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The Seismic Broadband Recording and Data Processing System FBV/DPS and Its Seismological Applications

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Abstract. A brief description of the present state of the feedback-controlled broadband seismograph system FBV installed at the Kašperské Hory (KHC) station and of the appertaining system DPS for processing the recorded broadband information is given. The FBV system provides three-component velocity proportional seismic information in a frequency band which covers nearly the whole standard short-period, intermediate period and long-period interval. Each component is recorded bi-level with an overall dynamic range of 80 db on analogue (FM) magnetic tape. The DPS system allows (i) the recorded data to be selected, reduced and transcribed onto library tapes or loops, (ii) to perform rotation of instrumental axes, determination of the azimuth of seismic events, identification of different wave groups by particle motion analysis, multichannel frequency filtering, plotting of frequency vs. time, rapid and efficient estimate of power spectra by proper analogue devices, and (iii) automatic A/D conversion of the part of the records which has to be treated numerically. The variety of seismological applications of the FBV/DPS complex is demonstrated by investigating teleseismic signals from different aspects. Hitherto the complex has been used for crust and upper mantle structure studies on the basis of body wave spectra and surface wave dispersion, for investigations of the influence of standard class seismographs and band-pass filtering on magnitude estimations, and for the identification of underground explosions.

Key words: Seismic broadband data recording and processing – Instruments and procedures – Seismological applications.

Introduction

A trend towards wide-band seismometry is recently much in evidence in instrumental seismology. The goal of wide-band seismometry is to record all the information, contained in seismic signals, with minimum distortion and in a form which can be evaluated quantitatively (Berckhemer, 1971).

In the last decade a number of papers has been published which deal with the theory of broadband seismographs (Lake, 1964; Sutton and Latham, 1964; Daragan, 1967; Plešinger, 1970), with the problem of the optimum selection of their responses taking into account seismological requirements (Berckhemer, 1971; Aranovitch and Kondorskaya, 1971; Aranovitch et al., 1972; Teupser et al., 1974) and with methods of designing broadband large dynamic range seismograph systems (Plešinger, 1973; Daragan, 1973). The work at several seismological institutions and observatories has presently reached the stage of experimental as well as routine operations of broadband systems with a large dynamic range of the recorded information (Burke et al., 1970; Wielandt 1970 and 1973; Jacoby, 1971; Plešinger, 1971, 1972 and 1973).

This paper gives a brief description of the seismic broadband recording and data processing system FBV/DPS, developed in the Geophysical Institute of the Czechoslovak Academy of Sciences, and outlines some possibilities of its seismological applications.

1. Concept of the FBV/DPS System

In designing the system the general purpose was to create an universal broadband station seismograph system with the largest possible dynamic range and with the possibility of as operative as possible automated processing of the recorded information. A more accurate concept was worked out taking into account the criteria specified by Berckhemer (1971) and Aranovitch and Kondorskaya (1971). The demands made on both parts were the following: (a) recording of 3 components of velocity in the period range from 0.3 to 300 s in a dynamic range of at least 80 db; (b) storing of the data in the most economic form on magnetic tape; (c) the possibility of carrying out procedures such as selection of events, azimuth determination, identification of different wave types, frequency filtering and frequency vs. time analysis immediately from station or library tape; (d) the possibility of rapid automated digitation of selected sections of records or of pre-processed analogue data for further processing on conventional digital computers.

An experimental seismograph, satisfying condition (a), was developed in our Institute already in 1968 (Plešinger, 1971 and 1972). The confrontation of the other demands with economic aspects led to the following concept: (1) establishing the broad-band large dynamic range channels by using conventional long-period seismometers controlled by active frequency-dependent negative feedback, (2) bi-level recording of each component on magnetic tape in analogue frequency modulated form, (3) storing of selected events in the same form, i.e. establishing library tapes by direct transcription, (4) carrying out the required routine procedures by means of economical and effective analogue equipment, (5) analogue-to-digital conversion of selected portions of records or of pre-processed signals in the first stage with single-channel equipment and punch-tape record, in the second stage with multi-channel equipment and magnetic tape record.

2. Description of the FBV/DPS System

The complex of instruments which was gradually established according to the concept outlined above now consists of five sub-systems.

2.1. Broadband Seismometric Channels

This sub-system is installed in the underground rooms of the Kašperské Hory (KHC) station. It is shown schematically in Figure 1. It consists of a set of long-period KIRNOS seismometers (SVK-D, SGK-D), the effective free periods and damping moments of which have been increased to the required values by means of frequency-dependent negative feedback (e.g., the period of the SGK-D from the original value $T_0 = 24$ s to $T'_0 = 360$ s and the damping factor from 0.06 to 0.7). Highly sensitive photoelectric amplifiers, the transfer properties of which are also controlled and stabilized by negative feedback, serve as active elements. The internal and external negative feedbacks markedly improve the overall linearity of the seismometric channels and increase their dynamic range to a value in excess of 100 db.

The outputs of the seismometric channels are fed via filters, in which noise components with frequencies $f < 0.001$ Hz and $f > 10$ Hz are suppressed, and via attenuators to voltage-frequency converters. The converters convert each seismic component in two levels with a mutual sensitivity difference of 30 db into the form of frequency-modulated carrier signals which are fed into a long-term magnetic tape recorder. The three components are simultaneously recorded by a standard three-component photorecording device and monitored on the screens of mirror galvanometers.

The system is equipped with a calibration unit which enables all channels to be calibrated by shock tests (impulses of acceleration), release tests (steps of acceleration) or by sinusoidal signals. Figure 2 shows the amplitude-frequency characteristic of the seismometric channels inclusive the magnetic tape recording unit and, for comparison, the magnification curves of the 3 standard class (A, B and C) seismographs.

