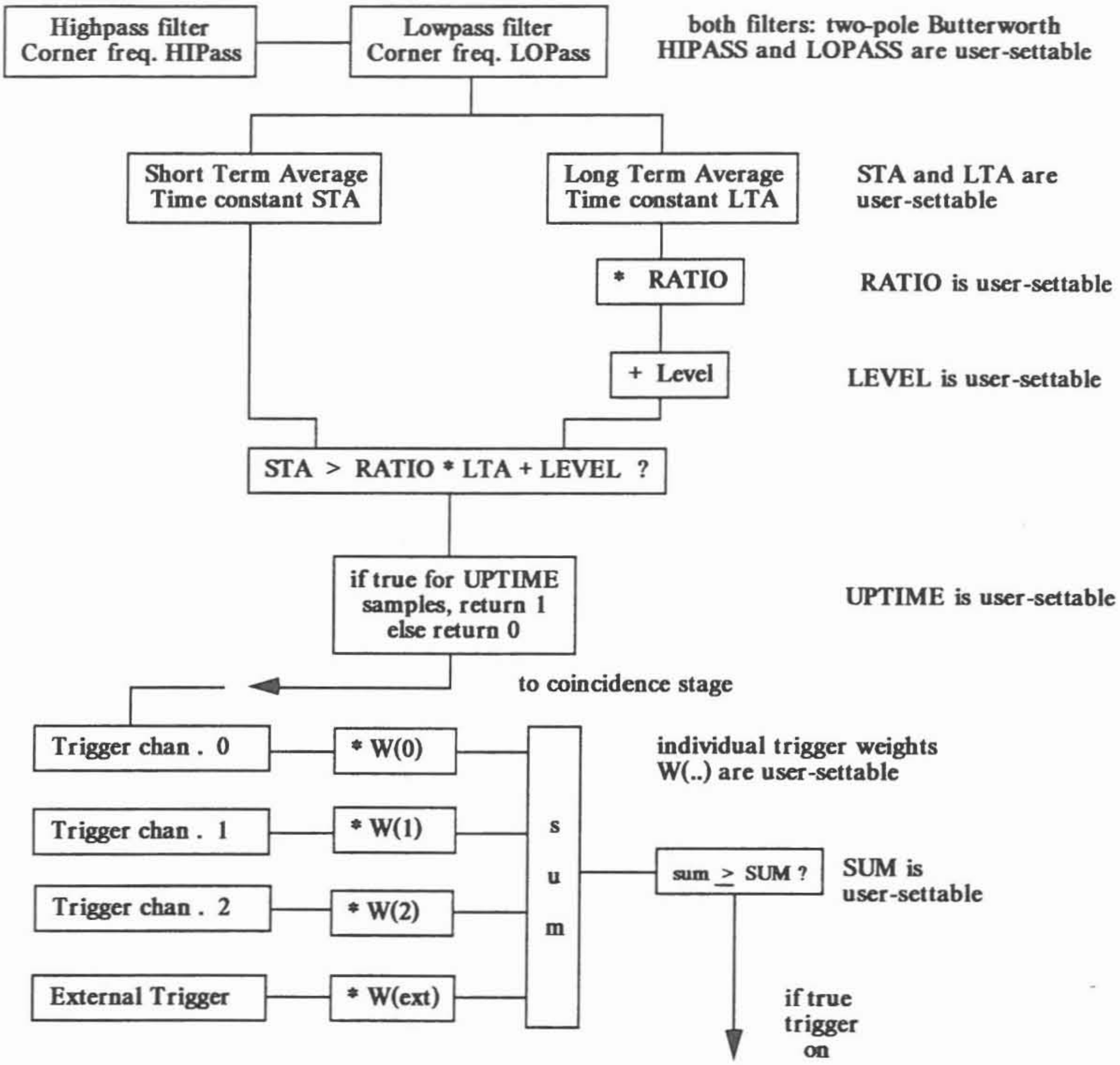


Fig. 8 Diagram of the MARS-88 triggering system.
(from Lennartz electronic GmbH)

processing.

By having a 88 min continuous data buffer on the seismic site, we use a dial-up cycle of every hour to request the status information. The status information is compared for coincidence and in a second dial-up cycle all coincident data are indexed network-wide. This includes data which had been not detected as an event at each site, but on at least two. Data recognized as events only by one station will be reset to none-triggered status. Only for station NOTT near the drill site, all locally triggered data are requested independently of coincidence with other stations. (This will allow to record weak events triggered by the drilling operation.) In a third cycle indexed data will be transmitted to the data center. These networking operations are handled by the 'MARS-88 Modem Control-and Gateway-Module' software.

Tab. 2 Trigger parameter settings of the MARS-88 at the seismic stations of the KTB Seismological Network; output from the MARS-88.

```
MARS-88/MC              device id 00083   UDP/IP remote interface

1> date 1992 Feb 05
1> time 16:46:15 UTC
1>
1> SELected parameter set: 0
TEXt: "KTB-Lokalarray Station Nottersdorf"
SAMple rate:  8 msec [bandwidth DC..50 Hz];   3 CHAnnel(s)
PRE_event time: 8 block(s) [32 s], POSt_event time: 25 block(s) [100 s]
COIncidence sum: 2;   MONitor channel off

Parameter       |     Channel 0    |     Channel 1    |     Channel 2  [ext]
----------------+------------------+------------------+------------------
SCAle           |        8         |        8         |        8
----------------+------------------+------------------+------------------
Trigger WEIght  |        2         |        1         |        1          0
Trigger UPTime  |        8         |        8         |        8
STA time const. |   .025 [  2 s]   |   .025 [  2 s]   |   .025 [  2 s]
LTA time const. |   .001 [ 50 s]   |   .001 [ 50 s]   |   .001 [ 50 s]
Trigger LEVel   |       8 counts   |       8 counts   |       8 counts
Trigger RATio   |     3.000        |     3.000        |     3.000
Low  pass corner|  .050 [  6 Hz]   |  .050 [  6 Hz]   |  .050 [  6 Hz]
High pass corner|  .004 [  2 s]    |  .004 [  2 s]    |  .004 [  2 s]
----------------+------------------+------------------+------------------
1>
1> exponent 3
1> measurement on
1> sync_mode 2   # automatic time setting DCF-77
1>
```

After the routine network-wide calls the incoming data are stored in a commercial database system, under the control of the 'MARS-88 Data Base Module'. The database, implemented for seismological applications by Lennartz electronics GmbH has been structured in two levels, the event and raw data level. On the event level, selected information like time of data blocks, maximum amplitude of each data block and their location in the raw data level is stored to provide the user quickly with information without the need to access the whole data. On the raw data level, the waveform data are stored as standard UNIX files using the C-ISAM (Indexed Sequential Access Method for C language) commercial product of Informix Software, Inc.. This allows a convenient and time saving data handling and book-keeping by any standard UNIX routines.

We are using for example the seismic analysis software package XPITSA (X-Window Programmable Interactive Toolbox for Seismological Analysis), by F. Scherbaum and J. Johnson, 1992 from Lennartz electronic GmbH, with direct access to the database. Additional database software, like SQL (Structured Query Language) and ESQL/C (Embedded SQL for C) has been implemented. It will allow to integrate results from data analysis, e.g. earthquake parameters, into the database, for example in forms of tables. They can be tailered by the user, and later consequently used as the input to further analysis steps.

TIMING

To keep the individual station fully autonomous each site is equipped with its own DCF-77 time signal receiver of 50 Hz bandwidth, precision of ±1ms over temperature and a signal delay of 12 ms with 2ms variance. This external time signal is continuously and automatically decoded and compared with the internal clocks of the MARS-88. An automatic synchronization follows, if needed. In general, the DCF-77 time signal is constant available and of high quality. Therefore, with the high precision of the internal clocks of the MARS-88, the individual station times can be considered to be within the variance of the delay times of the individual time signal receivers. The time corrections of the internal time against DCF-time are recorded in the header of the data blocks.

COMMUNICATION

Presently, all communication links are established from the data center. On request by the networking software on the Sun Sparcstation 1 a PC, performing as a gateway, is setting up the communication link to the requested site. The communication to the central site is done by optical cable with a baud rate of 19,200 BPS and by telephone to the remote site, using USDS V.3240 Modems from Motorola GmbH with a baud rate of 9,600 BPS and Data Compression with a factor of 2 using MNP Protocol. The modem settings are listed in APPENDIX 4.

DATABASE and EXAMPLES OF DATA

Since recording started with the central site selection in October 1987 an extensive database has been collected. The continuous operation started in January 1989 with a network of 4 stations. This includes the period of site selection, construction, installation, with the final configuration in June 1991, up to present. Almost a complete set of triggered data is available for this time period. For details of the network development and recording see Table 3.

The database consists of local, regional and teleseismic recordings, with a huge number of events of artificial origin. The latter are mainly quarry and mine blasts, but also the shots of the seismic experiments of ISO 89, MVE 90 and CSFR refraction profiles have been recorded.

