ESD-TR-68-7

Technical Note

1968-4

ESL

Preliminary Design of a Long-Period Seismic Array for Norway

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24 January 1968

Prepared for the Advanced Research Projects Agency
under Electronic Systems Division Contract AF 19(628)-5167 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

AD 665404

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. This research is a part of Project Vela Uniform, which is sponsored by the U.S. Advanced Research Projects Agency of the Department of Defense; it is supported by ARPA under Air Force Contract AF 19(628)-5167 (ARPA Order 512).

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

PRELIMINARY DESIGN OF A LONG-PERIOD SEISMIC ARRAY FOR NORWAY

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Group 64

TECHNICAL NOTE 1968-4

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ABSTRACT

A preliminary design study for a long-period seismic array in Norway has been completed. It has been shown that if the array contains more-or-less uniformly distributed seismometers over a disc then the spacings between adjacent elements should be between 20 and 25 km. Larger spacings would result in spacial aliasing of organized noise and signals. Smaller spacings would decrease the array resolving power. Properties of specific array configurations are given.

A brief discussion of some engineering considerations is also included.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

I. INTRODUCTION

This preliminary design study for a long-period seismic array in Norway is structured as follows. First, a number of assumptions, which constitute boundary conditions for the design, are listed. Then, subject to these conditions, a number of possible idealized array designs are considered and evaluated using a worst case philosophy. Following the study of idealized arrays some possible arrays which take into account first order effects of the population and geography of Norway are presented and evaluated. A short discussion is then given of many of the assumptions which constituted the design boundary conditions. Finally, a short section is included which deals with engineering considerations related to a long-period array.

It should be understood that some of the recommendations made may well be tempered by the results of a long-period noise survey now in progress.

II. INITIAL ASSUMPTIONS (See Discussion in Section V)

The following is a list of assumptions.

1. Fundamental Rayleigh wave signals from events are of primary interest.
2. An array of long-period vertical seismometers is to be constructed in order to enhance signals.
3. The frequency band of interest is from 0.065 Hz (about 15-sec period) to 0.025 Hz (about 40-sec period).
4. Signal-to-noise ratio improvement is to be achieved by delay-and-sum processing and must be greater than or equal to $\sqrt{N}$ (10 log N in db) where N is the number of seismometers.
5. Fundamental mode Rayleigh wave noise is to be rejected by the array.
6. The array is sufficiently small so that dispersion across the array can be neglected. A typical Rayleigh wave velocity, $v = 3.5$ km/sec, is used for the frequency band of interest.
7. The angular resolving power of the array is to be as great as possible consistent with other requirements. That is, the azimuthal separation, α, between a signal and a noise source for which significant signal-to-noise gain can be achieved is to be minimized.

III. MIN-MAX EVALUATIONS OF ARRAY DESIGNS

Figure 1a shows noise reduction contours in wavenumber space of a hypothetical array which is steered (delay-and-sum processing) to receive Rayleigh waves from the north. The frequency, f, and phase velocity, v, are fixed. All possible fundamental Rayleigh wave noise must lie on the circle (C) of radius f/v. Given that the array is steered north and that Rayleigh noise with an azimuth less than α away from north is of no concern, it is clear that array performance is satisfactory if noise rejection is high at all points on circle (C) which are situated at an angle greater than α away from north. However, array performance must be considered for other steerings. For example, Fig. 1b shows the effect of steering west of north by an amount, β. The low noise reduction sidelobe (P) is now on circle (C) and more than α away from the steering direction. In fact, it should be clear that any low noise reduction point between circles (A) and (B) can be placed on circle (C) at some point more than α from the steering direction by an appropriate choice of β. Therefore, good array patterns will be those having a low sidelobe level between circles (A) and (B) which have their centers at the point to which the array is steered.

