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VII.4 Regional arrays and optimum data processing schemes

In a series of contributions (see reference list) we have addressed various aspects of array design, data processing schemes and past, present and likely future developments in this field. The research to be reported here is tied to an evaluation of the prototype regional array NORESS (configuration shown in Fig. VII.4.1). In this respect a two-fold analyzing strategy was chosen, namely, first to estimate from NORESS data standard noise and signal characteristics like correlation functions and spectra under a variety of conditions/events and secondly, with a basis in Wiener filtering theory, to evaluate the relative merits of various array data processing schemes for SNR-enchancements. In the following the essence of results obtained will be presented.

Noise and signal characteristics

SNR-spectra for events in different tectonic environments are presented in Fig. VII.4.2a,b,c; evidently only P-waves with a predominant shield path exhibit a significant amount of high-frequency energy so as to produce peaks in the SNR-spectra above 5 Hz. Signal paths in oceanic and mobile tectonic belt types of lithosphere appear to be depleted in high-frequency signal energy; the spectra here are not too different from those typical of teleseismic events.

Noise spectra between 2-10 Hz appear to decay like ω^{-4}, and besides that are generally independent of time of day, day of week and seasonal variations as well. In other words, the high-frequency part of the noise field is not dominated by cultural and microseismic noise contributions.

Noise correlations as functions of sensor separations have to be calculated under a variety of conditions, that is, sensor time lags tied to both vertical and horizontal beams. Despite large fluctuations in individual estimates here, significant differences exist as a function of beam location, e.g., see Figs. VII.4.3a and b. This feature is rather obvious from Table

VII.4.1, where SNR-enhancements as a function of phase velocity and azimuth for different bandpass filters and processing schemes amounts to approximately 3 dB!

Array data processing schemes

Within the general class of Wiener filtering 3 array data processing schemes have been considered, namely, standard beamforming, optimum weighting and maximum likelihood (ML) filtering. The mathematics of these approaches are detailed in Ingate et al (1985). Standard beamforming is optimum for uncorrelated noise ($\sqrt{N}$ gain) which in general takes place above 4 Hz for the NORESS array configuration. Optimum weighting may give an additional 2-4 dB gain for correlated noise, while ML-processing is clearly superior vis-à-vis the other two processing schemes, as evident from Fig. VII.4.4. The well-known problem with more advanced array data processing schemes is their rather severe computer loads. For example, for the optimum weighting scheme the noise covariance matrix has to be updated each 2.5-5.0 sec because of a general noise non-stationarity as illustrated in Fig. VII.4.5.

Discussion

After extensive analysis and processing of the NORESS data, some remarks on regional array design and operation may be justified. First of all, array design is problematic as the operational bandwidth reflecting SNR-spectra from different tectonic regimes should cover roughly the 3-8 Hz range in contrast to "teleseismic" arrays, where the bandwidth is 1-2 Hz. To ensure adequate seismicity surveillance capabilities in the 3-8 Hz band very many beams have to be formed, otherwise signal decorrelation losses would be severe, even when the data processing is restricted to simple beamforming. Indeed, if relatively better performance is desired, this may most easily be achieved on the hardware side by adding more instruments and/or using the "analog sensor clustering" commonly used in seismic land surveys. As regards array configuraiton per se, a reasonably flat sensor spacing distribution has to be ensured if we want a reasonably flat array response as a function of frequency. For example, from Fig. VII.4.4 we see that the NORESS performance is far from optimum below 4 Hz due to high noise correlation and likewise beyond 6-8 Hz due to poor signal correlations.

Arrays are relatively costly to build and operate so there have been limited possibilities for practical experimentation. However, taking advantage of recent advances in microprocessor and communication technology, it is feasible to construct and deploy small, inexpensive arrays as discussed in detail by Husebye et al. This would naturally add to the flexibility of practical array experiments, and also increase the number of arrays being operative. Apparently, most of the seismological community takes part in these new developments as the newly formed IRIS-consortium plans for a digital, global seismograph network and mobile seismic arrays comprising hundreds (thousands) of instruments. These and likely future trends in digital seismometry are discussed in all papers referenced below.

Result summary of the prototype NORESS evaluation

The major problem here was that of suppressing ambient noise, and major results obtained are as follows.