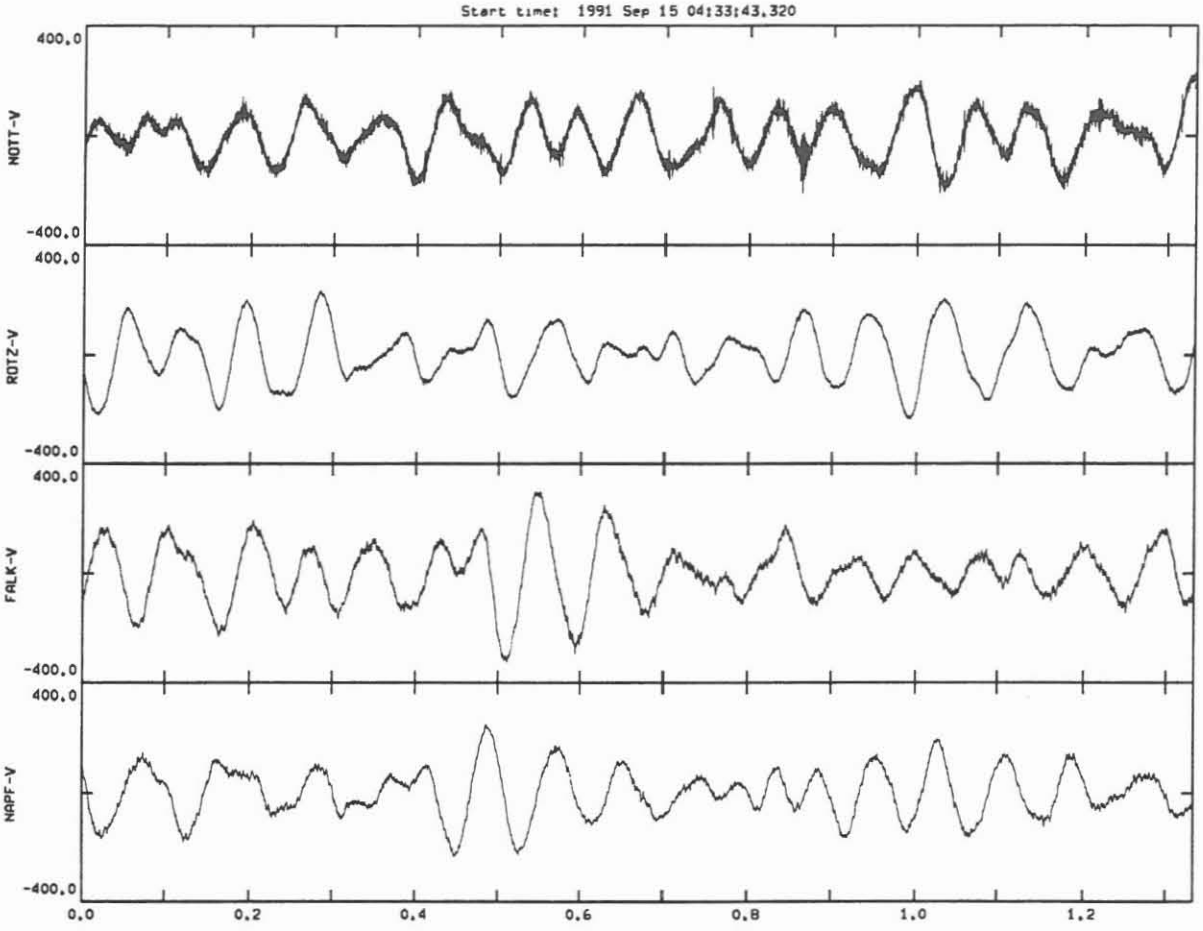
Tab. 3 Database and developement of installation at the KTB Seismological Network

time period	data acquisition system		sampling rate	seismometer	no. of stations	installation	comments
Oct 87-Nov 87	PCM 5800 (Tape)	12 bit	200 Hz	3-comp 1 Hz Mark L-4C	2	field	site selection central station
Nov 87-Jan 89	PCM 5800 (Tape)	12 bit	200 Hz	3-comp 1 Hz Mark L-4C	1	field	at central site
Jan 89-Sep 89	PCM 5800 (Tape)	12 bit	200 Hz	3-comp 1 Hz Mark L-4C	4	field	site selection remote stations
Sep 89-Sep 90	MARS-88 (Floppy)	16 bit	125 Hz	3-comp 1 Hz LE-3d	4	field	at selected network sites
Sep 90-Feb 91	MARS-88 (Modem)	16 bit	125 Hz	3-comp 1 Hz LE-3d	4	vault	networked
Feb 91-Jun 91	MARS-88 (Modem)	16 bit	125 Hz	3-comp broad-band STS-2	4	vault	networked
Jun 91-present	MARS-88 (Modem)	20 bit	125 Hz	3-comp broad-band STS-2	4	vault	networked

Noise measurements

The efforts for choosing good sites and in the installation are resulting in high quality data. Figures 9, 10, 11 are showing for the same time window, broad-band data, 1 Hz high-pass filtered data and spectra, as an example of seismic noise measurements. The data have been recorded early Sunday morning, a period of generally lower noise, than daytime and/or weekdays, but during the drilling operation.

The **long period noise** on the vertical component of all stations is of the same amplitude (Fig. 9a). Already here we can observe the higher noise level in the high frequencies of sta-



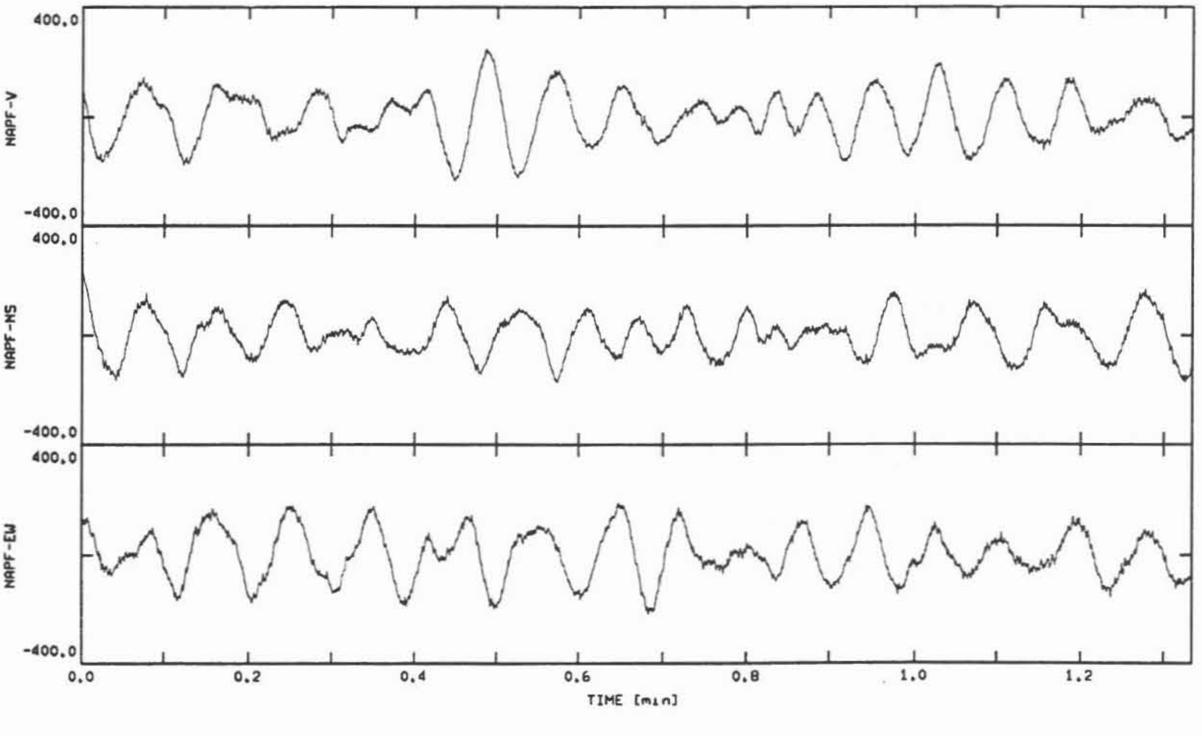
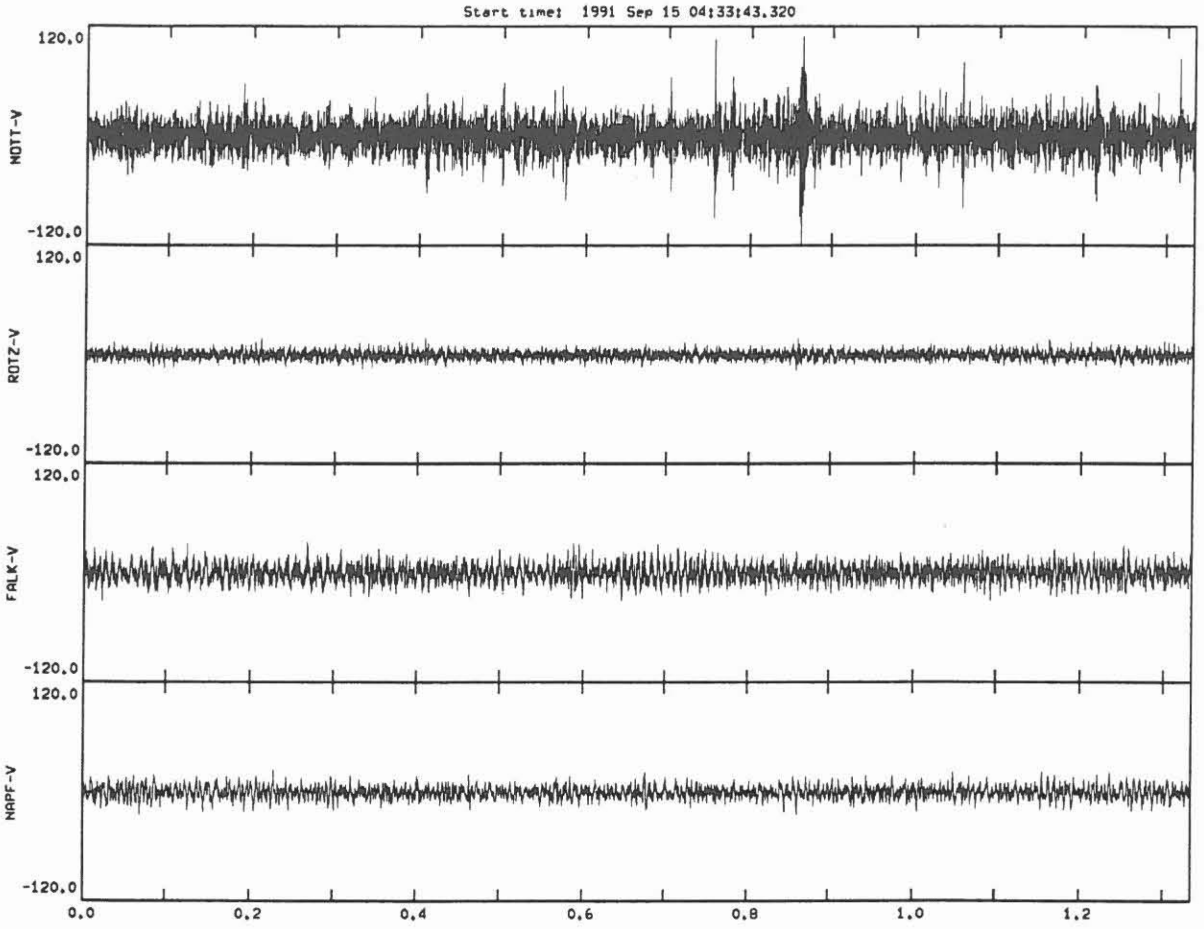


Fig. 9a (top) Broad-band seismic noise measurements in nm/sec of all 4 vertical components of the KTB Seismological Network. The dominating microseismic periods are superimposed at station NOTT with high frequencies from the drilling operation.