2.2. Magnetic Tape Recorder

The FM-signals are recorded on magnetic tape by a Racal-Thermionic T8100 Recorder. The necessary additional signals (real time, time code, pilot frequency) are generated in built-in units. The real-time marks are derived from the station time service and used to check and correct the coded time signal, generated by the electronics of the T8100 Recorder. The time code gives the year, month, day and minute of the record each minute between the 0th and 40th second (modified I.R.I.G. standard code).

The speed of the magnetic tape is 3 mm/s. One tape reel has a capacity of 108 h of 12 channel record. The subsidiary information mentioned above is recorded on traces 4, 5 and 6, respectively, and the remaining traces (1–3,

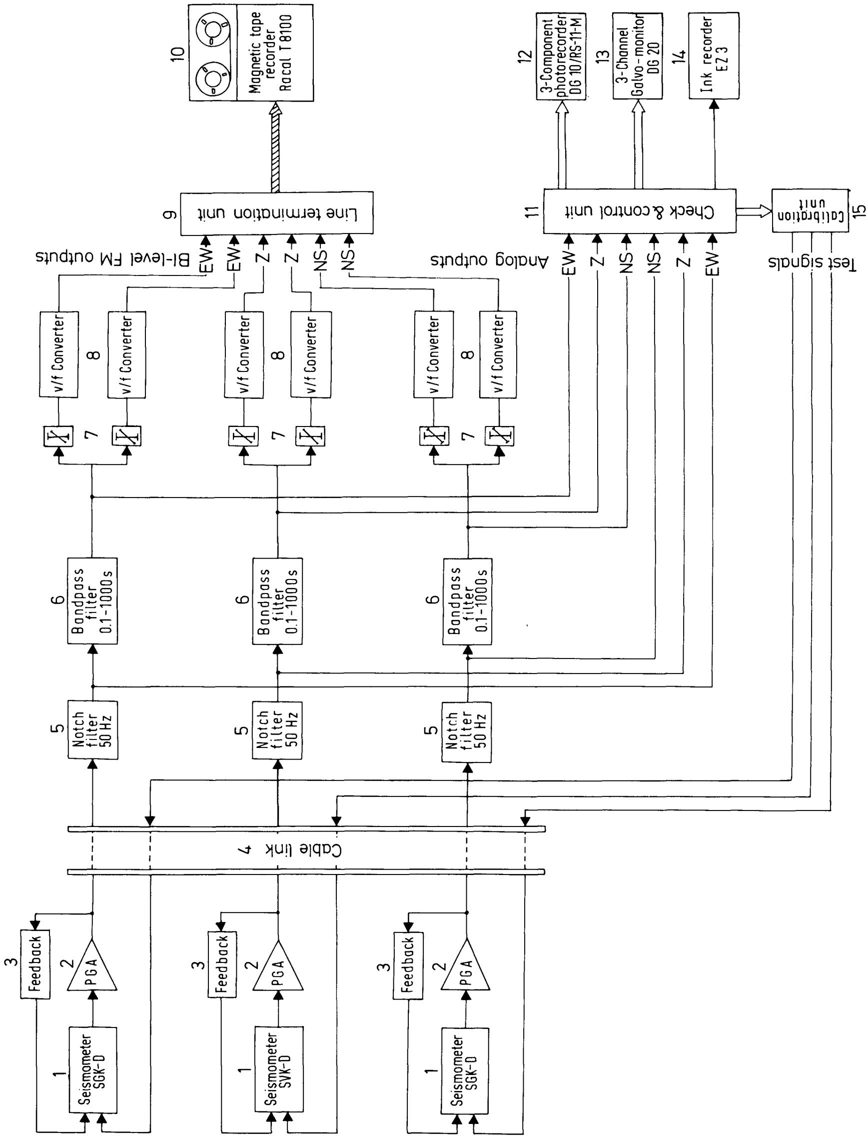


Fig. 1. Structural diagram of the FBV system. The seismometers are installed in the Kristina gallery of the KHC station (gneiss, overburden 30 m, 80 m from opening) under pressure tanks. PGA – photogalvanometric amplifiers EL 022/F 117

7–9, 10–12) carry the seismic information. The whole FBV system is supplied from battery sets and is capable of operating on its own for 4 days.

2.3. Analogue Data Processing

The structural diagram of the subsystem for reproducing, transcribing and analogue processing of the data recorded by the FBV system is shown in Figure 3.

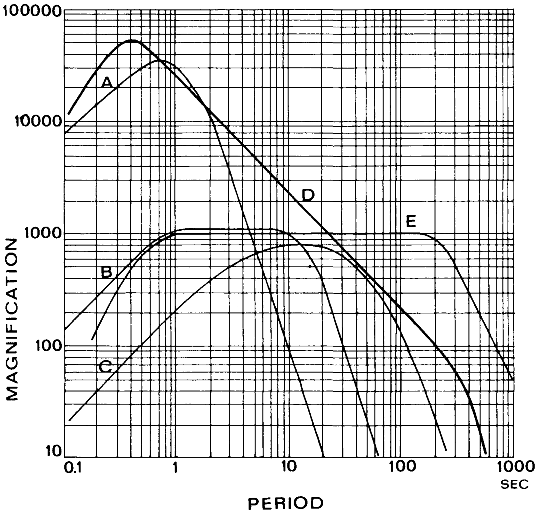


Fig. 2. Response curve for the magnetic-tape record of the FBV system (D) compared with the magnification curves of standard class short-period (A), intermediate band (B) and long-period (C) seismographs. E is the supposed response of the new FBD system (see Conclusion)

The part for reproducing and transcribing the data consists of two tape transports Racal-Thermionic TDR 8(L) the first of which is equipped with demodulation electronics and an additional unit for drop-out elimination, the second with transcription electronics and an additional unit for selecting the type of operation. The first unit is intended for replay from tape only, the second for replay, erasing and recording on tape as well as loop. This set-up, together with the time decoder, performs three fundamental operations: automatic search for seismic events, transcription of selected events onto library tape or a loop, and reproduction of the data from station tape, library tape or loop in analogue form. These operations can be carried out at replay speeds of as much as 256-times the recording speed. Routinely a time transformation to 1/64 of the real time is used

The set-up for the analogue processing of signals replayed from tape or loop consists of a set of analogue processors (units 5–9 in Fig. 3) and a set of output units for representing the results (units 10–13). The output periphery is formed by a six-channel slow-motion oscilloscope which also allows vectorial representation, an eight-channel heat-pen recorder, an X-Y plotter and a storage oscilloscope. The analogue outputs from the tape replay unit, the inputs and outputs of the analogue processors and the inputs of the output devices are located on a central patch panel which is used to connect the individual units up into the required configuration. Below the functional principles and purposes of the individual analogue processors are explained.

