A digital very-broad-band seismograph

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ABSTRACT. A digital seismograph is presented which uses only one sensor and one digital data stream for each component of ground motion to record nearly the entire teleseismic spectrum. We call this system very-broad-band or VBB. As sensors we use the STS-1 (leaf-spring) seismometers (Wielandt and Streckeisen, 1982). Their feedback circuit has been modified to make the response at the BB output flat to ground velocity from 0.2 to 360 s period. Long-period and free-mode signals are now resolved in the broad-band signal. Narrow-band data can be obtained by digital filtration and decimation of the VBB data stream, on-line or off-line. This paper describes the modifications in the STS-1 sensor and presents seismogram examples and results from calibration experiments and cross-spectral noise analysis. The digital system will be described in a subsequent publication.

Key words : seismograph, broad-band, global networks, digitizer noise.

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INTRODUCTION

The division of the seismic spectrum into a short-period and a long-period band is determined not by the nature of earthquake seismic signals but by the presence of marine microseisms which obscure all but the strongest earthquake signals at intermediate periods. Seismographs with visible recording are designed to suppress microseisms by some form of bandpass filtration in order to display weak short- or long-period signals. The historical development of seismic instrumentation has been away from broad-band recording, which has not been uncommon in the time of mechanical seismographs, and towards high-gain recording in a restricted bandwidth.

The interest in broad-band recording was renewed when magnetic tape recording became available (Berckhemer, 1971). The introduction of electronic force feedback to seismic instrument design at about the same time made it possible to realize the wide, flat response required in a broad-band seismograph. Plesinger and Horalek (1976) installed in 1972 at Kasperske Hory, CSSR, a three-component set of feedback seismographs the response of which was flat to ground velocity from 0.3 to 300 s. The signals were recorded on magnetic tape in bi-level, multi-track FM; the station is presently being converted to digital recording. A similar station was installed in 1978 at Ksiaz, Poland.

Despite their potential advantages, broad-band seismographs have not been widely used. This is because a broad-band seismograph alone is not a very useful instrument. It requires playback and processing equipment to produce visible seismograms. Only digital recording and processing will permit the retrieval of a maximum amount of information. The computing facilities and software that make this practical are only now becoming available to many seismological observatories.

The first major digital broad-band installation was the German GRF array (Harjes and Seidl, 1978). Since the array dimensions would not permit wavenumber resolution at longer periods, a velocity sensor with a corner period of 20 s had been specified for the array. When the first STS-1 sensors were manufactured for the GRF array, their response was shaped accordingly even though this is not an optimal broad-band response for a general purpose sensor. The performance of the GRF array at long periods is therefore limited. Long-period responses such as WWSSN-LP and SRO-LP can be simulated from the digital broad-band data (Seidl, 1980), but ground noise is not resolved beyond a period of 100 s. Also, gainranging has been found to cause transients in low-pass filtered records. Data from GRF are therefore not useful for very-long-period seismology.

The recent interest in the establishment of global networks of digital broad-band seismographs (Romanowicz *et al.*, 1984; Romanowicz and Dziewonski, 1985) has motivated us to reconsider the problem of digital broad-band recording. With hardware similar to that required for a digital system of the GRF type, it should be possible to record the whole spectrum of teleseismic signals, say up to a period of one hour. The most obvious argument in favour of such a VBB system is that it does not *a priori* determine the seismological research. Every user would simply extract that band of frequencies in which he is interested, unrestricted by any artificial subdivision of the spectrum. As compared to conventional narrow-band systems, a VBB system is not only more useful but also technically simpler. It avoids the use of analog response-shaping filters with their traditional calibration and noise problems. Although new semiconductor components would now permit the construction of more satisfactory low-frequency filters, these components can be used more efficiently in the feedback loop of a broad-band seismometer so that separate filters are no longer needed.