Fig. 9b (bottom) Broad-band seismic noise measurements in nm/sec of the 3 components of station NAPF.



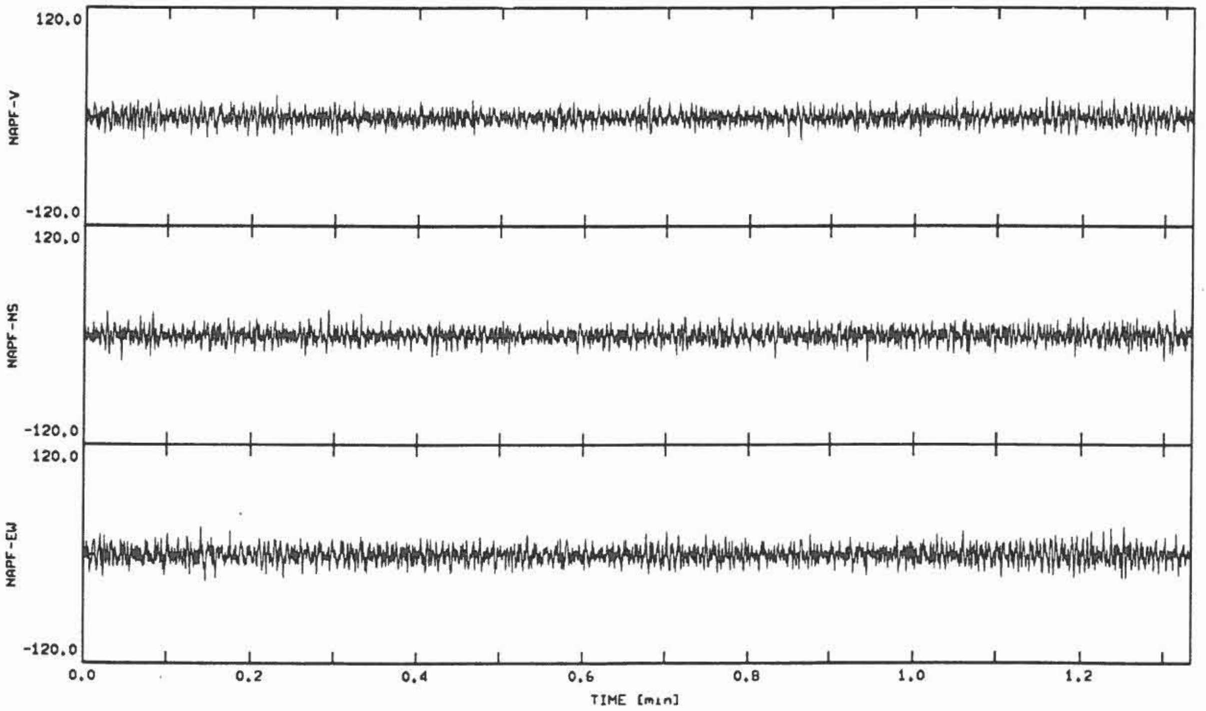
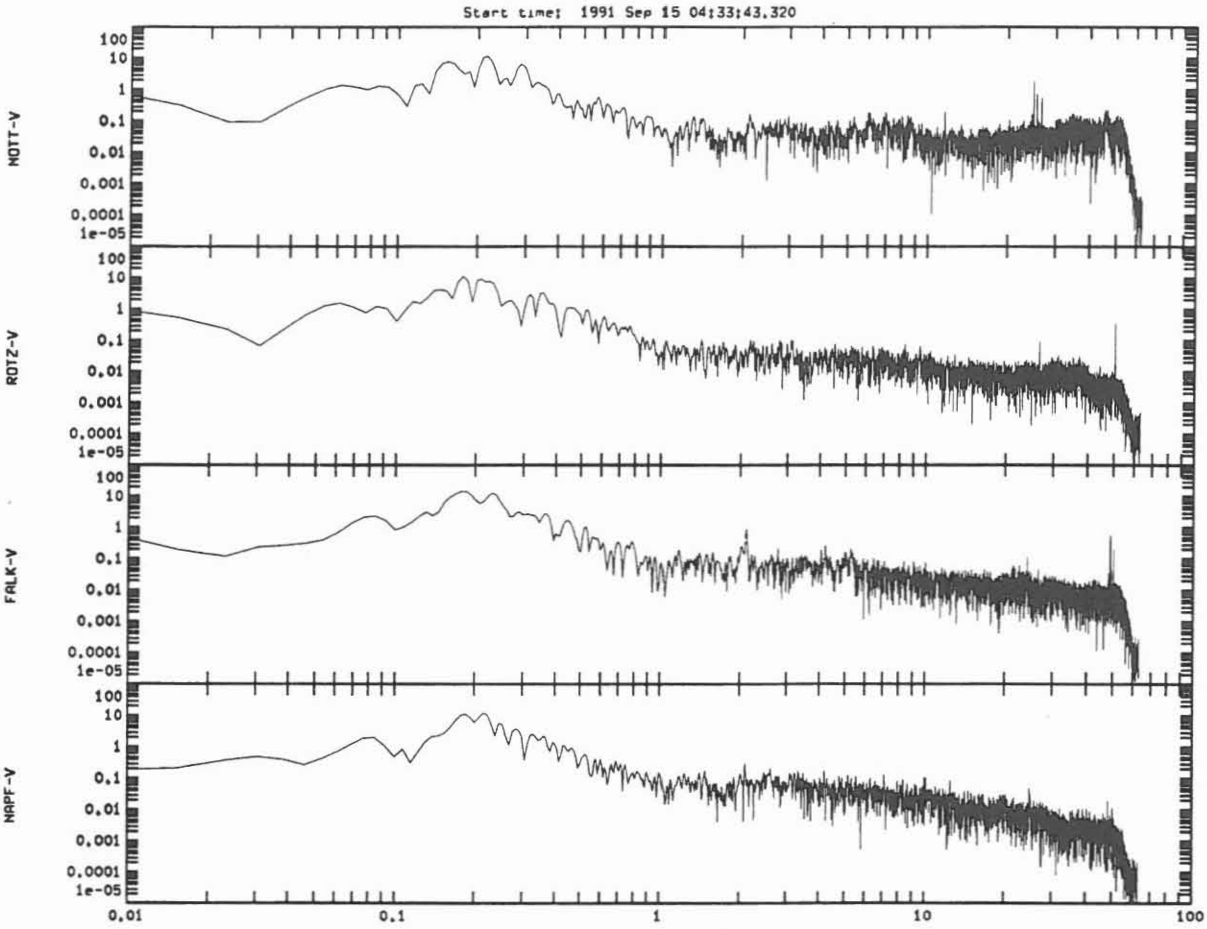


Fig. 10a (top) 1 Hz highpass filtered seismic noise measurements in nm/sec of all vertical components of the KTB Seismological Network. The higher noise level at station NOTT is caused by the drilling operation.

Fig. 10b (bottom) 1 Hz highpass filtered seismic noise measurements in nm/sec of the 3 components of station NAPF.