Integrators. In order to obtain the largest possible dynamic range of recorded seismic information the FBV system has a flat-velocity response (see e.g. Lake, 1964). For certain purposes (earthquake mechanism studies, structure investiga-

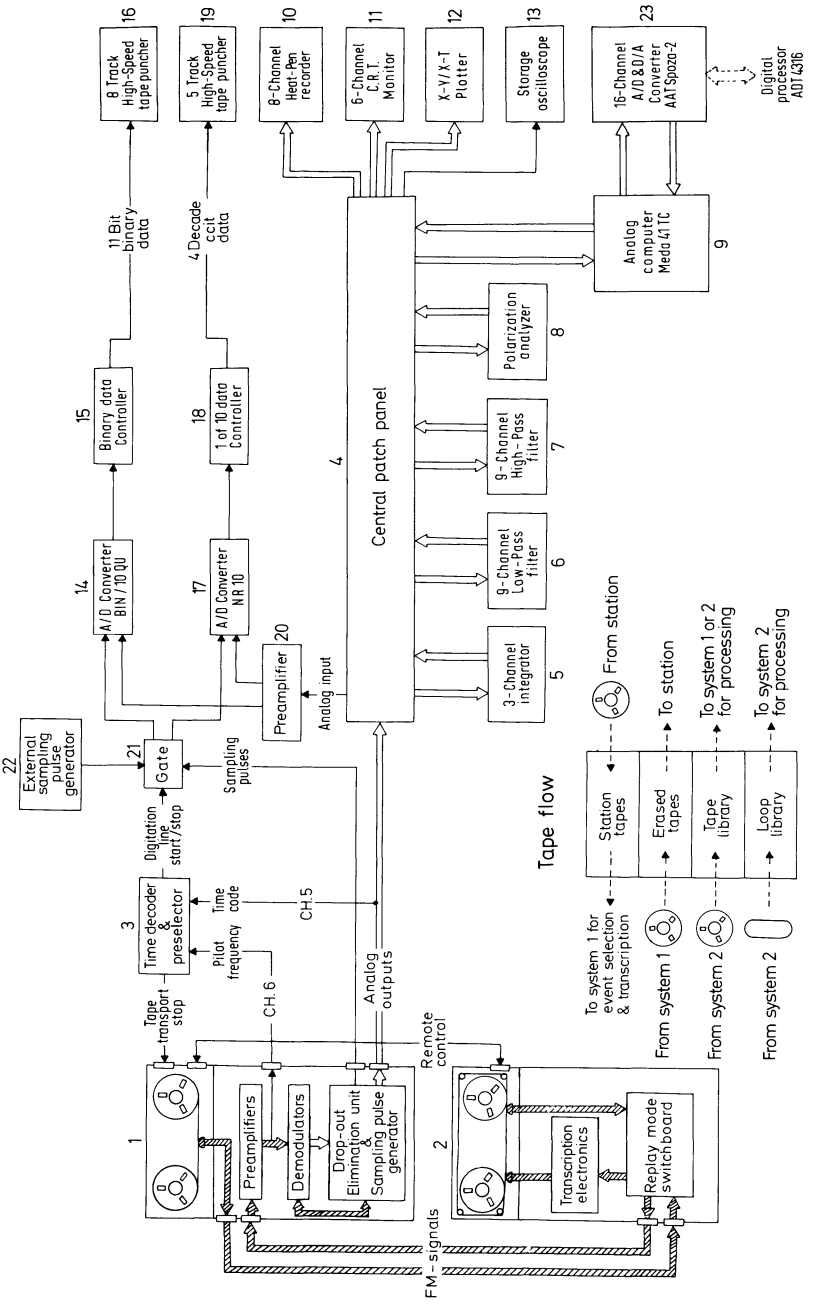


Fig. 3. Structural diagram of the DPS system. 1—Racal-Thermionic T8100 Replay Unit, 2—Racal-Thermionic TDR 8(L) Tape Transport equipped with additional electronics

tions on the basis of surface wave dispersion etc.) displacement-proportional information is, however, more convenient. Active integrating filters are used to modify replayed data into this form. The transfer function and frequency response of the filters is given in Figure 4. The filter works as an ideal integrator in the period range of $T < 300$ s (expressed in real time). A derivating circuit stabilizes the function of the integrator, i.e. eliminates the D.C. component from the input signal and suppresses longperiod noise.

Frequency Filters. The set of frequency filters is composed of nine high-pass and nine low-pass sections with 4th degree Butterworth responses (Fig. 5). The cut-off frequencies can be chosen arbitrarily in the range 0.1–100 Hz and are indicated by a digital panelmeter. Each filter consists of two active filter modules Barr & Stroud EF 40, connected into cascade, and an I.C. buffer amplifier. The individual sections can be used to form various band-pass filters or they can be used independently. They are utilized as anti-aliasing filters, for current frequency filtering and for rough frequency vs. time analyses.