Figure 2a shows a typical possible array configuration. The size of the array is fixed by the distance, d = 10 km, from the center element to its nearest neighbor. Note that d is approximately the nearest neighbor distance for all elements. The beam pattern which gives the noise reduction contours of the array in wavenumber space is shown in Fig. 2c. Only the first quadrant of the beam pattern is shown, since it repeats every 360/14 degrees in azimuth due to the seven-fold angular symmetry of the array. Figure 2b shows a curve, obtained using the pattern, which has been constructed to facilitate an investigation of the region between (A) and (B) of Fig. 1 for various α, f, v and d. Specifically, the value of G(x) on Fig. 2b at $x = df/v$ is the worst gain (the least amount of noise rejection) which will be achieved on circle (B) for the given d, f and v. Simple trigonometry shows that the radius of circle (A) is sin $(\alpha/2)$ times that of circle (B). The worst gain on circle (A) is found from G(x) at $x = (df/v) \sin(\alpha/2)$. For α, f, v and d fixed the worst gain between (A) and (B) can be found from G(x) with $(df/v) \sin(\alpha/2) \leq x \leq df/v$. If the frequency range of interest is $0.025 \text{ Hz} \leq f \leq 0.065 \text{ Hz}$ and $v = 3.5$ km/sec, the worst possible noise rejection can be found by looking at G(x) for

$$(d \sin \frac{\alpha}{2}) \left(\frac{0.025}{3.5}\right) = 0.0071 \sin \frac{\alpha}{2} \leq x \leq 0.0186\, d = \left(\frac{0.065}{3.5}\right) d\ .$$

Rather than assuming d and α to be given and evaluating the array, it is possible to choose d to yield satisfactory rejection of Rayleigh noise and minimize α. For this purpose assume that array noise rejection will be satisfactory if it is greater than or equal to 10 log N where N is the number of sensors in the array. The vertical dotted lines on Fig. 2b delimit the high gain region for an array configured like the one in Fig. 2a. The horizontal lines shows 10 log N. The dotted line at x = 0.476

implies that d_{MAX} = 25.7 km is the largest d which can be used without admitting regions with less than 10 log N of gain. Since large d will imply small α, assume d_{MAX} = 25.7 km is specified. From the dotted line at $0.0071\, d_{MAX} \sin \frac{\alpha_N(0.025)}{2} = 0.105 = x$, it follows that $\alpha_N(0.025) \simeq 70^o$ to the 13.4 db = 10 log N point. The quantity $\alpha_N(f)$ is the angular resolution at frequency, f, to a point 10 log N down on the array pattern. Note that $\alpha_3(0.025)$, the 3 db beamwidth at frequency 0.025 Hz, which is often quoted, is $\pm 35^o$. These beamwidths are fixed by the lowest frequency of interest. At 0.045 Hz, which is at the center of the frequency band, the 13.4 db and 3 db beamwidths become

$$\alpha_N(0.045) = 2 \sin^{-1} \{(0.104) [\frac{3.5}{(25.7)(0.045)}] \} = 37^o$$

$$\alpha_3(0.045) = 2 \sin^{-1} \{(0.055) [\frac{3.5}{(25.7)(0.045)}] \} = 19^o$$

Array behavior at 0.045 Hz is of particular interest since it is a frequency at which there is considerable signal power.

Figures 3a, 4a, 5a, 6a and 7a show a variety of other possible array geometries. Figures 3b, 4b, 5b, 6b and 7b show the corresponding worst gain curves which have been used to pick d_{MAX} and determine resolution for the arrays. The gain patterns from which the worst gain curves were developed are shown for some of the arrays in Figs. 3c, 4c and 5c.

The same procedure described in the preceding paragraph has been repeated for each of the arrays and the results tabulated in Table I. It is clear from the table that d_{MAX} has not changed much for the various cases. For all of the arrays nearest neighbors for seismometers tend to be 20 – 25 km apart. The beamwidths of the arrays tends to decrease as the number of sensors is increased since the array diameter is increasing.

The beam patterns discussed thus far are for narrow band signals. It is of interest to gain some information concerning the average behavior of the array across the band of frequencies of interest. It is possible to generate special beam patterns for this purpose.[1] Then when one considers a situation such as that shown in Fig. 1 the frequency must be the center frequency of interest, f_o, and the gain pattern must be a wideband pattern. Fixing f_o, it is possible to generate worst gain curves just as in the narrow band case.