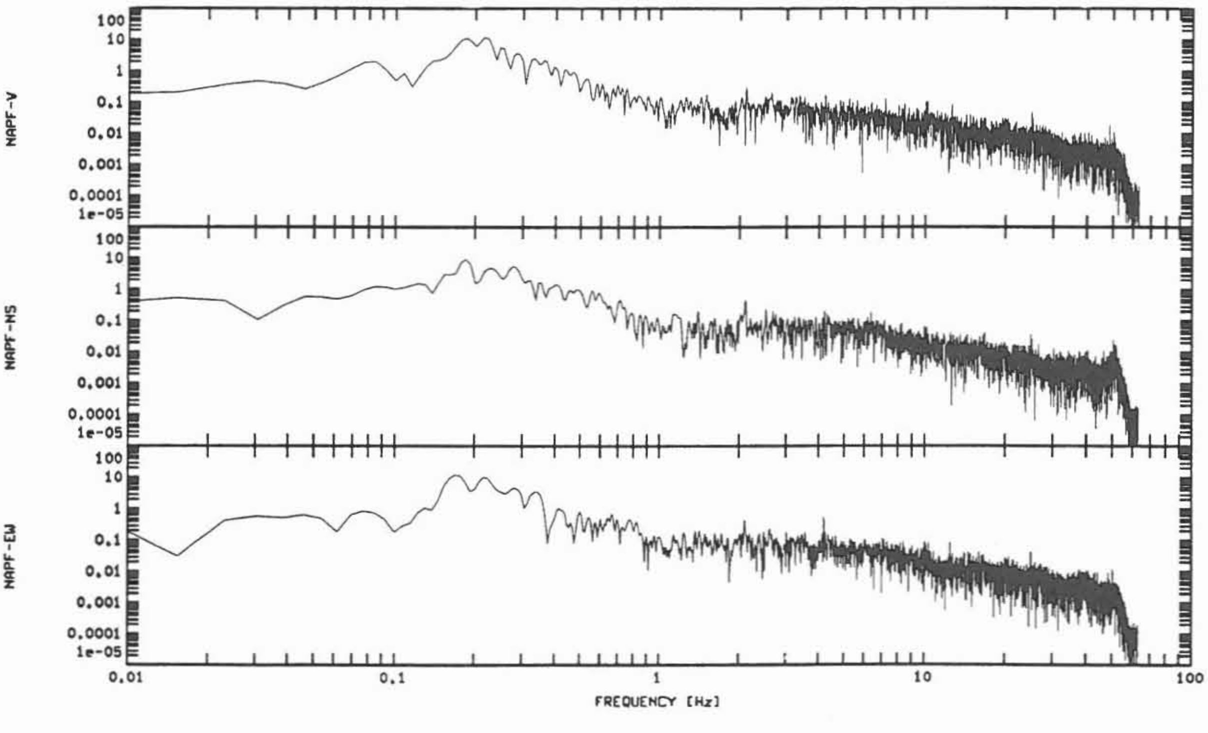


Fig. 11a (top) Spectra of the broad-band seismic noise measurements in (nm/sec)/Hz of all vertical components of the KTB Seismological Network, using 10,000 data points.

Fig. 11b (bottom) Spectra of the broad-band seismic noise measurements in (nm/sec)/Hz of the 3 components of station NAPF, using 10,000 data points (80 sec).

tion NOTT, caused by the drilling operation. There is no obvious coherence in the microseismic periods, even the extend of the array is within the microseismic wavelengths. A simple stack of the vertical components of all stations results in a maximum amplitude in the shown window of 685 nm/sec, which is only 2/3 of sum of the maximum amplitude of the individual traces (1010 nm/sec), e.g. the microseimsic noise is quite efficiently reduced as compared to the theoretical expectation of (SQRT 4)=2 for uncorrelated noise. In Figure 9b, showing the 3 components of station NAPF, the horizontal components have almost the same amplitude as the vertical component, indicating a superposition of Rayleigh and Love waves. In the 1 Hz high-pass filtered section (Fig. 10a) the **high-frequency noise** of the drilling operation is dominant at station NOTT. The quality of the sites, see station NAPF (Fig. 10b), is reflected by the fact, that the noise on the horizontal components is hardly greater than on the vertical components.

The above observations are confirmed by the spectra shown in Figure 11. In the long period range, the spectra for the vertical components (Fig. 11a) are very similar. Station NOTT shows more energy in the period range above 2 Hz, but mainly above 10 Hz. The energy at around 25 Hz is expected to be caused by the shakers, cleaning the drill-mud (Müller, Bochum; pers. communication). A disturbance by the public power supply system is indicated by energy at 50 Hz at station FALK and ROTZ. In comparison station NAPF is supplied with 12 VDC by a solar power system and shows no energy above the average noise level at 50 Hz.

For periods of low noise, as nighttimes and weekends, and for times without drilling, the average noise level for frequencies above 1 Hz is for all sites below 10 nm/s (Tab. 4), with station NAPF having the lowest noise level. For periods of higher noise, like daytimes, the noise level is for NAPF and ROTZ usually still below 10, for FALK and NOTT between 12-15 nm/sec.

Tab. 4 Average noise level at the KTB Seismological Network for the 1 Hz high-pass filtered seismic traces in Figure 10; RMS values in nm/s.

station code	vertical comp	NS-comp	EW-comp	comments
NOTT	15.61	15.22	15.46	during drilling
ROTZ	4.36	8.39	6.53	- " -
FALK	9.04	13.61	11.90	- " -
NAPF	6.76	7.18	8.27	- " -

Local event close to the **drill site**

One of the local events recorded is shown in Figure 12. The event is located 6 km north of the drill site within the seismic network.

Origin time: 91-Apr-16 23:40:18.7 UTC,
LAT 49.87 N, LONG 12.13E, Depth 7 km,
ML=0.3 with ML(NAPF)=0.5, ML(FALK)=0.6,
ML(ROTZ)=0.1, ML(NOTT)=0.1
(using Bakun and Joyner, 1984).

A significant difference can be seen in the P/S-amplitude ratio dependent on the azimuth to the hypocenter. This is reflected by the variation of the local magnitudes. The epicenter is located at the south-east foot of the Steinwald ridge at an intrusion of tertiary basalts. The 3-D seismic survey of DEKORP finds a major south-east dipping reflector about 500-600m below the calculated depth of the event (Stiller, 1991). From the first motion a nodal plane orientation is expected to be between N-S and NW-SE.

Local event from the **Vogtland** region

Figure 13 shows a recording of a local event near Adorf in the Vogtland region, 55 km north of KTB. It is the first event of a swarm of almost 100 events within 3 days.

Origin time: 91-Mar-24 05:05:06.5 UTC,
LAT 50.28 N, LONG 12.22 E, depth 13 km,
ML=2.5 (using Bakun and Joyner, 1984).

For this event, the first motion polarity is identical on all stations. For other events of this swarm the polarity of the first motion is usually not uniform within the network, thereby providing important information for the orientation of the nodal planes. There are significant differences in the amplitudes from station to station (Fig. 13a). The vertical components show simple S-arrivals besides station NAPF, which generally shows more complicated signals and increased energy between 10 and 20 Hz for local and regional events, but surprisingly not in noise measurements.

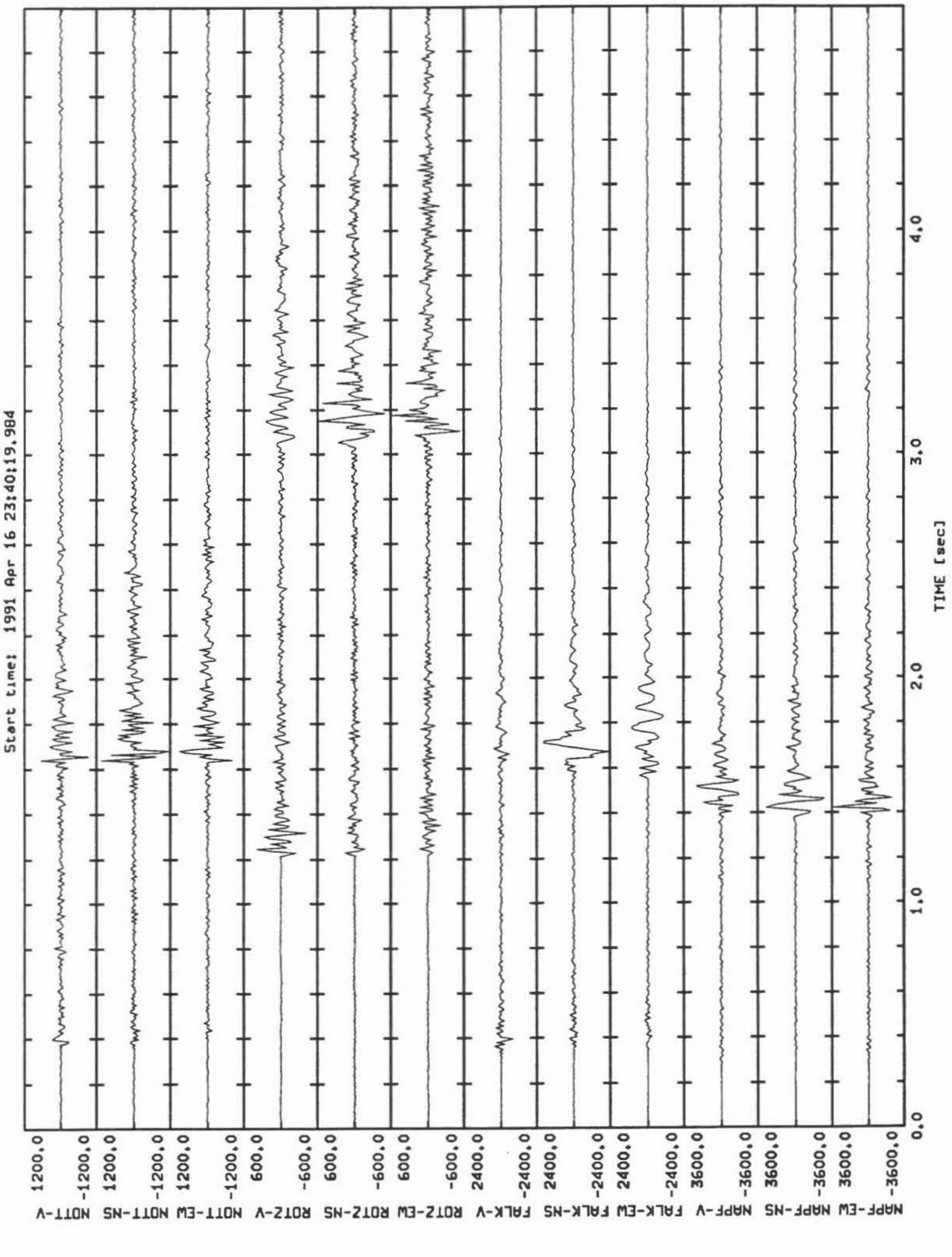
Teleseismic recording

A teleseismic recording of a deep event at Fiji Islands is shown in Figures 14 and 15.

Origin time: 91-Aug-28 21:32:35.9 UTC,
LAT 22.028 S, LONG 179.622 E, depth 605 km,
MB=5.5 (after QED/USGS).