Polarization Analyzer. The polarization analyzer is a single-purpose processor which enables seismic phenomena to be investigated on the basis of particle motion (Sutton and Pomeroy, 1963; Houliston, 1972). The principle of the method can be seen from the simplified diagram of the analyzer in Figure 6. The individual components of the investigated event, reproduced from magnetic tape or loop, are fed to the inputs. With the aid of a pair of coupled sine-cosine potentiometers the longitudinal component $L = NS \cos \Theta + EW \sin \Theta$ (L positive towards the epicentre) and transverse component $T = NS \sin \Theta - EW \cos \Theta$ (T positive to the right of the epicentre direction), Θ being the angle of the azimuth set on the potentiometers, are formed from the NS and EW components. The L and T components can then be multiplied by the vertical component Z. The product $L \times Z$ has the property that it is positive for ground motion of the compression type and negative for ground motion of the SV type. A Rayleigh type surface wave is reflected in the $L \times Z$ product as an alternately positive and negative signal with half the period of the original wave. Thus, the processor separates the following types of ground motion: horizontal transverse, horizontal longitudinal, compressional, vertically polarized transverse, and elliptical longitudinal.

The P-wave azimuth of the investigated event can be determined with the polarization analyzer in the following manner. The wave group P of the given event is first transcribed onto a loop. It is then repeatedly replayed into the polarization analyzer and the potentiometer position is found at which the product $T \times Z$ has its minimum. The potentiometer scale, which is calibrated in degrees, then gives the sought azimuth (the turning of the potentiometer axes simulates the turning of the instrument axes; for P-waves, recorded in the direction of their propagation, $T = 0$). The multiplication of component T by Z only has the auxiliary purpose that it facilitates the determination of the minimum of the signal T.

In fact the product $T \times Z$ is never quite zero. This is due to the presence of secondary waves generated at boundaries below the point of observation. The polarization analyzer may, therefore, also be utilized for the study of particle motion with the purpose of separating local effects from teleseismic signals.

Analogue Computer. The analogue computer considerably expands the range of applications of the DPS system. The device is used for simulating responses of standard class seismographs, of inverse, preshaping and other special (integrating and derivating) filters, and as a correction unit in dispersion analyses

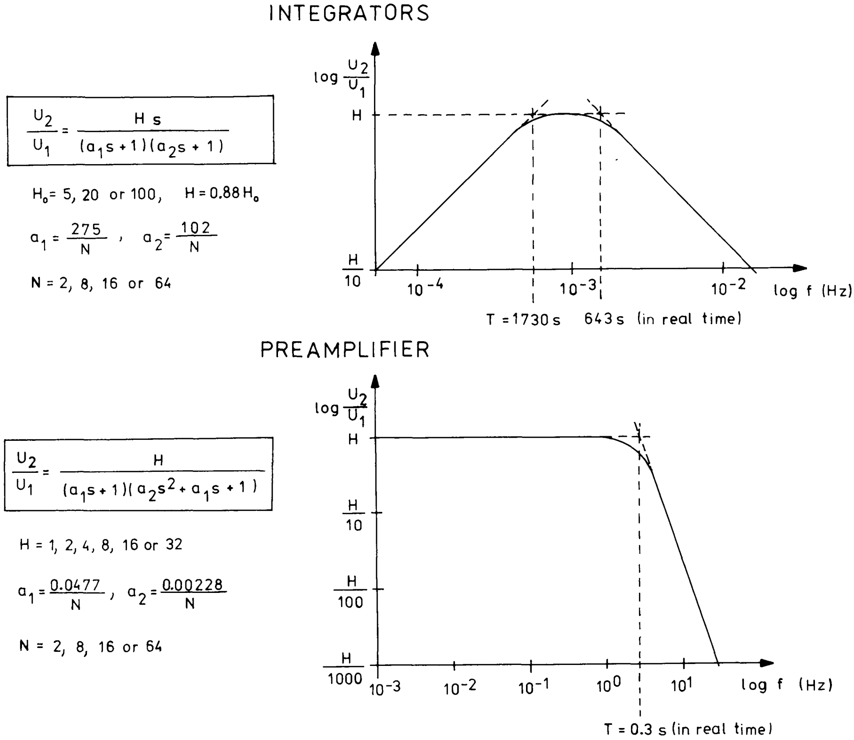


Fig. 4. Transfer functions and frequency responses of the integrators and preamplifier. N is the ratio of replay to record speed. Routine procedures are performed at $N = 64$

performed with the aid of narrow band-pass filters. The type of the analogue computer (iteration computer MEDA 41 TC with multichannel A/D and D/A converter unit SPOZA-2; producer AAT Praha) has been selected with a view to a future hybrid processing of the FBV broadband records. For this purpose the completion of the DPS system by an ADT 4316 minicomputer (producer ZPA Praha) is anticipated in near future.

2.4. Analog-to-Digital Converters

In order to be able to process sections of broadband records or analogue pre-processed signals further on commercial digital computers, the DPS system was equipped with two digitizing devices. In Figure 3 the units are numbered 14–19. The analogue signal is fed to the A/D converters via a preamplifier the transfer function and frequency response of which is given in Figure 4. The sampling pulses are derived either from the 100 Hz pilot frequency, recorded on trace 6 of the magnetic tape, or from an external pulse generator. The conversion start-up (beginning of time series) is controlled via decoder 3 by the time code recorded on trace 5 of the magnetic tape.

Fig. 5. Transfer functions and frequency responses of the low-pass and high-pass filter sections. The pass-band gain of all sections is adjusted to 0 db by output buffer amplifiers

LOW-PASS

$$\boxed{\frac{U_2}{U_1}(s) = -\frac{1}{(s^2 + 1.848\,s + 1)(s^2 + 0.756\,s + 1)}}$$

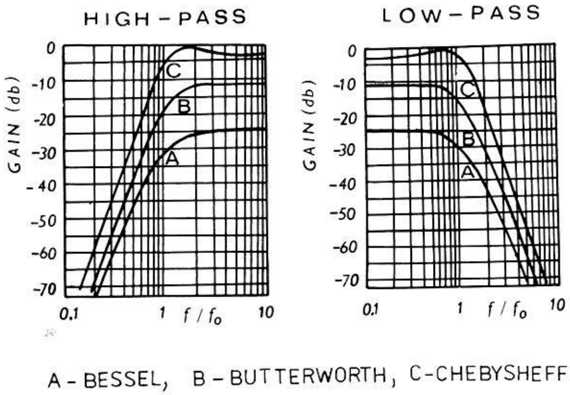
$$s = j\frac{f}{f_0} \qquad f_0 = 0.1 \div 100 \text{ Hz}$$

HIGH-PASS

$$\boxed{\frac{U_2}{U_1}(s) = -\frac{s^4}{(s^2 + 1.848\,s + 1)(s^2 + 0.756\,s + 1)}}$$

$$s = j\frac{f}{f_0} \qquad f_0 = 0.1 \div 100 \text{ Hz}$$

FREQUENCY RESPONSES



The first digitizing line punches the data into a 5-trace punch tape in the C.C.I.T. telex code at a maximum speed of 17 samples/s, the second into an 8-trace punch tape in 11-bit binary code at a maximum speed of 56 samples/s.