Signal and noise field characteristics

- SNR spectra peak at ca 2, 3 and 6 Hz, respectively, for events whose signal paths are predominantly oceanic, mobile cratonic belt and shield. Teleseismic arrays like LASA and NORSR operate generally in the narrow 1-2 Hz band.
- Above 2 Hz noise spectra are essentially time invariant and besides have approximately a ω^{-4} decay rate in the 2-10 Hz band.

- Noise correlation distance is clearly frequency dependent and is such that noise suppression by simple beamforming will be degraded relative to $\sqrt{N}$ up to about 4 Hz.
- The noise field cannot be considered stationary even for short windows of 2.5-5.0 sec. This is most easily seen in standard beamforming gain variation up to 3 dB as a function of beam location or azimuth and phase velocity.
- Signal correlations for P and Lg phases decrease with increasing sensor separation becoming ca 0.5 at about 3 km. This in combination with steering delay errors, including insufficient number of beams deployed, would severely affect array performance above 6-8 Hz.
- Horizontal seismometer recordings exhibit noise and signal correlations, etc., roughly similar to that observed for vertical instruments.

Noise suppression schemes - variants of Wiener filter theory

- Simple beamforming is optimal or $\sqrt{N}$ for uncorrelated noise, but this cannot be achieved using all instruments due to the relatively small NORESS array aperture of 3 km.
- Optimum weighting based on characteristics as manifested in the noise covariance matrix (multichannel) will give an additional gain of 2-4 dB relative to standard beamforming up to about 5 Hz. A simplification here, reducing these weights to the 0/1-type, gives 1-2 dB less gains but still better than standard beamforming.
- Maximum likelihood filtering, computationally demanding, gave approximately $\sqrt{N}$ gains even for lower frequencies where simple beamforming was inefficient.

On the basis of the above results and technical considerations as well, our conclusion is that seismic surveillance is most effectively attained by deploying rather many seismometers (regional arrays) combined with simple processing schemes rather than few instruments combined with sophisticated processing schemes like ML-filtering - simply because investments in array hardware are considered more cost-effective than array software investments.

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References

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Husebye, E.S., E. Thoresen and S.F. Ingate (1984): Seismic arrays for everyone. Terra Cognita (in press).

Husebye, E.S. and S.F. Ingate (1984): Seismic arrays - a new renaissance (in press).

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Filter (Hz)	Phase velocity (km s^{-1})	Azimuth (deg)	Gain (dB) Std. beam	O-weighting
1.0-3.0	4.60	0	3.63	4.82
		90	2.46	3.56
		180	3.94	5.41
		270	5.24	7.15
1.5-3.5	6.20	0	6.50	7.50
		90	5.34	6.61
		180	5.25	6.04
		270	6.71	7.88
2.0-4.0	8.10	0	10.0	11.37
		90	8.82	10.23
		180	7.81	8.94
		270	9.79	10.97
2.5-4.5	12.0	0	11.29	13.90
		90	10.42	12.38
		180	9.94	11.94
		270	11.14	13.36

Table VII.4.1 Standard beamforming and optimum weighting gains as functions of primarily azimuth but also phase velocity and filter passband. The thirteen NORESS-sensors used were nos. 1, 5 to 9 and 10 to 16. Azimuthal gain variation amount to approximately 2 dB, which may increase 1 dB if finer azimuth sampling intervals of 30 deg had been used.