The broad-band recordings of the vertical components of all stations and the 3-components of station NAPF are shown in

Fig. 12 Local seismic event 6 km north of the KTB drill site, recorded at the KTB Seismological Network (in nm/sec); origin time: 91-04-16 23:40:18.7 UTC, Lat. 49.87N, Long. 12.13E, depth 7 km, ML 0.3; amplitude scaling: 1:1.5/3/6 for NAPF:FALK/NOTT/ROTZ.



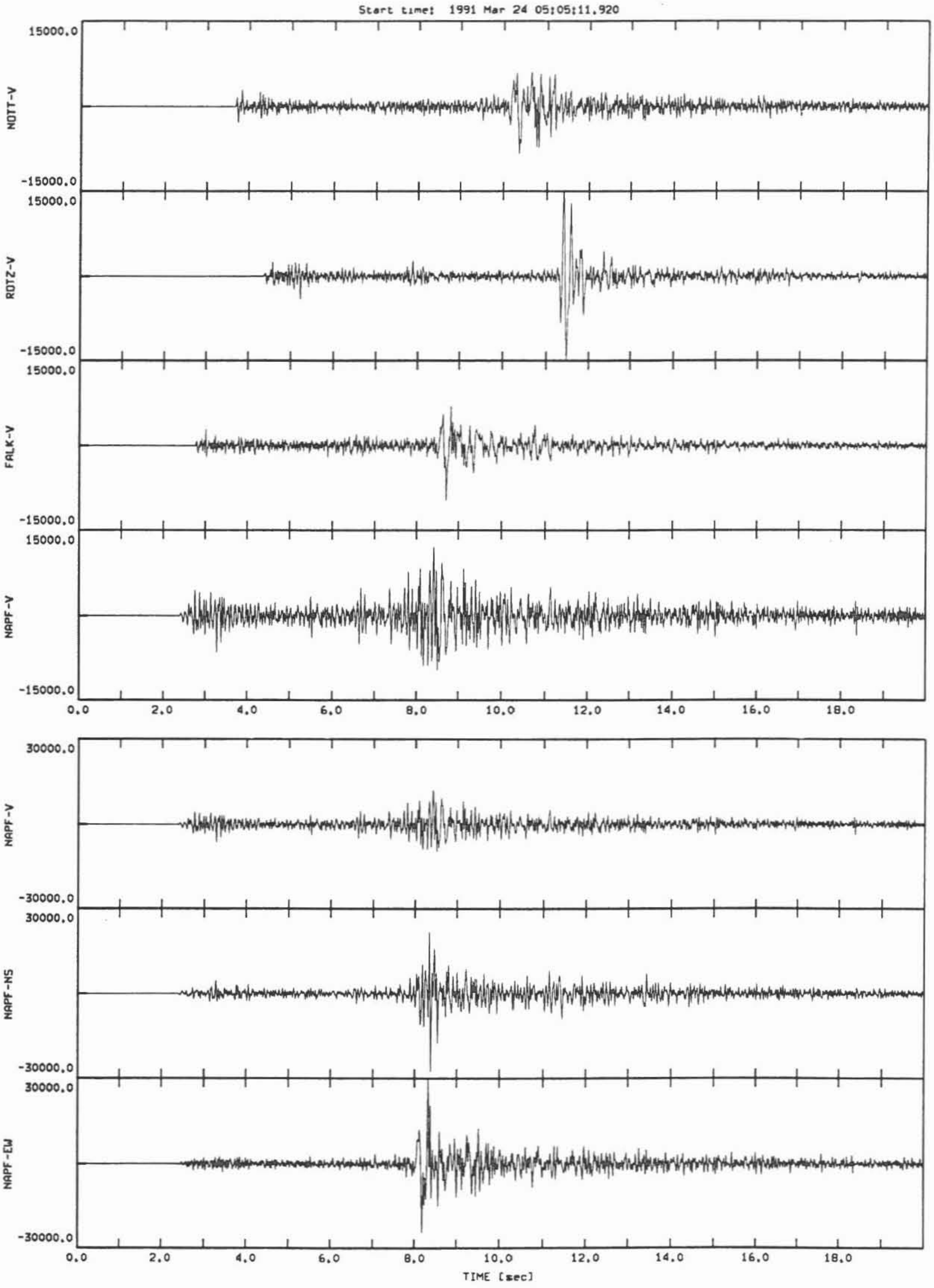


Fig. 13a,b Local event from the Vogtland area recorded at the KTB Seismological Network (in nm/sec); origin time: 91-03-24 05:05:06.5 UTC, Lat. 50.28N, Long. 12.22E, depth 13 km, ML 2.5;
a (top) all 4 vertical components; **b** (bottom) 3 components of station NAPF.

Figure 14a,b, the same data, but band-passed filtered between 2 Hz and 2 sec in Figure 15a,b. Three core phases PKIKP, PKP1 and PKP2 can be clearly identified. The coherence is quite good, but differences between stations are obvious. For example station NAPF and FALK, both located in granite, have equal amplitudes of PKP1, but greater than the other two stations. There is a significant amount of high frequency signal content, which reaches up to 5 Hz (Fig. 16).

Event caused by the **drilling operation**

As final example an event caused by the drilling operation and recorded at station NOTT is shown (Fig. 17). The event was caused by the use of the Jar-King, a drilling-tool from Eastman-Christensen, designed to free the drill string, if stuck. On 91-Dec-08 the Jar-King was used below 5200 m in the KTB borehole with a jarring force in upward direction. The jarring load was 620 kN. The 1 Hz high-pass filtered 3-component recording (Fig. 17a) shows strong signals on the vertical and the NS-, but little energy on the EW-component. This would be difficult to explain, if the signal would originate from 5200 m depth. The larger NS-component and the low frequencies of 2-8 Hz may indicate, that only the rebound vibrations of the derrick have been observed. All recordings, presently compared, show identical wave-forms for jarring upwards. Even if details of the seismic signals are not yet fully understood, their monitoring is useful for the drilling operators.

CONCLUSION

The concept of a very-broad-band 3-component seismological network at KTB has been successful realized. It is operational in its final configuration since June 1991. First results demonstrate its broad range of applicability and the excellent data quality.

Acknowledgement. The installation and equipment for the KTB Seismological Network was made possible by the financial support of the Ministry of Research and Technology of the Federal Republic of Germany (BMFT) research grant RG8804-4/AZA07 and by the German Research Foundation (DFG) research grant So 72/41. We like to thank the KTB project management, especially Kurt Bram, Geological Survey of Lower Saxony (NLfB), for the continuous support and for providing laboratory space in the KTB field laboratory. We gratefully acknowledge the support and assistance of the personnel of the KTB field laboratory, specifically of the KTB computing center.

The DEKORP steering committee and the Free University of Berlin, provided us with instruments for the site survey. The technical staff of the Institute of General and Applied Geo-

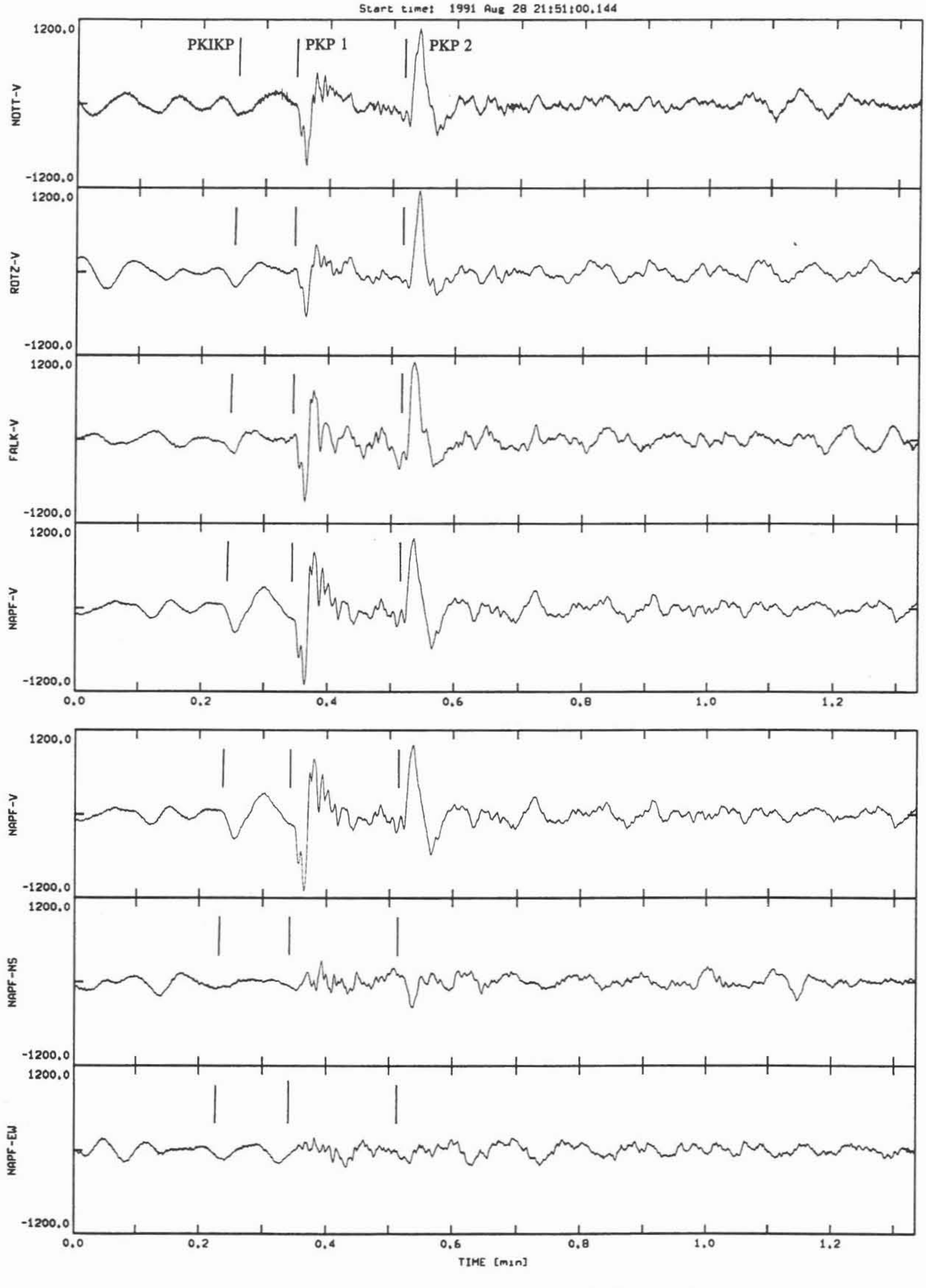


Fig. 14a,b Core phases of teleseismic event from Fiji Islands recorded at the KTB Seismological Network (in nm/sec); origin time: 91-Aug-28 21:32:35.9 UTC, Lat. 22.028 S, Long. 179.622 E, depth 605 km, MB=5.5.
a (top) all 4 vertical components; b (bottom) 3 components of station NAPF.