The data punched in the telex code can be introduced into computers directly, however, the digitizing process is slow. The second line is faster, but the binary data can only be transcribed onto digital computer tapes by means of a special reading programme. The common disadvantage of both digitizing devices is their low speed and the fact that only a single-channel A/D conversion is possible.

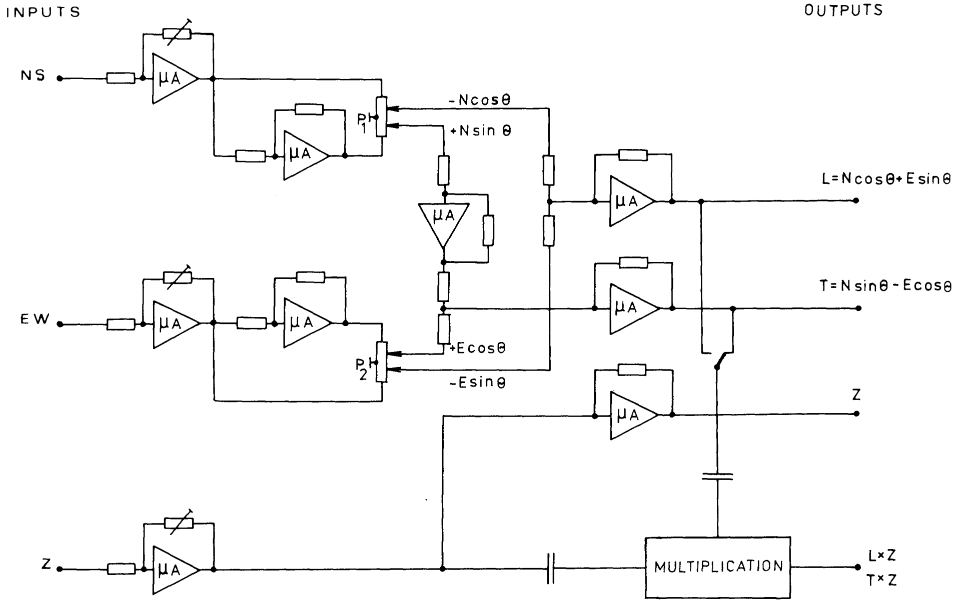


Fig. 6. Simplified wiring of the polarization analyzer. µA — IC operational amplifiers, P_1 and P_2 — coupled sine-cosine potentiometers. The multiplication is performed by a monolithic AD 530 multiplier

2.5. Subsystem for Digital Data Checking and Plotting

For checking and plotting of digital data a special subsystem was developed. It consists of two devices the first of which is intended for checking and D/A conversion of data punched in the C.C.I.T. form and the second has the same function for data punched in the 11-bit binary form.

The data are read from the punch tape at a maximum speed of 1500 characters/s by photoelectric readers, checked for errors in error identifiers and transformed to analogue form. Counters simultaneously generate the time axis for plotting the data on an analogue X-Y plotter. Coincidence circuits stop the reading if a given maximum permissible value is exceeded or if a predetermined symbol or combination of symbols (e.g. end of data series, error, etc.) occurs. The values of the individual samples are currently given in decadic form on digital displays.

The first device also permits the checking and plotting of two-dimensional (x,y) sequences punched in C.C.I.T. form and of time series punched into 8-trace tape in 7-bit binary code with odd parity. The device can also be used for fast copying of arbitrary 5- to 8-trace punch tapes.

3. Seismological Applications of the FBV/DPS System

In this section we give a few examples of how the analogue processors can be used to investigate teleseismic signals under different aspects.

Figure 7 shows the result of a qualitative investigation of the effect of standard class seismograph responses on the wave image of a distant earthquake

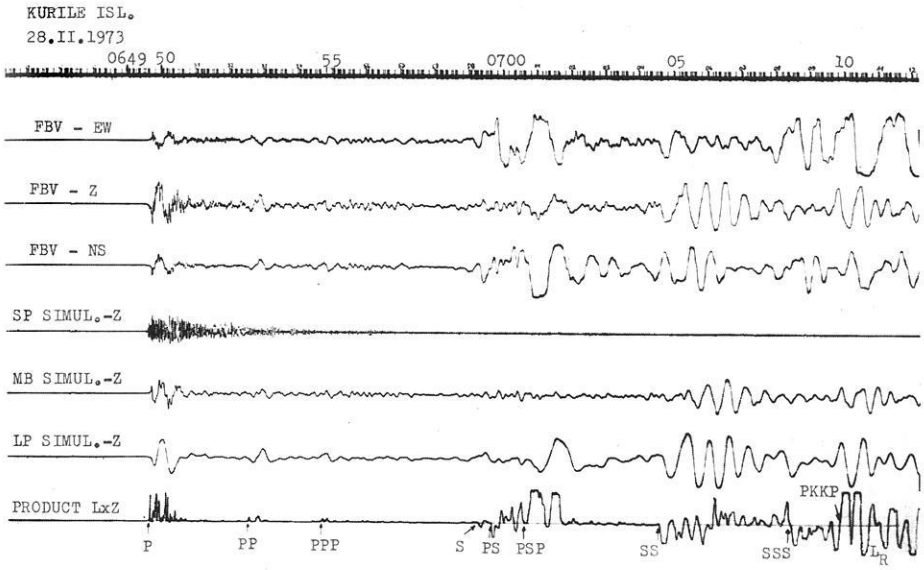


Fig. 7. Simulation of standard class A, B and C seismograms from a broadband FBV recording and result of polarization analysis of the event. The procedures are performed simultaneously with a speed corresponding to 1/64 of the real time