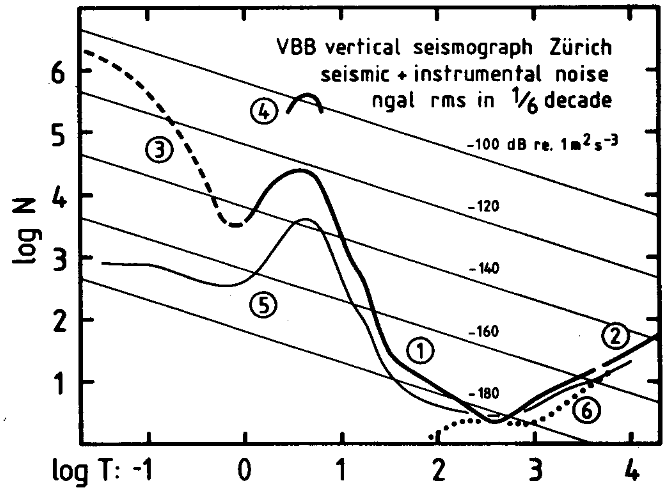

Figure 1

Seismic and instrumental noise of the vertical VBB *seismograph at Zurich, measured in a constant relative bandwidth of* 1/6 *decade.*

1) *Total noise observed on January* 1, 1985; *a typical result.*

2) *Total noise at very long periods, average of two noise samples* 11 *and* 14 *days long.*

3) *Local short-period noise.*

4) *Ground noise during a microseismic storm.*

5) *The low-noise model, a simplified representation of minimum observed vertical seismic noise, taken from Peterson and Tilgner* (1985).

6) *Instrumental noise of the* VBB *seismograph as inferred from the cross-spectral analysis (average of three typical results).*

CONSTRAINTS ON THE RESPONSE OF A DIGITAL BROAD-BAND SEISMOGRAPH

For the purpose of this discussion we will think of a digital broad-band seismograph as consisting of a sensor, a digitizer, and a recorder; practical instruments are normally designed around a microcomputer for greater flexibility. If an anti-aliasing filter or gain-ranging amplifiers are necessary, we will consider them part of the digitizer.

A digital VBB seismograph is expected to have the following characteristics (cf. IRIS, 1985) :

1) Its sensitivity must be adequate to resolve seismic signals at the level of minimum ground noise over the entire teleseismic spectrum, approximately from 0.3 mHz to 10 Hz.

2) Its operating range should be large enough to record the largest teleseismic signals on scale (say, those from a magnitude 9 earthquake at 20° distance).

3) The largest ground noise that is likely to occur in any part of the seismic spectrum must not interfere with the resolution of small signals at other frequencies. Especially, the system must deliver undisturbed free-mode records during a microseismic storm or occasional bursts of local noise.

General considerations

The first two requirements specify the sensitivity and operating range of the system but not its response. However, we cannot meet the specifications unless we choose the sensor response appropriately. The dynamic range of seismic signals extends over 140 dB at long periods; this is already at the limit of what can be handled in electronic circuits without major problems. The seismic signal levels depend on frequency; if we convert them into electric levels using a given sensor response, we will in general arrive at a still larger range of electric signals that may be too large for any available digitizer. We must therefore minimize the required performance of the digitizer by an appropriate choice of the sensor response.

Similar considerations apply to the third specification. Winterly marine microseisms can be 200000 times larger than ground noise in the free-mode band in an electric signal that is proportional to ground acceleration (fig. 1) but « only » 4000 times larger in a signal proportional to ground velocity (fig. 2). A resolution and linearity to one part in 200000 are beyond the capabilities of all but the most sophisticated digitizers.

On the other hand, we cannot build a sensor with an arbitrarily defined response. Although feedback seismometers are very flexible in this respect, complicated transfer functions can be realized only at the expense of dynamic range. Practically we have the choice of making the response flat to velocity or flat to acceleration (or a combination of these) over most of the teleseismic band. Over the bandwidth of a VBB seismograph, this choice has a large effect on the dynamic range of signals present in the system.