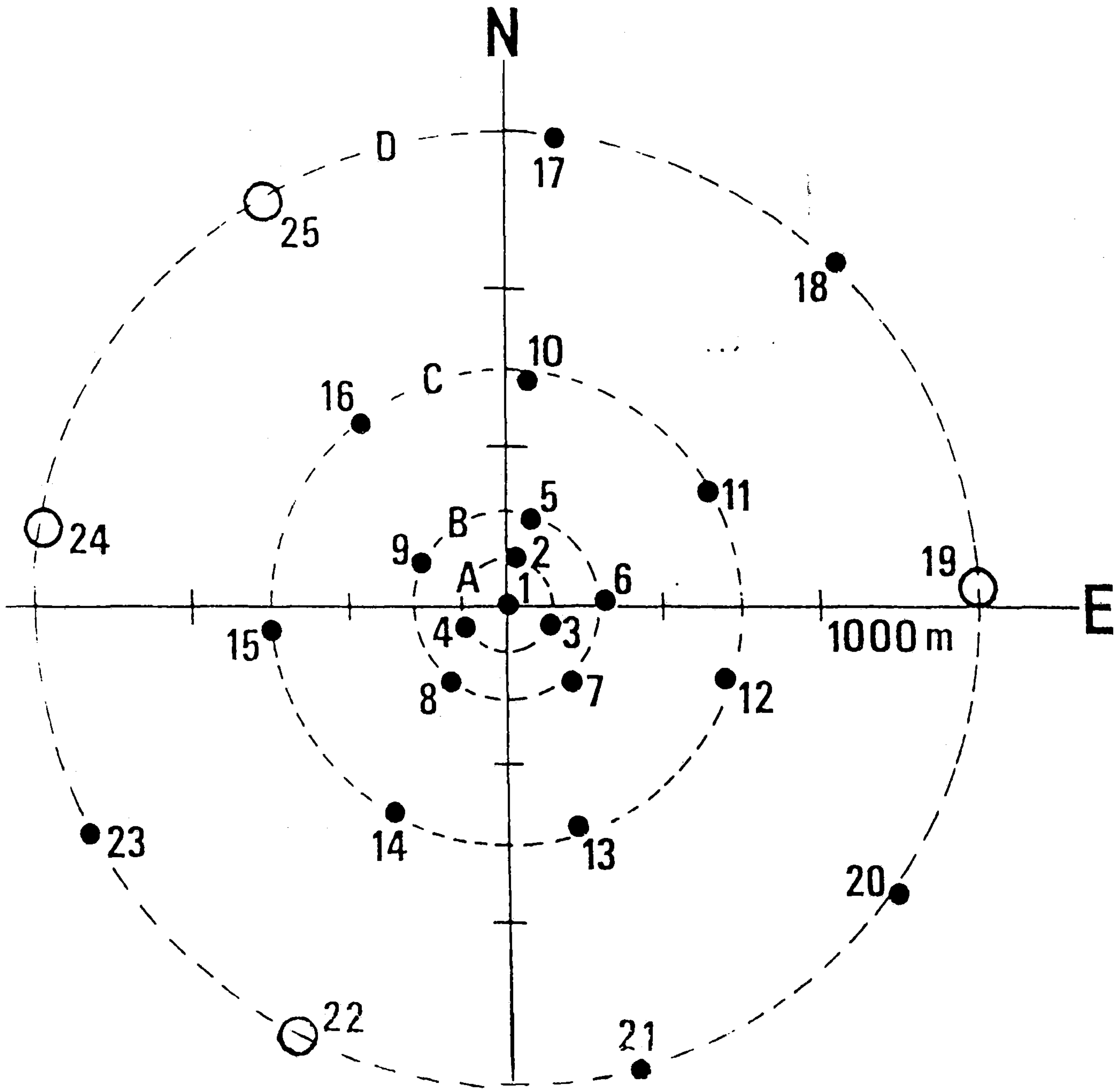

Fig. VII.4.1 The experimental NORESS array located near NORSAR site 06C. Instruments at sites indicated by open circles will be in operation in late 1984.