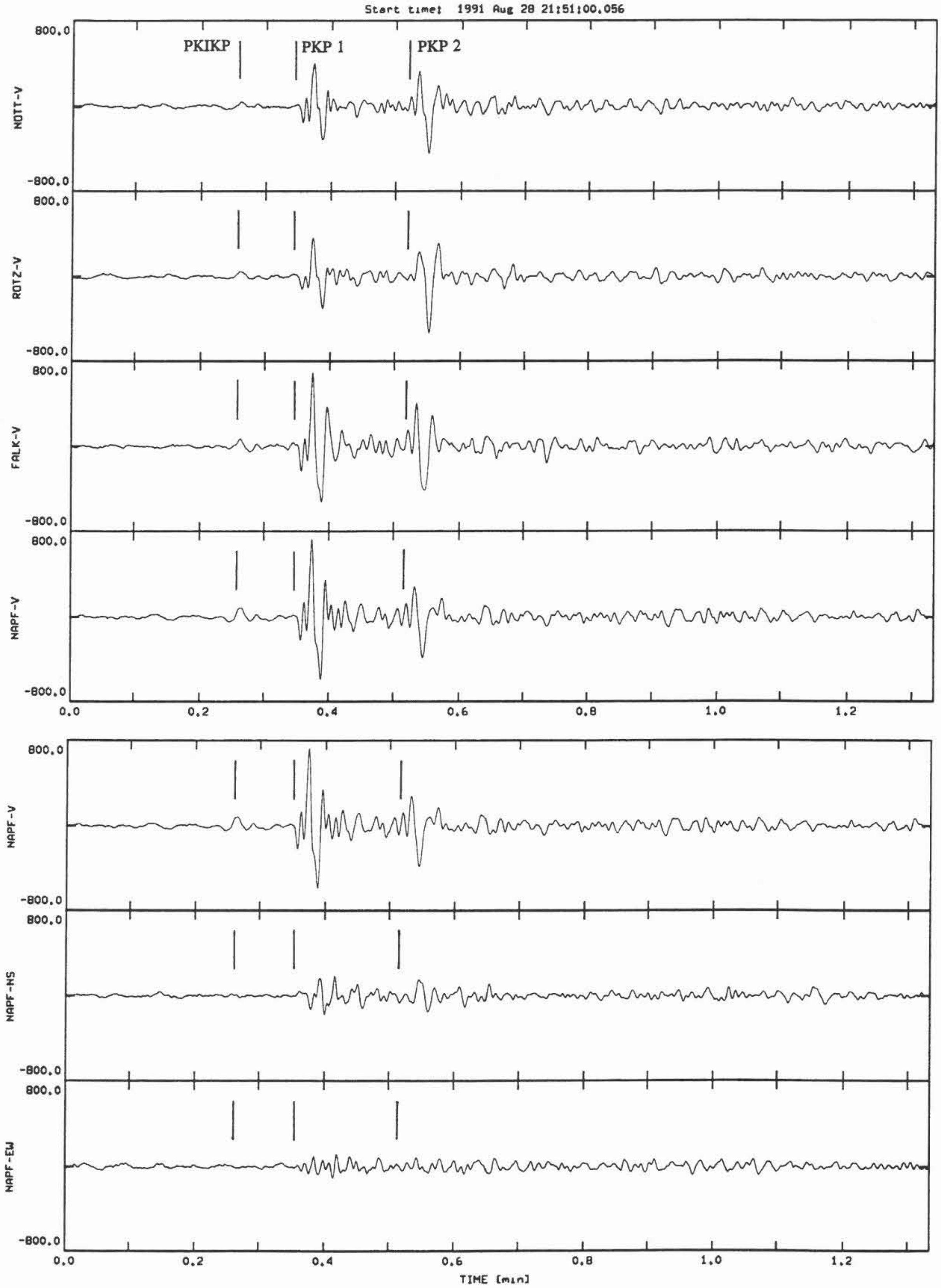


Fig. 15a,b Band-pass filtered (2 Hz- 2 s) teleseismic event from Fiji Islands (Fig. 14) recorded at the KTB Seismological Network (in nm/sec).
a (top) all 4 vertical components; b (bottom) 3 components of station NAPF.

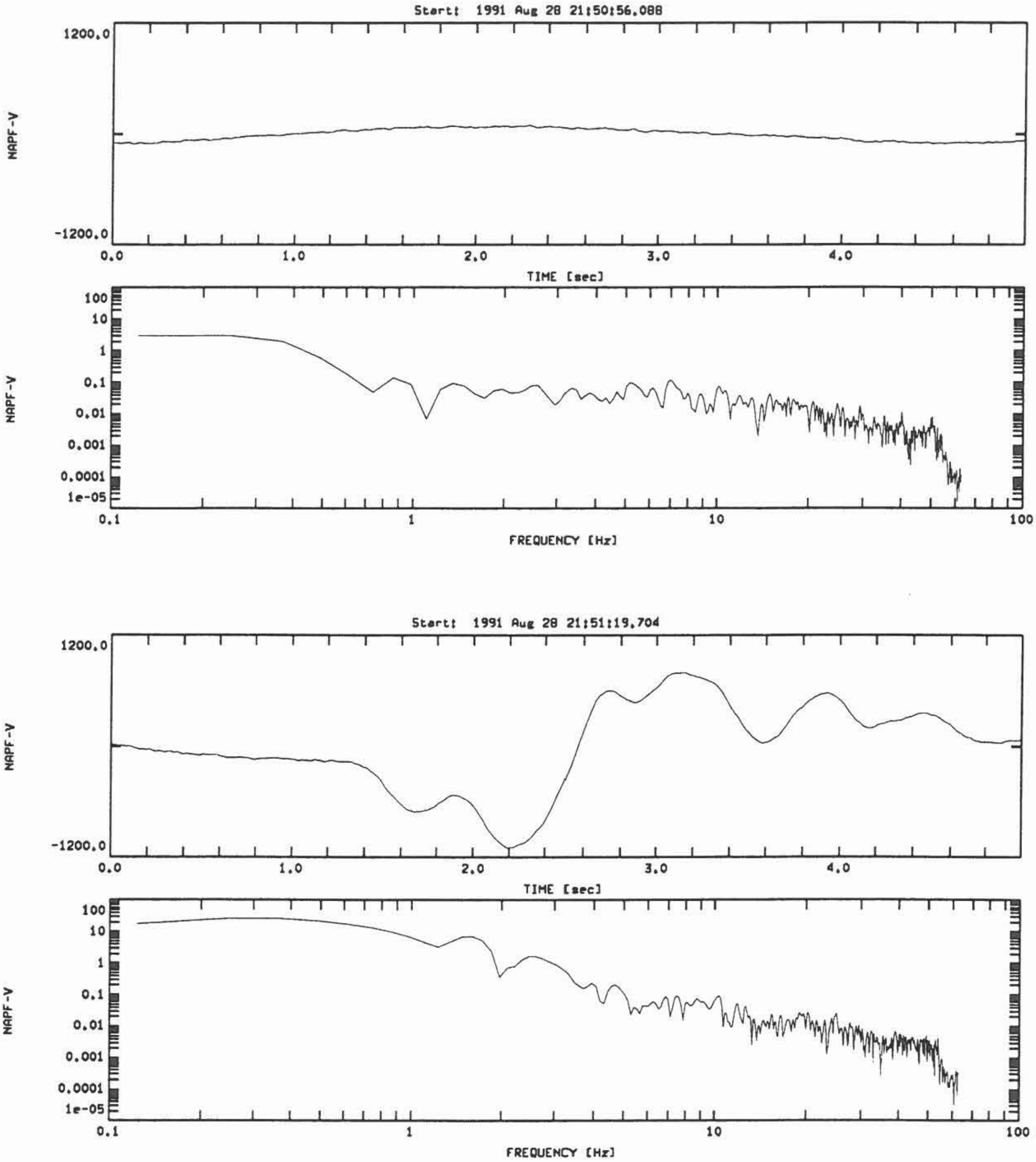


Fig. 16a,b 5 sec broad-band records (in nm/sec) and spectra (in (nm/sec)/Hz) of vertical component of station NAPF for sections of event from Fiji Islands (Fig. 14). **a** (top) noise record before first arrival; **b** (bottom) PKP1 phase of event.