Determination of the « ideal » response

At all frequencies where the system is to resolve ground noise, the sensor response must raise it above the noise generated in the digitizer, which we refer to its input. The gain margin must however be as small as possible because any extra gain reduces the range of input signals and may also cause nonlinear distortions. A gain margin of about 2 is normally sufficient to make

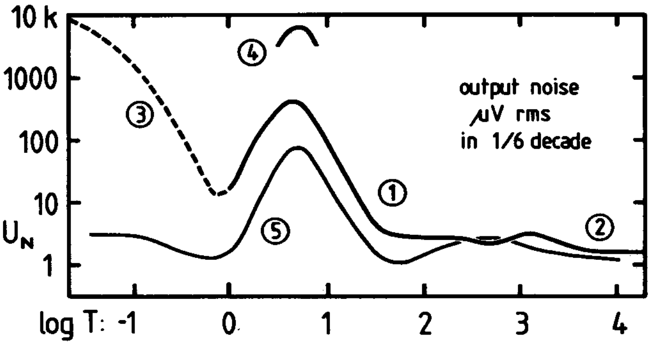

Figure 2
Seismic noise at the output of a sensor whose response is flat to acceleration at short periods, flat to velocity at periods between 1 *and* 360 s *with a responsivity of* 2400 Vs/m, *and flat to the second derivative of velocity at longer periods. Legends* 1 *to* 5 *as in the previous figure.*

the contribution of the digitizer to the total noise insignificant. The ideal response can thus be defined as two times the frequency-dependent ratio of digitizer noise to ground noise. A frequently used formulation is that the sensor response must « pre-whiten » ground noise; however this formulation assumes that digitizer noise is white, which is an oversimplification at seismic frequencies.

Digitizer noise

Noise generated in the digitizer can be subdivided into three major contributions :

1. *Quantization noise*

An ideal digitizer rounds the input value to the nearest integer multiple of a quantum q (one count), which can be expressed as an equivalent step of the input voltage. The sequence of rounding errors constitutes the quantization noise. This noise is white under certain conditions, for example when a certain amount of high-frequency noise is present in the signal. Quantization noise has a constant total power of $q^2/12$ in the bandwidth between zero frequency and the Nyquist frequency. Its spectral density therefore depends on the sampling rate, and can be reduced by oversampling and subsequent bandwidth reduction. This process naturally takes place when VBB data are low-pass filtered, and can give a VBB system a substantial advantage in resolution over a narrow-band system with a lower sampling rate. Gainranging systems have, of course, a signal-dependent level of quantization noise.

2. *Semiconductor noise*

Like any other active semiconductor device, digitizers suffer from electronic noise both of the « white » and the « $1/f$ »-variety. The corner frequency below which the $1/f$-component is predominant usually lies in the seismic band. While semiconductor noise may be masked by quantization noise in low-resolution (8 to 12 bits) digitizers throughout the seismic band, it normally limits the long-period resolution of digitizers with a higher numerical resolution.

3. *Signal-generated noise or intermodulation*

A nonlinear system generates, in the presence of non-stationary signals at its input, among other distortions a spurious long-period signal that follows the envelope of the input signal. This may severely reduce the ability of the system to resolve long-period input signals. The problem of nonlinearity is of course not restricted to the digitizer; however gainranging and multiplexing digitizers are notorious for nonlinear distortions and must be used with the greatest care in a VBB seismograph.

The VBB response

If we ignore all but the white components of digitizer noise and assume a « low-noise » model for ground noise (Peterson and Tilgner, 1985; curve 5 in our figure 1), then we arrive at an ideal response that is nearly flat to acceleration (except for the microseismic peak). Our experience is, however, that digitizers do have substantial $1/f$-noise at seismic frequencies, and that most sites have an elevated level of short-period noise while the very-long-period noise is close to the observed minimum. In that case, the ideal response is nearly flat to velocity. Although we consider this response to be the better choice for most sites, none of these simple responses is fully satisfactory if we consider the variety of noise conditions encountered in practice. A system that records acceleration would require an extremely good digitizer as pointed out earlier, and might not operate satisfactorily at a site with cultural noise. A system that records velocity would fail to resolve minimum ground noise at very short periods if its gain is set properly for the rest of the spectrum.