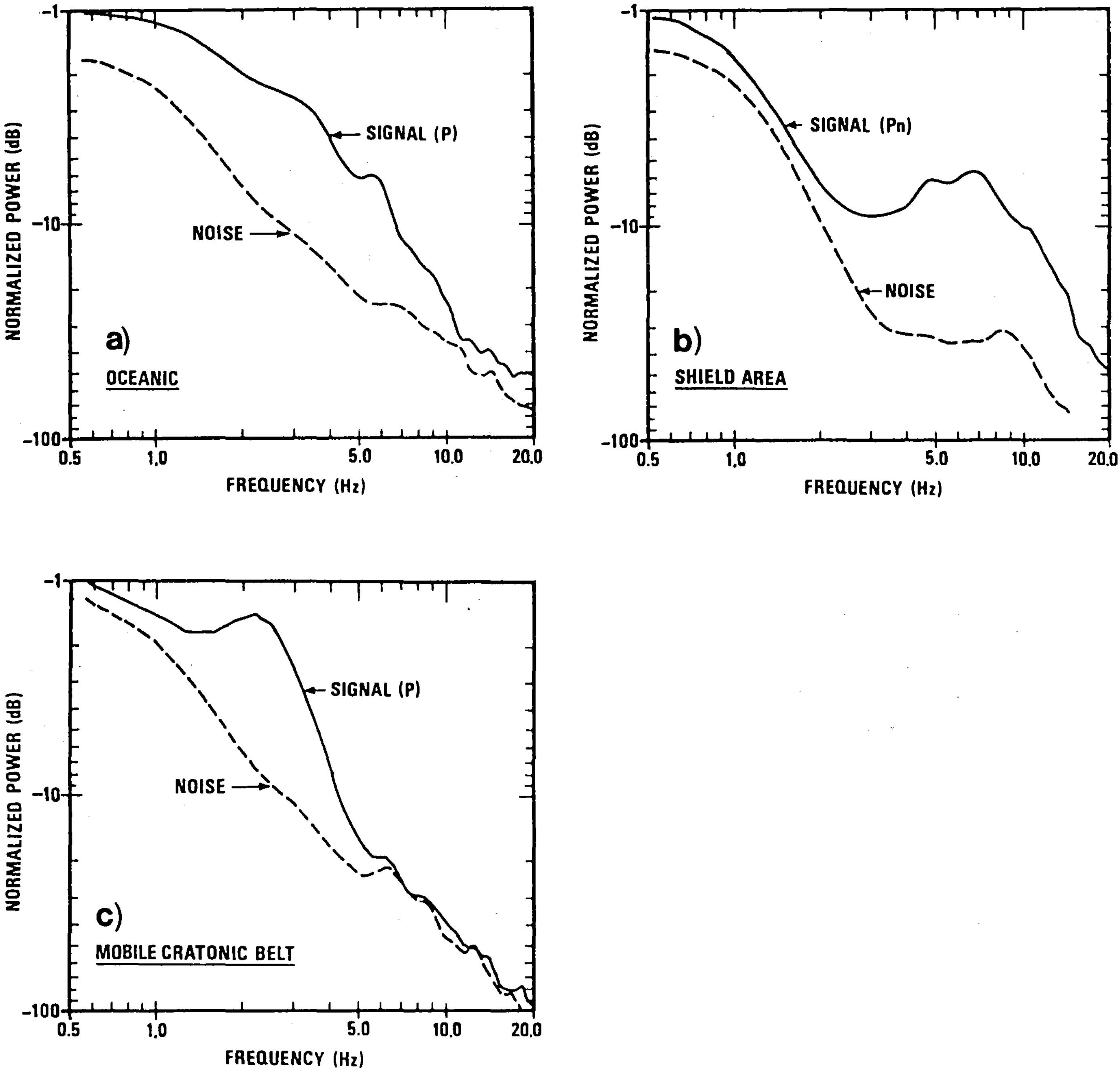

Fig. VII.4.2 Power spectra of events recorded by NORESS. Also shown are spectra of noise before event arrival. Each represents a spectrum averaged over 21 sensors. a) oceanic events; b) shield events; c) events within mobile cratonic belts.