(Kurile Is., 28 FEB. 1973, KHC 06 50 39.7 UT, $D_c = 75.8°$, $m_{\mathrm{ISC}} = 6.8$), and the result of the polarization analysis of this event. The first trace carries the record of time, the second to fourth the individual components of the broadband flat-velocity recordings, the fifth, sixth and seventh the filter outputs simulating the outputs of, respectively, a vertical standard class short-period, intermediate period and long-period seismograph. The last trace carries the product $L \times Z$ obtained from the polarization analyzer. It can be seen that the teleseismic signal is recorded relatively most faithfully by the long-period simulation, whereas the short-period record clearly contains also information on local effects. The individual wave groups are distinctly distinguished on the $L \times Z$ record even in sections where waves of different types follow each other closely. The polarization analysis evidently makes it possible to determine more accurately the arrival times of different phases, is capable of separating phases which cannot be distinguished on the direct records and also provides—together with frequency filtering—a certain amount of information on local effects.

Figures 8 and 9 represent examples of the results of an extensive study intended to determine the effect of the recorded frequency band on the determination of the magnitude of earthquakes. In this study a set of band-pass filters with an upper limiting frequency of 2.5 Hz ($T = 0.4$ s) was used and the lower limiting frequencies were set at intervals of one octave over a period range of $T = 2$ to 256 s (expressed in real time). Figure 8 shows the responses of this set of filters to the vertical component of the same event as in Figure 7, and in Figure 9 a detail of the filtered P-wave group is shown. The example proves that recording of the surface waves of the investigated event would require the use of a seismograph with a passband of at least up to $T = 30$ s and that the passband has considerable effect not only on the dynamic characteristics but also on the kinematic parameters of the recorded signals. In the event investigated the difference between the time of the first onset on the records *F* 0.4–2 s and *F* 0.4–256 s in Figure 9 is 5.3 s.

Figure 10 shows the result of a rough frequency vs. time analysis of the broadband record of another distant earthquake (Alaska, 1 JULY 1973, KHC 13 13 34.6 UT, $D_c=70.7°$, $m_{ISC}=6.5$) by means of a set of one-octave band-pass filters. The uppermost trace carries the record of the broadband signal (vertical ground displacement obtained by integration of the *Z*-component from the FBV system) and below it the outputs of the individual filters are recorded. This type of processing is used to identify various phases of earthquakes, to separate higher mode surface waves from the basic mode, to investigate the relation between the spectral distribution of an earthquake record and the process in its focus or, respectively, the earthquake magnitude, to construct three-dimensional period vs. time vs. A/T value diagrams etc. Analyses of this type have been also used for investigating the frequency dependence of $(A/T)_{max}$ data and their relation to earthquake magnitudes. One example of band-pass filtering of FBV broadband records for this purpose is reproduced in Figure 11 (investigated event Japan 17 JUNE 1973, KHC 040702.9 UT, $D_c=77.8°$, $m_{ISC}=6.5$).

In Figure 12 the result of an attempt to estimate the group velocities for surface waves of a distant earthquake (Japan, 8 MAY 1974, KHC 2345 56.3 UT, $D=85°$, $m_b=6.1$) with the aid of a set of narrow-band filters is represented. The time is plotted at the very top and bottom, the first trace carries the broadband signal and the other traces represent the outputs of the individual filters the resonance periods of which were 14, 19, 25, 33, 45, 60 and 75 s (in real time). The direct presentation of the filter outputs only allows one to observe the spread features of the dispersion curve. Besides, the signals are delayed in time due to the filter phase lags. It is, however, possible to emphasize the maxima of the envelopes of the signals by using squaring devices and a sharp filter with zero phase lag can be established in analogue form using the technique of double filtering in positive and negative time (Sutton and Pomeroy, 1963).

Figure 13 demonstrates the difference between broadband velocity and displacement recordings. The FBV record of the Alaska earthquake of July 1, 1973, was reproduced from the magnetic tape directly (traces 2, 4 and 6) and via integrators (traces 3, 5 and 7). Trace 1 carries the time code, trace 8 the $L \times Z$ signal from the polarization analyzer. It can be seen at first glance that recording the velocity has the advantage that it reflects the short-period and long-period components of the wave image with compatible amplitudes. On the displacement records, on the other hand, the wave image is simpler, short-period components are suppressed (or long-period enhanced) and the amplitude dispersion of the surface waves is smaller. Velocity recording is, therefore, obviously more advantageous for direct interpretation in the classical sense (the amplitudes directly yield the quantity A/T, the onsets of the individual phases can be distinguished better), whereas for earthquake mechanism studies and structure investigations on the basis of surface waves displacement records are more suitable.