For the case that minimum ground noise must be resolved above 3 Hz (which is beyond the specifications of the STS-1 sensor), we propose to use a composite response, one that is flat to velocity at periods longer than 1 s and flat to acceleration at shorter periods. At periods longer than 300 or 400 s, a second-order rolloff from the velocity response is adequate because ground noise increases rapidly there (fig. 1). Figure 2 shows the ground noise spectra of figure 1 as they would appear at the output of the composite system. Except for the microseismic peak, minimum ground noise now closely follows a $1/f$-distribution (which would be represented by an horizontal line). A simple calculation shows that in the presence of maximum microseisms, we would need a numerical resolution of 11 bits to resolve minimum short-period noise. Long-period noise can theoretically be resolved with 8 bits.

REALIZATION OF A VBB VELOCITY RESPONSE

The STS-1 seismometers have been the subject of a previous paper (Wielandt and Streckeisen, 1982). We will therefore only describe the modifications necessary to obtain the VBB response. Since at frequencies below 5 Hz the response of the sensor is determined by the elements of the feedback circuit, we need not modify the mechanical sensor. The capacitor C (fig. 3) and the integral-feedback resistor R 2 determine the operating

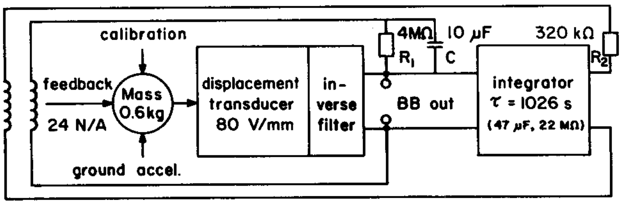

Figure 3
Block diagram of the modified feedback circuit. Compare figure 6 *of Wielandt and Streckeisen* (1982).

range at short and intermediate periods and the drift range, respectively, and therefore should not be changed. We can then use the time constant τ of the integrator to bring the apparent free period to any desired value, and the proportional-feedback resistor R 1 to restore subcritical damping (compare the formulae given by Wielandt and Streckeisen, 1982, pp. 2355-2356). For a free period of 360 s, τ must be increased from 3.2 s in the original STS-1 to 1026 s, and R 1 from 0.22 to 4 megohms. An integrator with a time constant of more than 1000 s and a noise level of one microvolt has only recently become practical; we need such low noise in order to maintain the large dynamic range of the sensor.

There remains, however, a problem with the loop gain at long periods. Loop gain is a measure of the effectiveness of the electronic force feedback in determining the instrumental response. A high loop gain, say 1000 or more, means that the response is almost entirely determined by the feedback system. This is desirable because electronic components are much more stable and « ideal » than a mechanical long-period suspension. The indicated changes would reduce the loop gain at the new free period from about 2000 to about 10 (depending on the mechanical free period of the suspension), a value that is probably too small to suppress the influence of the suspension on the overall response. We have therefore inserted after the displacement transducer a filter whose response is inverse to that of the suspension, making the latter appear to the rest of the circuit like one whose mechanical free period is infinitely long. This raises the loop gain to more than its value in the unmodified sensor.

The composite response that was mentioned earlier can be implemented with a simple modification of the line driver circuit outside the feedback loop. It will reduce the range of the system at short periods compared to a VBB velocity response, but not the range of the feedback loop. Large short-period signals may then be clipped but will not cause long-period transients. We have not implemented this variant in our present systems.

The modification of the free period from 20 to 360 s has no effect on the range at short and intermediate periods and at subseismic frequencies, but the elevated LP response reduces the range in the LP and VLP seismic bands. Clipping now occurs at a uniform ground velocity of $\pm$ 8 mm/s up to 360 s. Still, the maximum permitted ground displacement is one-half meter p-p at 200 s, which should be sufficient to record mantle waves from a magnitude $Mw = 9.5$ earthquake at 30° distance.

TEST RESULTS

We are operating a total of four VBB seismographs at the time of writing, in a vertical seismograph at ETH Zurich and a three-component system at Harvard College Observatory. While the sensors are nearly the same in both places, the data acquisition systems are different. None of them covers the full operating range of the sensor, which would require a numerical range of 20 to 24 bits, depending on local noise levels and on the performance of the digitizer at long periods.