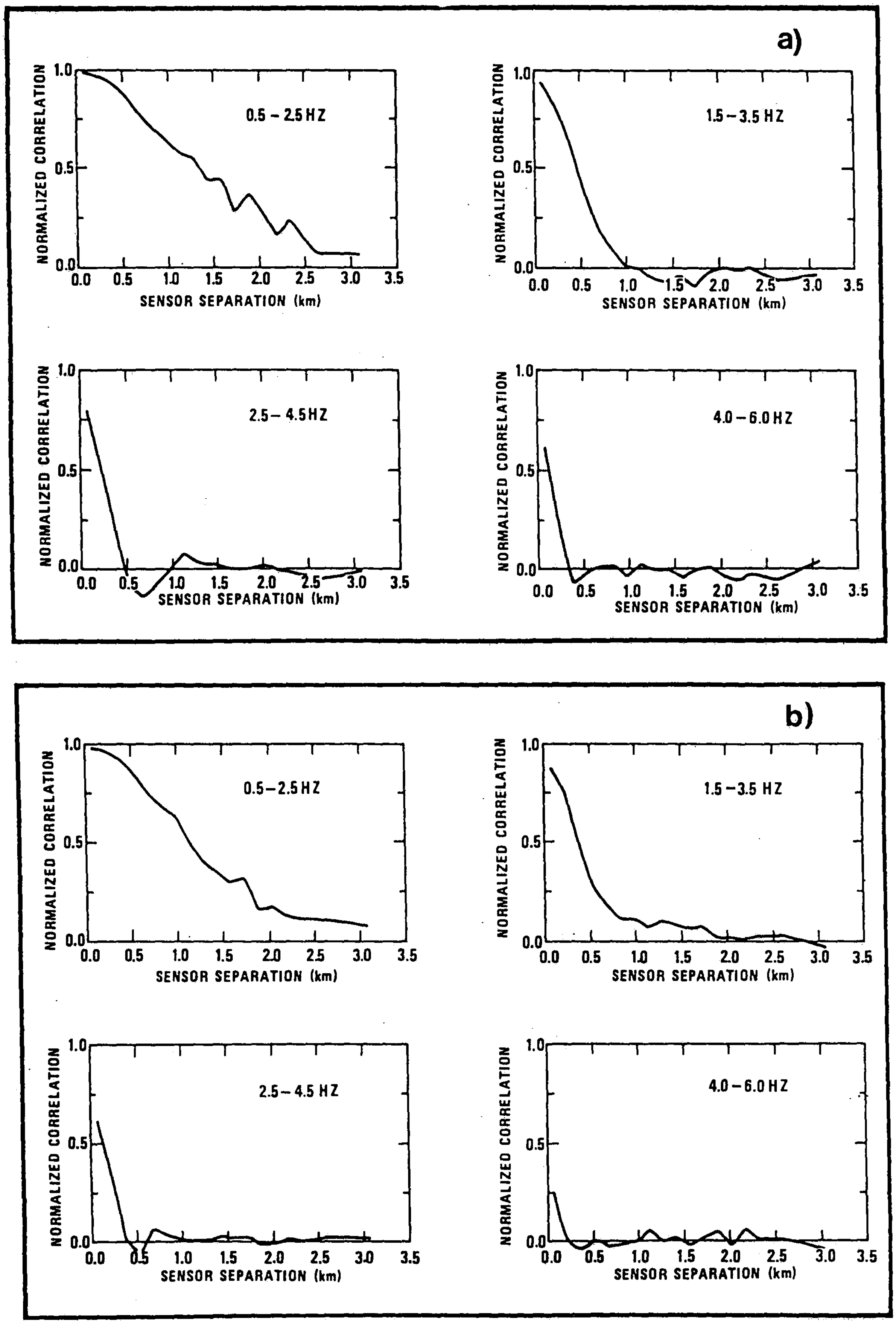

Fig. VII.4.3 Mean normalized correlation curves for noise on the NORESS array as a function of inter-sensor spacing and frequency. a) vertical beam lags; b) horizontal beam lags (azimuth = 0^{o}, velocity = 4.2 km/s). Each curve is an average of 100 sec windows sampled every 5 hours for two days.

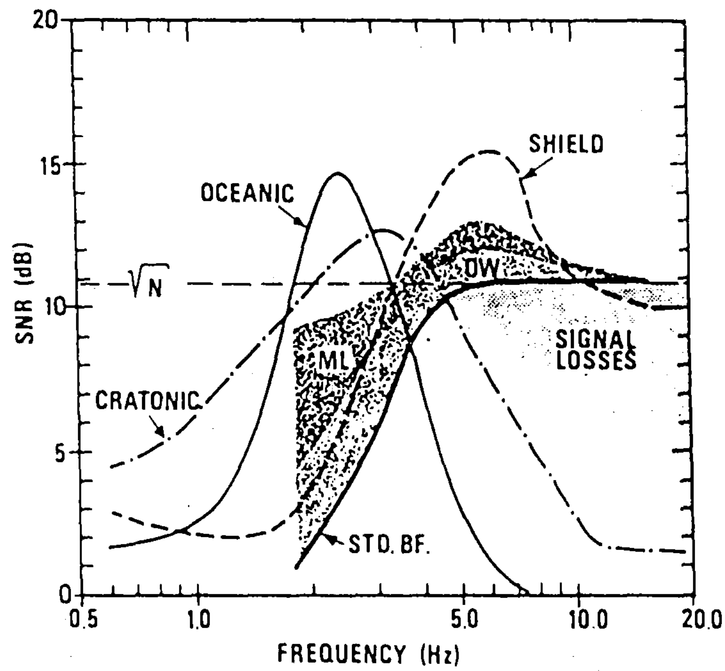

Fig. VII.4.4 SNR-array suppression performance.