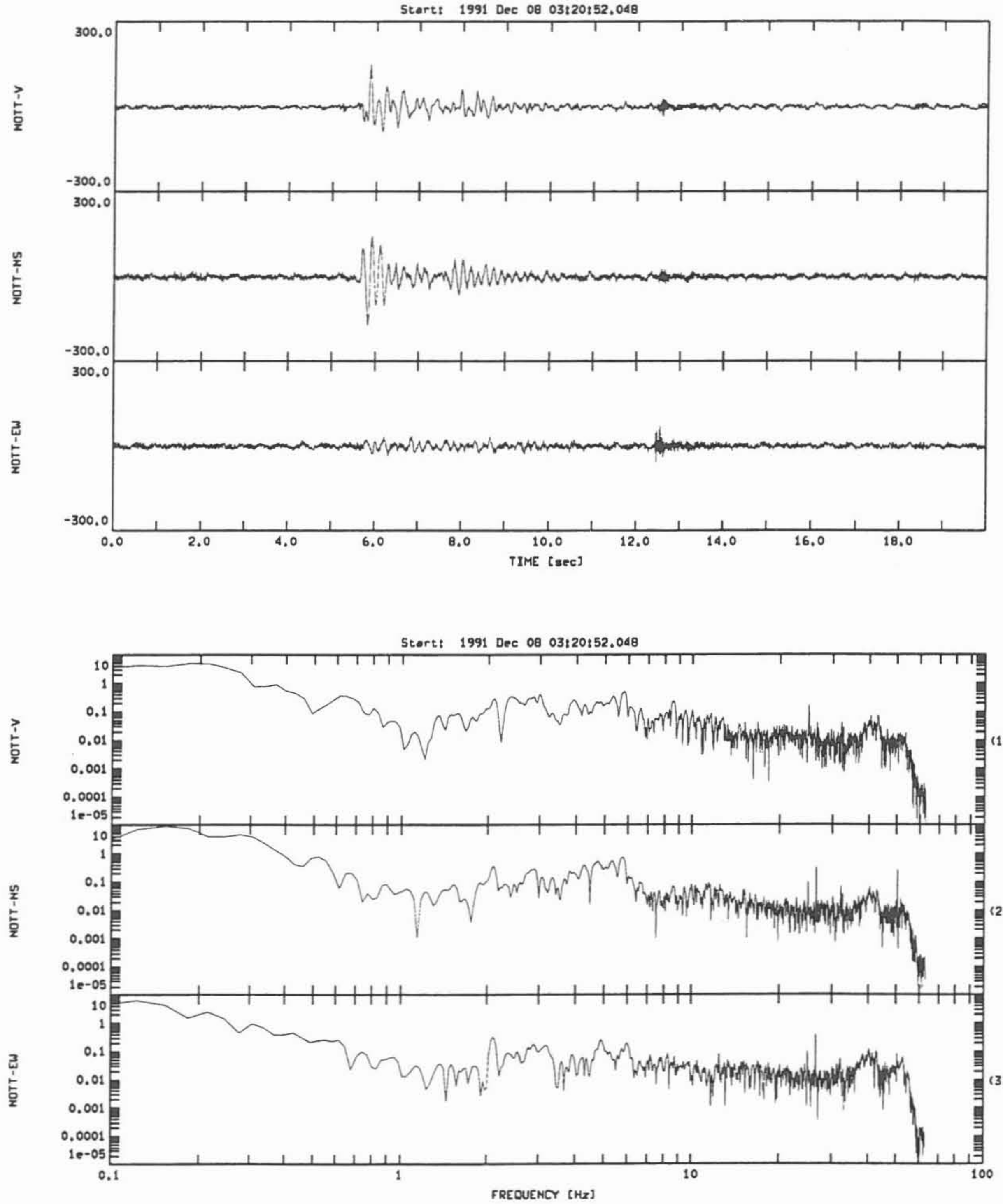


Fig. 17a,b Event caused by using the Jar-King tool upwards to free the drill string in the KTB drill hole; recorded at station NOTT.
a (top) 1 Hz high-pass filtered record in nm/sec of all 3 components;
b (bottom) spectra in (nm/sec)/Hz of 20 sec broad-band record.

physics, the Geophysical Observatory Fürstenfeldbruck, both University of Munich, and the Gräfenberg Array (GRF) gave the necessary technical support. We specifically thank the landowners of the seismic sites: Mr. Enslein (ROTZenmühle), the Forestry Headquarter Kemnath with the Foreststation Erbendorf (NAPFberg), Mr. and Mrs. Höfer (FALKenberg) and Mr. and Mrs. Kraus (NOTTersdorf), for permitting our installations and for their support during the site survey and construction phase.
We thank Günter Asch for his valuable contributions in the earlier phase of the project and Frank Scherbaum for software support.

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Data Acquisition System

- MARS-88/MC Operating Manual, Rev. 2.1
- MARS-88 Short Form Description, Rev. 1.4

Lennartz electronic GmbH, Bismarckstr.136, D-7400 Tübingen, FR Germany

Database Software

- MARS-88 DBM (Data Base Module) User's Guide Rev. 1.1

Lennartz electronic GmbH, Bismarckstr.136, D-7400 Tübingen, FR Germany

- C-ISAM Programmer's Manual Version 3.10
- SQL Reference Manual Version 4.00
- SQL User Guide Version 4.00
- ESQL/C Programmer's Manual Version 4.00

Informix Software, Inc., 4100 Bohannon Drive, Menlo Park, CA 94025, USA

Networking Software

- MARS-88 Gateway (Modem Option) Operating Manual Rev. 1.3
- MARS-88 MCM (Modem Control Module) User's Guide Rev. 1.1

Lennartz electronic GmbH, Bismarckstr.136, D-7400 Tübingen, FR Germany

Seismometer

STS-2 Manual, Portable very-broad-band Triaxial Seismometer, G.Streckeisen AG Messgeraete, CH-8422 Pfungen, Switzerland

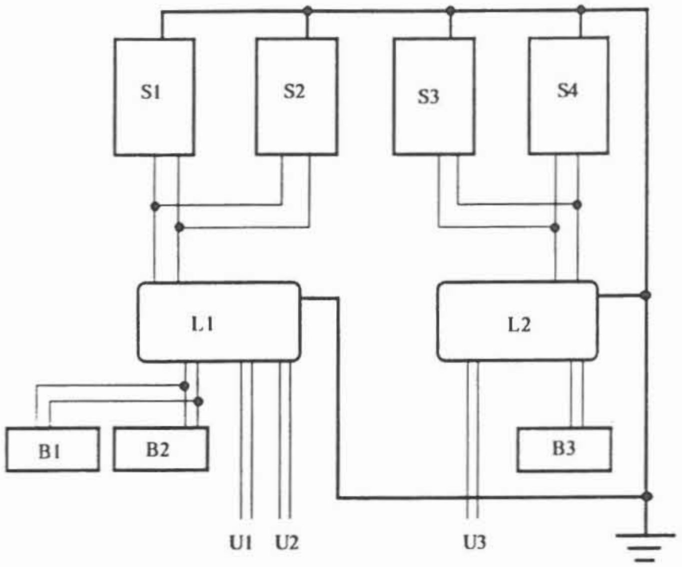
Telephone-Modem

V.3240i Handbuch, Dokument Nr. 3240IG, Dez 1989
Motorola GmbH, Dolivostr.9, D-6100 Darmstadt, FR Germany

Time signal receiver

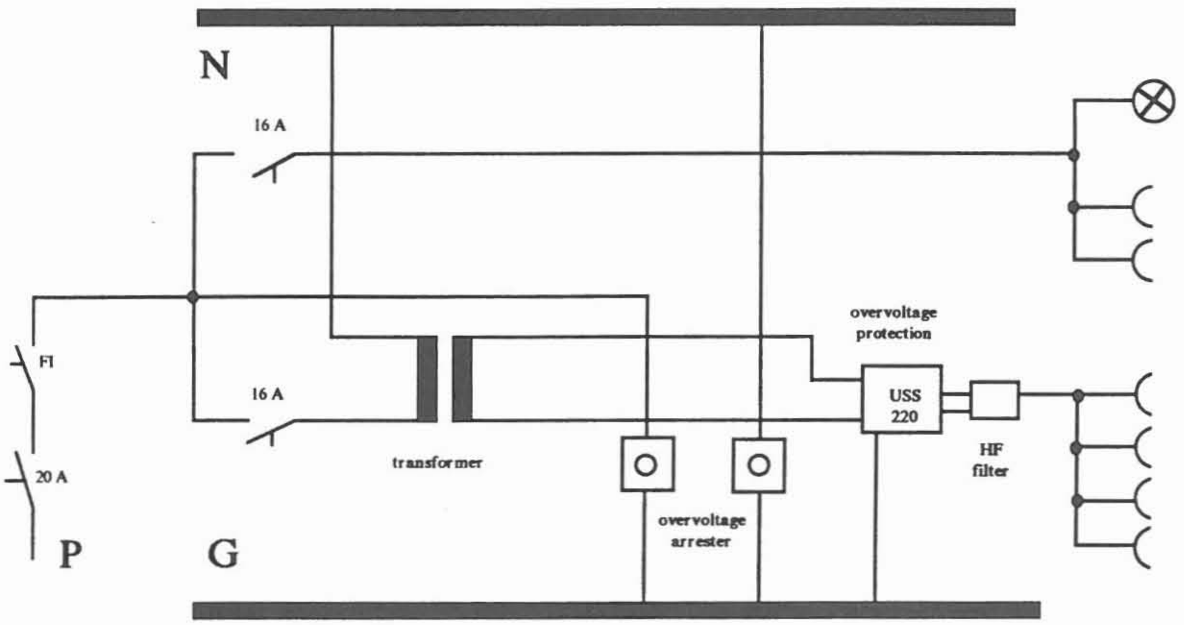
DCF receiver/antenna 280.004 general description,
Lennartz electronic GmbH, Bismarckstr.136, D-7400 Tübingen, FR Germany

APPENDIX 1a Solar power system at station NAPF.