At Zurich, the signals are low-pass filtered at 1 Hz and sampled at 5 Hz. The digitizer has a fixed 12-bit range that covers only 0.25 percent of the operating range of the sensor, but is still sufficient to record distant events up to magnitude 7 on scale. We have the prototype leaf-spring seismometer of 1976 available for comparison at this site.

The digital system at Harvard is more advanced. Its primary sampling rate is 20 Hz with an analog bandwidth of 5 Hz. It normally uses a 15-bit digitizer and two gain levels a factor of 32 apart which cover 10 percent of the sensor range. The processor corrects the data from the two gain ranges for offset and gain errors and combines them into one 32-bit floating-point number for each component. Additional data streams with 1 Hz and 0.1 Hz sampling are derived in the station processor by digital filtration and decimation. This system is still evolving and will be described in a separate publication.

Since the modification of the sensor from a BB to a VBB response does not affect its behaviour at short and intermediate periods, we present here only results for long periods.

Calibration

The VBB seismometer at Zurich was calibrated twice : in November 1984 in a laboratory room (in the tenth floor of an ETH office building), and in February 1985 when it was installed in a vault. In both cases, a series of step responses was digitally recorded, and a steady-state calibration in the period range from 1 s to 1000 s was done manually (Mitronovas and Wielandt, 1975). The data were then inverted for the two instrumental parameters, free period and fraction of critical damping, with a least-squares method. (Unknown parameters in the inversion are also a constant delay in the recording system, and a constant amplitude factor). The results are given in table 1. The observed change in the free period, including the effects of reinstallation, aging, and temperature changes, is only 0.012 s out of 362 s as inferred from the more precise steady-state method. This is probably coincidental since the calibration itself is not that precise, still it demonstrates the stability of the feedback system. The damping factor did change by 2 parts in 1000; this parameter is coupled to the mechanical free period, which is tilt sensitive and can change when the sensor is reinstalled.

The deviation of the actual response from that of the best-fitting harmonic oscillator is very small in all cases. The calibration pulses fit their theoretical counterparts within 0.1 percent of the peak amplitude. The error

Table 1

Results of four calibration experiments

Steady-state calibration :			
Date	Period(s)	Damping	max. phase residual
Nov. 84	361.94	0.7069	0.0008 cycles (1-720 s)
Feb. 85	361.93	0.7053	0.0007 cycles (1-1000 s)
Transient calibration (step response) :			
Date	Period (s)	Damping	max. residual
Nov. 84	359.59	0.7055	0.001 of peak
Feb. 85	360.57	0.7066	0.001 of peak

reflects the relative amplitude of marine microseisms. The phase delay measured with the steady-state method differs from the theoretical value by less than 0.1 percent of the signal period at all periods longer than 5 s, and less than 5 ms at shorter periods; this accuracy is typical for the original version of the instrument as well. A maximum in the residuals can be recognized at a period of 20 s. We explain it by an imperfect match between the mechanical suspension and the inverse filter; in fact the filter was not matched at all but was computed for some nominal values of the mechanical parameters. The observed amplitudes agree with the theoretical ones within one percent, which is the accuracy of our *XY*-recorder.

We have not found an explanation for the persistent, although minor, discrepancy of the free period between the two calibration methods.

Instrumental noise

The best way to study the instrumental noise of a seismometer is to cross-correlate its output signal with that of a different instrument. When the instrumental noise is uncorrelated between the two sensors and also with the seismic noise, the method provides separate estimates of the three noise levels. We performed this analysis in frequency bands of constant relative bandwidth of one-sixth decade. Fairly long time series are needed for significant results; two of our noise samples were 11 and 14 days long. These were however not sampled at 5 Hz but were prefiltered and sampled at 0.2 Hz; the perfect coherency of the prefiltered VBB data with the original ones was independently established using shorter time series. The results of the cross-correlation experiments are shown in figure 1. Curve 1 there gives the total noise of the VBB instrument as obtained from a typical 24-h sample of 5 Hz VBB data; curve 2 is its continuation based on the two long samples. Curve 6 represents the inferred instrumental noise of the VBB seismometer in the VLP band. The instrumental noise is below the seismic noise throughout the band, with the exception of a narrow region around 400 s period where the seismic noise has a distinct minimum and is not well resolved. The total noise observed there is however lower than what others have considered to be the worldwide minimum of seismic noise (curve 5), so the sensor would resolve that noise. The noise minimum near 400 s is persistent under normal weather conditions; it might be peculiar to the test site.