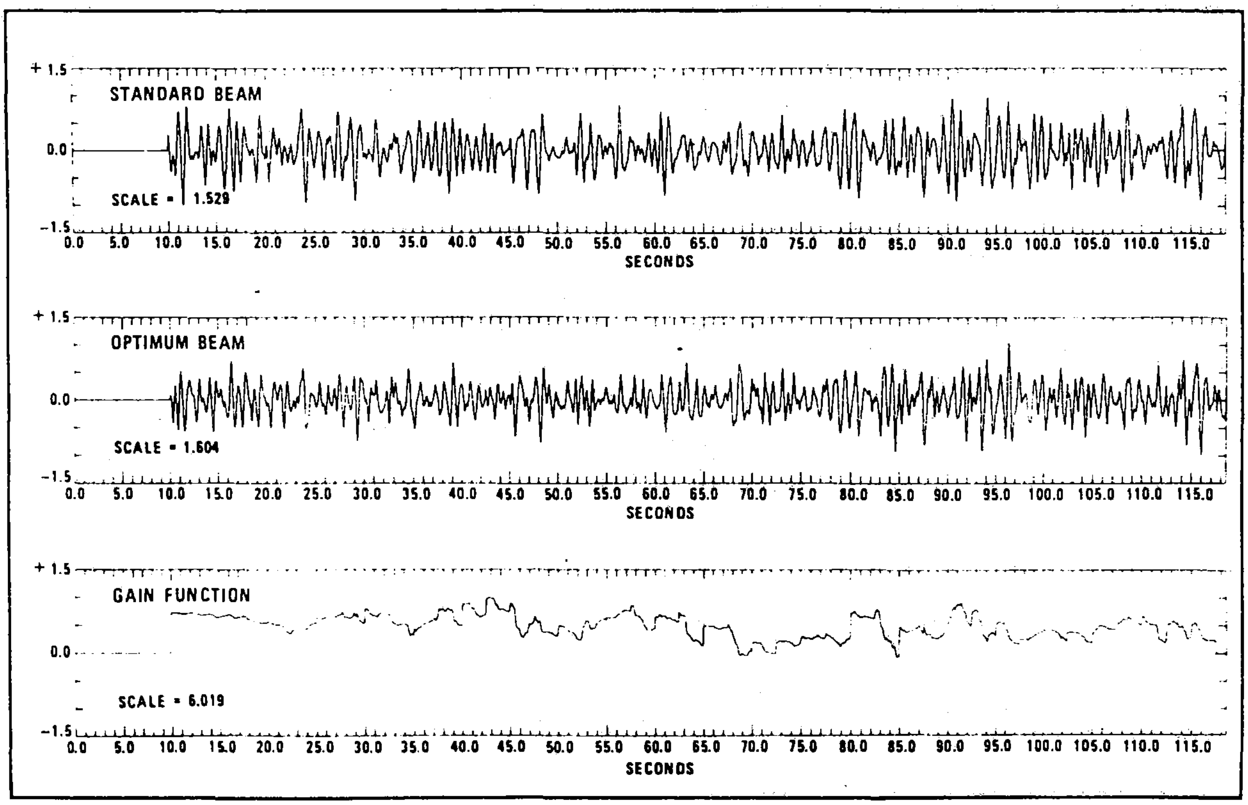

Fig. VII.4.5 Display of standard and optimum beam traces formed during the processing of noise recorded by NORESS. The corresponding gain function is not smooth, but rather fluctuates rapidly in certain time intervals which reflects a degree of non-stationarity in the ambient noise field. The first 10 seconds of data was used to stabilize the covariance matrix, and consequently, not included in the processing. Amplitude scales for the beam traces are in amplitude units, while the amplitude scale for the gain function is in dB.