S1, S2, S3, S4	solar panels 50 W
L1, L2	charging unit, control system, discharge regulator
B1, B2, B3	12 V DC 100 Ah batteries
U1, U2, U3	user 12 V DC

APPENDIX 1b Electric power supply system of seismic station. (P phase, G ground, N null)



APPENDIX 2a

STS-2 MANUFACTURER SPECIFICATIONS
(from Streckeisen AG Messgeraete)

GENERAL

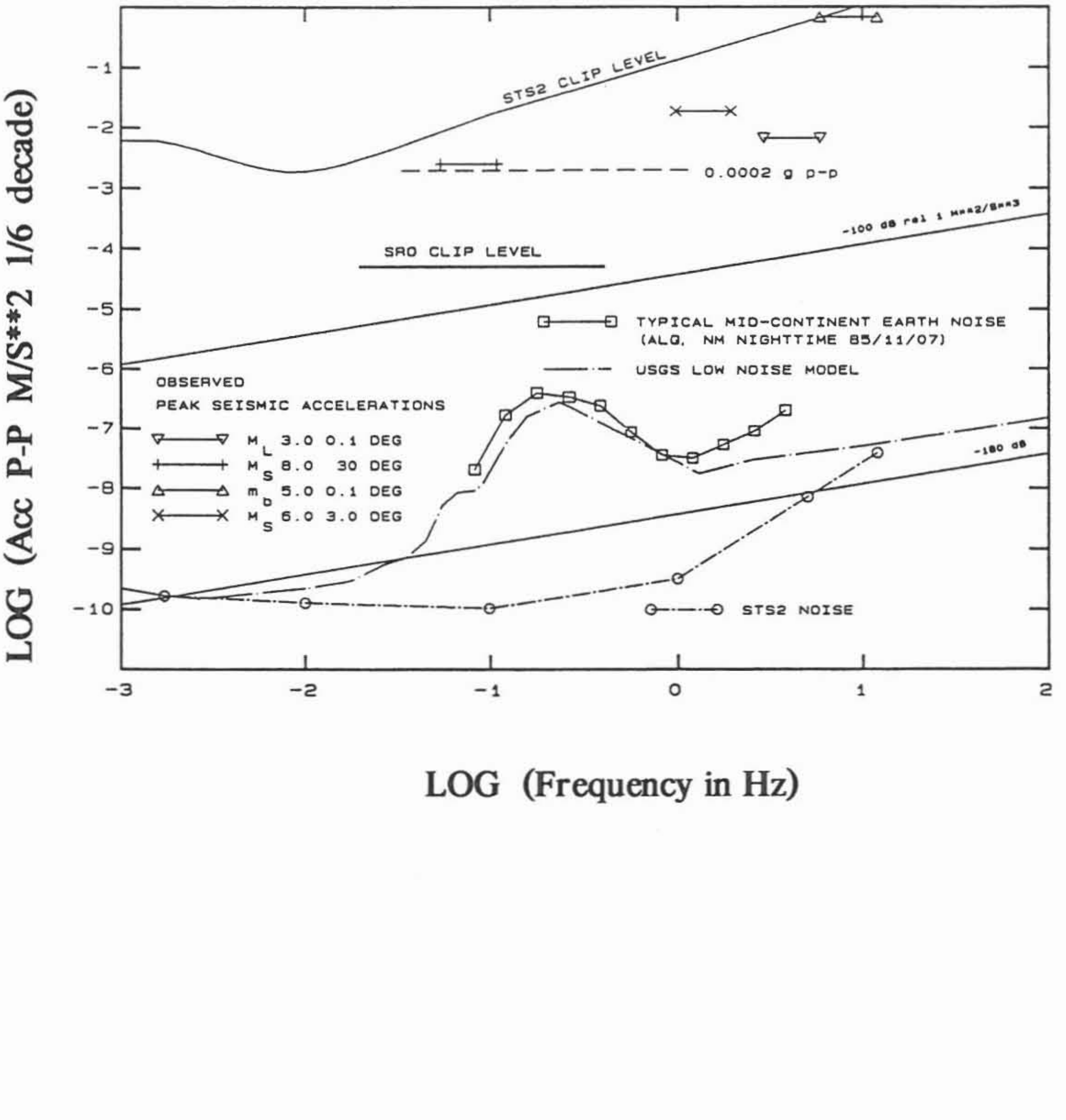
Principle of operation	Force Balance
Mechanical sensors	3 identical inertial pendula in a cube-corner geometry. The mechanical free period is virtually infinite.
Seismic output signals	2 horizontal (X,Y) and vertical (Z) broad-band velocity response
Size	Cylindrical package 235 mm dia., 260 mm high
Weight, complete with "host-box"	13 kg
Environmental protection	Vacuum tight, low-stress construction

ELECTRO-MECHANICAL

Generator constant	2 * 750 Vsec/m
Response	Ground velocity between corners 8.33 mHz (120 sec) and >50 Hz. See section 9 for details.
Seismic signal output	+- 20 V differential range, 100 ohms serial resistance per line
Auxiliary outputs	+- 10 V single-ended, 100 ohms serial
Electronic self-noise	approx. 6 dB below USGS low-noise model between 8.33 mHz and 10 Hz
Clip level	+- 13 mm/sec ground velocity equivalent to the following accelerations: g peak-peak — at Hz 0.17 — 10 0.017 — 1 0.0017 — 0.1 0.00055 — 0.03
Dynamic range	see figure "STS2 SEISMOMETER NOISE AND CLIP LEVEL" (APPENDIX 2b)
Parasitic resonances	vertical: >140 Hz, horizontal: >80 Hz
Power	< 1.8 W at 10 - 30 V DC, galvanically isolated
Control inputs (Remote connector)	"high": 3 - 30 V, 0.5 mA; "low": < 0.5 V; optically isolated
Calibration inputs	Calibration coils 30 Ohms each, approx. 0.002 g/mA (oblique), maximal current 50 mA each
Temperature range	+- 10 C without mass recentering
Mass centering	automatic on external command

APPENDIX 2b

STS-2 Seismometer Noise and Clip Level
(from Streckeisen AG Messgeraete)



APPENDIX 3

MARS-88 MANUFACTURER SPECIFICATIONS
(from Lennartz electronic GmbH)

ANALOG SECTION (20 bit)

Number of seismic channels	1 to 3
Electrical characteristics	2*100 kohm internal resistance, symmetrical 90 db CMRR; protected
Input sensitivity	125 nV, 500 nV, 2 uV, or 8 uV per LSB, corresponding to 66 mV, 262 mV, 1.05 V, or 4.2 V Full Scale sensitivity
Input sampling rate	8 Khz per channel
Anti-alias filter	analog: 3-pole Tchebycheff at 2 Hz digital: cascaded FIR filter with alias suppression > 120 dB zero phase; passband ripple < 0.2 dB
Oversampling ratio	only 2.5 with full alias suppression

DIGITIZATION

A/D Converter	16 bit wordlength; distortion < -95 dB autocalibrating
RMS system noise	approx. 0.12 uV RMS (125 nV)
Channel-to-channel skew	none!
Signal processor	16/32 bit CMOS 6 millions multiply/add cycles per seconds

TIMING SYSTEM

Source	temperature compensated and digitally regulated quartz oscillator
Precision	1ppm free run (0...50 degrees); else: precision of external time signal

USER INTERFACE

built in	6 keys, LCD display (32 char.) 15 LEDs for analog signal display control LED's for ext. and int. time signal ext. and int. trigger, charge
via terminal or computer	convenient command language; help system password protection

DATA STORAGE/RETRIEVAL

Recording modes	continuous; one-shot or repetitive time windows triggered
Buffer memory	/FD and/OD, 256 KB others, 1 MB (opt. 4 MB) static CMOS RAM standard 1 MB fits approx. 45 minutes at 3 channels, 25 Hz signal bandwith
Output medium	2 3.5" floppy disk drives (approx. 3 MB formatted capacity)(/FD) or 1 5.25" magneto-optical disk drive (rewritable media) with 325 MB formatted capacity per disk side (/OD) or 1 RS-232C interface for modem control; UDP/IP protocol (/MC) or bidirectional radio or cable telemetry with error correction (/RC)

MISCELLANEOUS

Firmware	powerful real-time multitasking operating system (written in C)
Main processor	NEC uPD 70108 (V20) running at 8 MHz
Housing	splashproof; black polyurethane; all connectors MIL-grade
Power supply	10 Ahg lead gel accu and charging unit built in > 60 hours autonomy; external 12 V DC supply possible
Sensor power ouput	12 V, 50 mA
Dimensions incl. handles	16 cm high (23 cm for /OD), 44 cm wide, 35 cm deep
Weight incl. lead battery	approx. 12 kg (/FD, /MC, /RC), approx. 20 kg (/OD)

APPENDIX 4

V.3240 Modem Setting (Asynchronous Dial-Up with MNP)

- Modem Parameters
    - DCE Rate 9600 trellis
    - Normal originate
    - V.32 fast train disabled
    - Auto retrain enabled
    - Transmit clock internal
    - Earthing key disabled
    - Line current disconnect long enabled
    - Long space disconnect enabled
    - V.22 guard tone disabled

- MNP Parameters
    - MNP protocol enabled
    - Auto fallback to async
    - MNP flow control disabled
    - XON/XOFF flow through enabled
    - Data compression enabled
    - MNP inactivity timer off
    - MNP break control 5

- DTE Parameters
    - Async data
    - DTE Rate 19200
    - 8 bit char size
    - No parity
    - AT command set enabled
    - Responds to DTR
    - DSR forced high
    - DCD normal
    - CTS forced high
    - DTE fallback disabled
    - Options retrained at disconnect

- Test Parameters
    - Bilateral analog loop disabled
    - Bilateral digital loop disabled
    - DTE local test disabled
    - DTE remote test disabled
    - Remote commanded test enabled
    - Test timeout off

- Dial Parameters
    - Pulse dial
    - Auto dial off
    - Wait for dial tone
    - Wait delay 2 seconds
    - Auto answer

- Speaker option
    - Volume low
    - Speaker off (in Data Center: on until carrier detect)