VBB seismograms and free-mode spectra

Unfiltered broad-band seismograms do, in general, not look very spectacular in comparison to narrow-band records (fig. 4). It takes a magnitude 6 earthquake to produce a signal that stands clearly out of the microseismic noise (fig. 5). What is remarkable in such a VBB seismogram is that body waves, surface waves, and even the mantle waves which make up the R 2 wave train, all have comparable amplitudes. Digital VBB records therefore provide perfect input data for subsequent filtration.

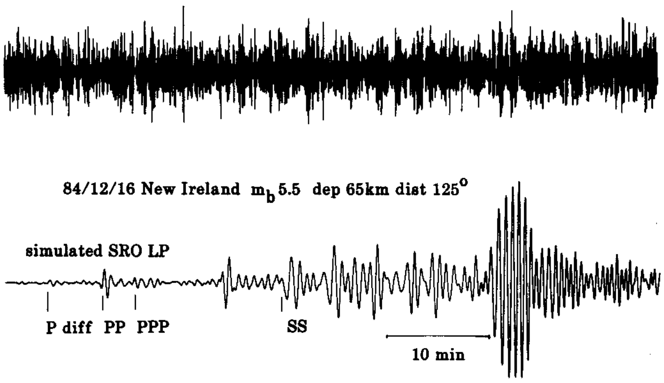

Figure 4

Seismogram of a M_b = 5.5 earthquake at New Ireland (16 *Dec.* 1984, 19:52. *Dist.* = 125°, *Station* HRV). *The top trace shows about* 1 h *of vertical* VBB *data sampled at* 1 Hz. *After digital filtration to the* SRO-LP *response, the event clearly emerges from the microseisms.*

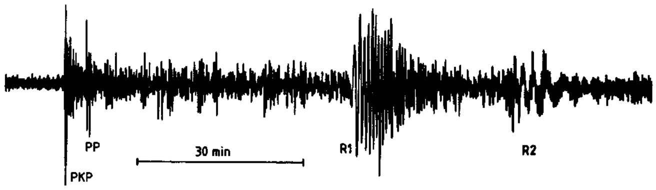

Figure 5

VBB *seismogram of the Loyalty Islands Earthquake of* 15 *Nov.* 1984, 02:46, M_b = 6.2, *Dist.* = 154°, *station* ZUR.

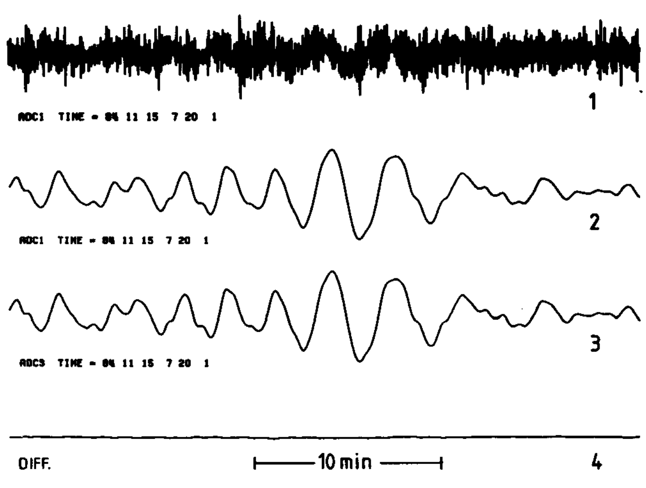

Figure 6

R 4 *wave train of the same earthquake.* 1) VBB *record,* 2) *the same filtered to* VLP, 3) *original* VLP *record from a different instrument,* 4) *differential signal. The length of each trace is* 35 mn.