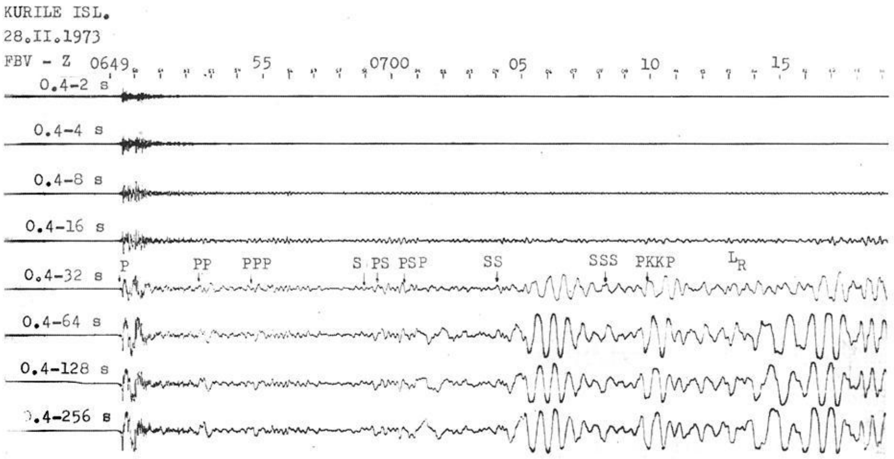


Fig. 8. Example of band-pass filtering with fixed upper and varied lower filter cut-off frequencies

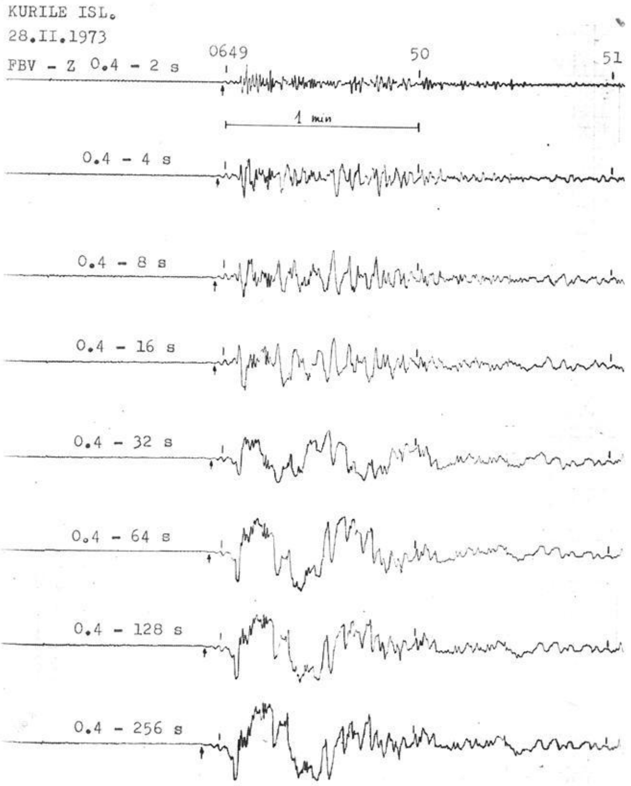


Fig. 9. Detail of the filtered *P*-wave group. The first onsets are denoted by arrows, the vertical dashes are minute marks

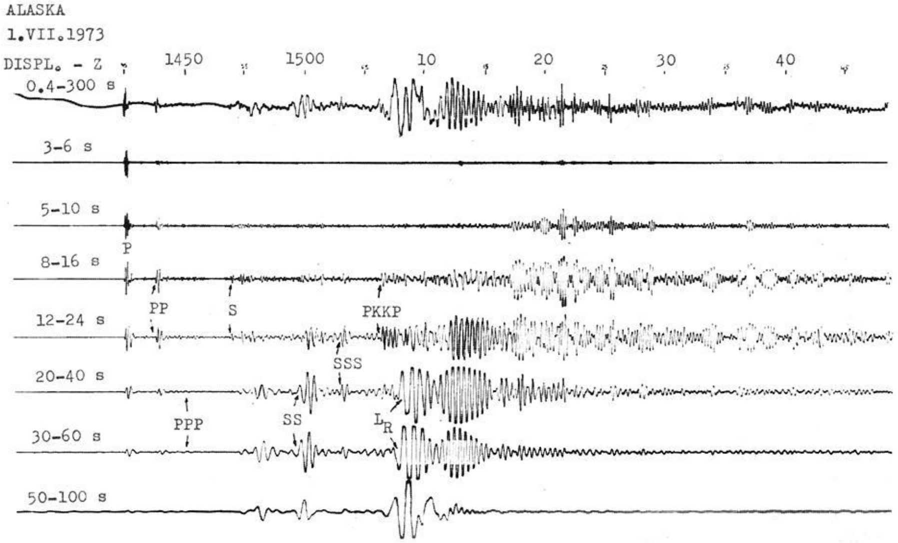


Fig. 10. Rough frequency vs. time analysis by means of a set of filters with pass-bands corresponding in real time to period intervals of 3–6, 5–10, 8–16, 12–24, 20–40, 30–60, and 50–100 s

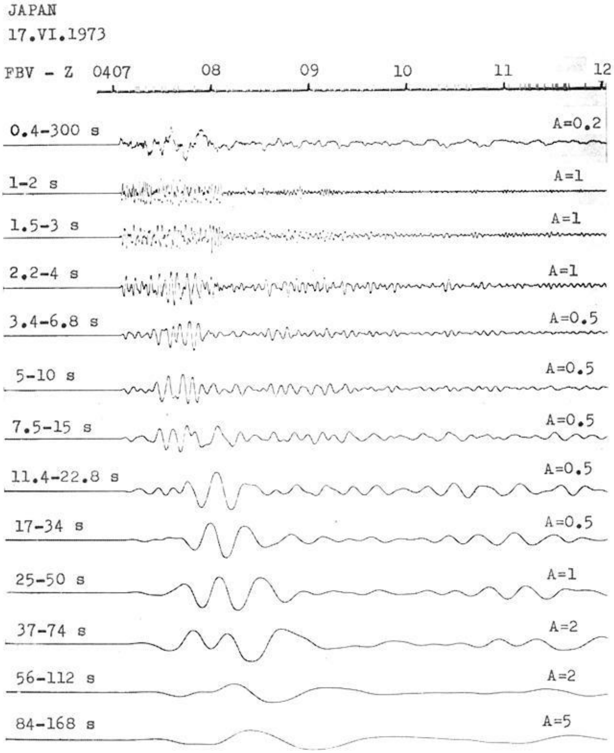


Fig. 11. Example of multichannel one-octave band-pass filtering

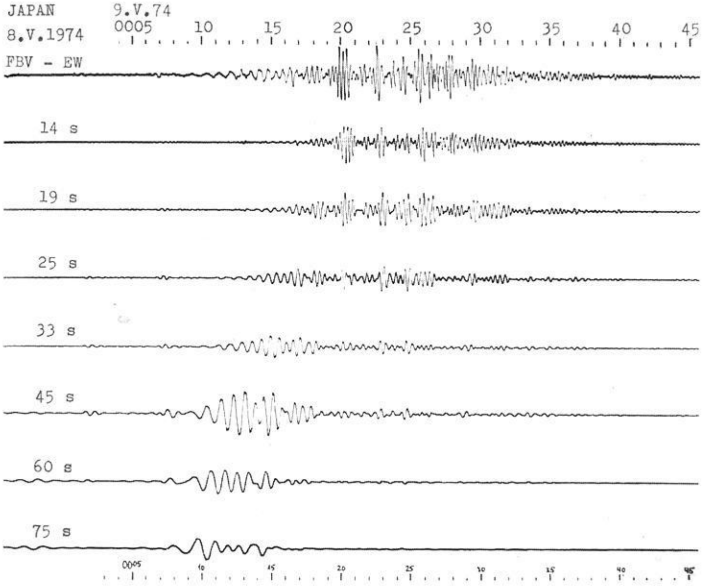


Fig. 12. Estimation of surface wave group-velocities with the aid of a set of selective filters

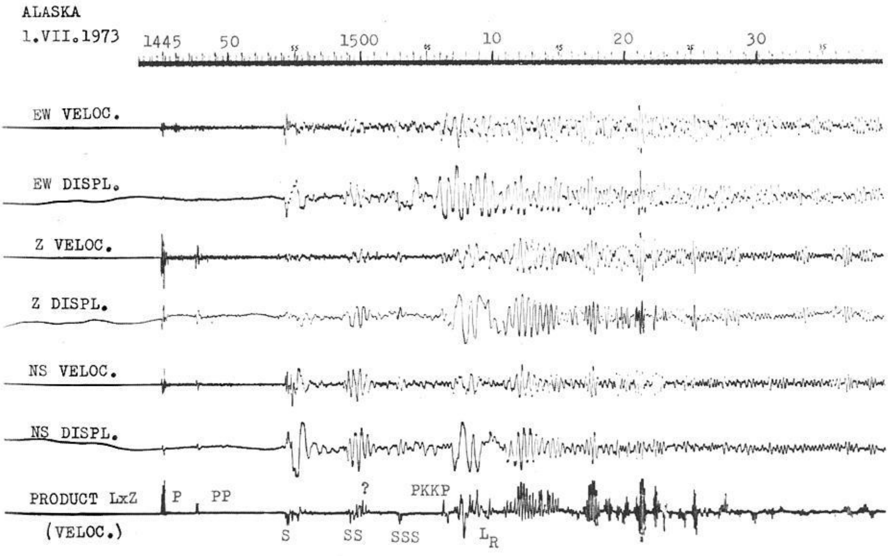


Fig. 13. Comparison of recordings of velocity, displacement, and L × Z signal

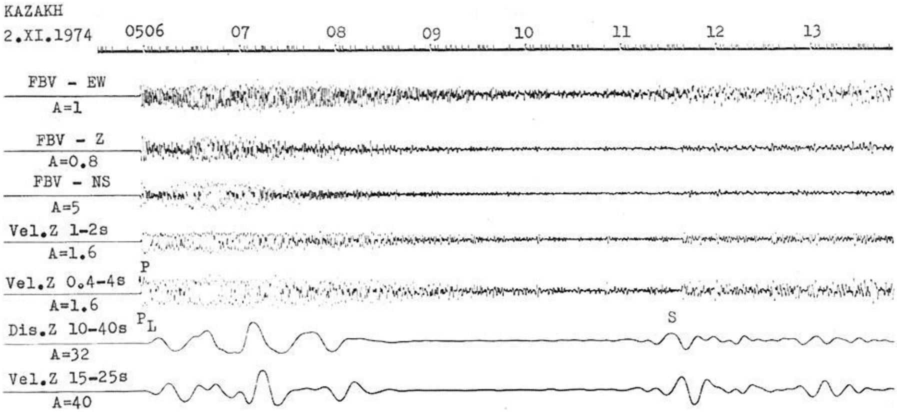


Fig. 14. Example of the application of different frequency filterings (simulations) to the FBV broadband record of an underground nuclear explosion

In Figure 14 the result of applying various filters to the broadband record of an underground explosion (Kazakh, 2 NOV. 1974, KHC 05 05 58.0, $D_c=31°$, $m_b=6.7$) is shown. In the integrated (diplacement-proportional) output passed through a 10 to 40 s band-pass filter (trace 7 in Fig. 14) P_L-waves and long-period S-waves are clearly detected. Trace 8 shows for comparison the velocity-proportional (direct FBV) output filtered by a 20 s narrow-band filter which approximately simulates the response curve of high-gain long-period LASA instruments (Molnar et al., 1969).

At present the complex FBV/DPS is used for crust and upper mantle structure investigations, for earthquake mechanism studies, and for studies concerned with the determination of earthquake magnitudes. The results will be published in separate papers.

Conclusion

This informative paper presents a comprehensive review of the present set-up and possibilities of application of the FBV/DPS system. The described devices and methods do not present a final stage of development. Preparatory work is underway for installing a further broadband recording system of the FBV type at the polish seismic station Ksiaz (KSP). Both the KHC and KSP stations are located near the international DSS profile VII which points towards the seismically active region of the Kurile Islands. The installation of a displacement sensing feedback-controlled broadband system (FBD) which is anticipated should record also free oscillations of the Earth is being prepared at the KHC station. The gradual improvement of the DPS system is also anticipated. This concerns in particular the installing of a multichannel subsystem for rapid data digitizing and of an ADT 4316 minicomputer.

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