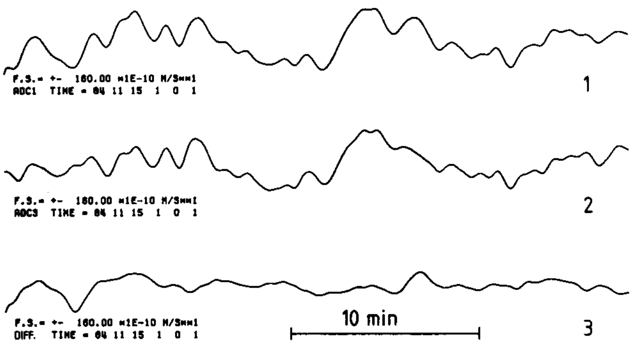

Figure 7
VLP *noise samples from the* VBB *seismograph* (1), *from the* VLP *seismograph* (2), *and the differential signal* (3). *Passband from* 60 *to* 600 s *(see text). The length of each trace is* 35 mn.

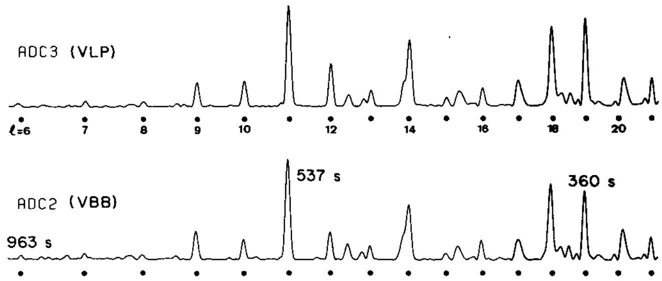

Figure 8
Free mode power spectra obtained after the Mindanao earthquake of November 20, 1984 (08:15, M_b = 6.4, *Dist.* = 104°, *station* ZUR). *The frequency scale is from* 1 *to* 3 mHz. *The frequencies of modes* $_0S_l$ *in a standard earth model are indicated by dots. Top :* VLP, *bottom :* VBB *seismograph. The amplitude of the largest peak,* $_0S_{11}$, *is* 11 ngal rms.

Trace 1 in figure 6 shows the R 4 arrival from the same event as in figure 5. Even here mantle waves can be recognized in the original record. After VLP filtration (trace 2), the VBB signal is visually identical to the VLP record obtained from the other instrument (trace 3). The difference (trace 4) is at the level of ground noise. Figure 7 compares the total VLP noise of the two instruments in time domain ; trace 1 is from the VBB and trace 2 from the VLP system. The signals have been converted to ground velocity in a band from 60 to 600 s period. The vertical offset between the traces is equivalent to a signal amplitude of 16 nm/s. Trace 3 is the difference between 1 and 2, representing the combined instrumental noise of both sensors.

A sensitive test to the performance of a long-period seismograph is its ability to record free oscillations of the Earth. Since about 24 h of data must be analysed to obtain a reasonable frequency resolution, only a sensor that is virtually free of transient disturbances will produce satisfactory free-mode spectra. Figure 8 shows power spectra from the two instruments at Zurich, after an earthquake on Mindanao on November 20, 1984 (M_b = 6.4). The largest peak associated with mode $_0S_{11}$ represents a time-domain signal of one count peak-to-peak in the original VBB record, and a seismic acceleration of 11 ngal rms. Figure 9 shows the spectral peak due to mode $_0S_0$, at a nominal period of 1227.5 s, ten days after the Chilean earthquake of March 3, 1985. This signal has an amplitude of 2.3 ngal rms, and contributes one-tenth count peak-to-peak to the digital data.

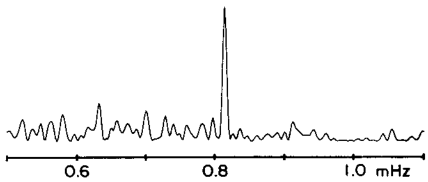

Figure 9
Power spectrum showing mode $_0S_0$ *after the Chilean earthquake of March* 3, 1985. *Spectrum based on* 48 h *of data from the* VBB *instrument at Zurich, recorded on March* 13 *and* 14. *The peak represents a frequency of* 0.815 mHz *and an amplitude of* 2.3 ngal rms.

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