Figures 2d, 3d, 4d and 5d are the wideband worst case gain curves corresponding to the arrays shown in Figs. 2a, 3a, 4a and 5a, Figure 8 shows the frequency spectrum which has been used. Two dotted vertical lines have been shown on each of the wideband worst case gain curves. The line on the right corresponds to circle (B) of Fig. 1 assuming a center frequency, $f_o = 0.045$, and that d_{MAX} of Table I is used. It is clear that no bad wideband sidelobes will pick up Rayleigh wave noise unless it is in the main beam. The left dotted line shows the 10 log N beamwidth of the arrays from the narrow band analysis. The beamwidth is slightly increased in the wideband case.

ARRAY	Figures for Reference	Number of Seismometers (N)	d_{MAX} (km)	α_3 (0.045) (degrees)	α_N (0.045) (degrees)	α_3 (0.025) (degrees)	α_N (0.025) (degrees)
1, 5, 10	6	16	19	28	48	46	94
1, 5, 10, 15	7	31	20.8	17	32	30	60
19 Hex	4	19	25.3	20	39	37	73
37 Hex	5	37	26.6	13	27	24	51
1, 7, 14	2	22	25.7	19	37	35	70
1, 7, 14, 21	3	43	26	13	27	23	50

TABLE I

Although it is recognized that the spectrum used for the wideband curves is not exactly the true spectrum, these curves do give some idea of the effects of the wideband nature of the actual noise and signals.

IV. TYPICAL FEASIBLE LONG-PERIOD ARRAY CONFIGURATIONS FOR NORWAY

The results of the previous section indicate that a long-period array of N sensors should operate satisfactorily if sensor spacings of about 20 – 25 km are maintained. With this in mind, four different possible array configurations for Norway have been constructed. Each of these includes the three noise survey sites which are currently being installed. An attempt was made to avoid water areas, areas of excessive population, and to locate sites in areas which should be relatively accessible. A typical spacing of 22.5 km was used.

Figures 9 through 12 show the arrays and their narrow-band worst gain curves. The axis has been adjusted so that at $y = f/v$ the curves give the worst gain on circle (B) of Fig. 1. The arrays with 24 and 43 elements were obtained by perturbations of the configurations of Figs. 1 and 2. Note that the 24-element array has two noise survey sites somewhat separated from the rest of the instruments. The other two arrays, in order to indicate the first order insensitivity to the details of geometry, were constructed with about 22.5 km minimum spacing while more or less uniformly filling an area. Table II shows the narrow band beamwidths achieved by the arrays. The frequency above which poor narrow band sidelobes might appear also is tabulated.

The overall performance of these arrays is generally satisfactory. However, the two with about 20 elements have some slightly higher sidelobes than do those shown in Figs. 2a and 4a and those with about 40 elements have sidelobes larger than those

ARRAY	Figures for Reference	Number of Seismometers (N)	Spacing	α_3 (0.045) (degrees)	α_N (0.045) (degrees)	MAX f for $\sqrt{N}$ Rejection
Norway 1, 7, 14, 2	9	24	22.5	18	39	0.066 Hz
Norway 1, 7, 14, 21	10	43	22.5	12	29	0.064
Norway 21 Random	11	21	22.5	21	43	0.054
Norway 37 Random	12	37	22.5	15	32	0.064

TABLE II

shown in Figs. 3a and 5a. Thus although performance is relatively insensitive to the details of the configuration, it would be better to attempt to conform more closely to one of the idealized geometries since they appear to have somewhat better sidelobe structures.

The actual number of instruments in a long-period array must be determined either by cost or by establishing some desired capability for the detection of events. All the arrays discussed above were designed so that at least 10 log N noise rejection could be obtained against Rayleigh waves. Noise which is independent between sensors will be reduced by 10 log N. Thus, let us assume that at least 10 log N noise reduction will be achieved by any well designed array. Figure 19 shows the surface wave detection level which might be expected for an array at 40^o, 60^o and 80^o from an event. The curve was constructed assuming that vertical instruments with about the same noise level as in Montana are to be used, that chirp filtering can obtain about 8 db of gain, and that a 6 db signal-to-noise ratio is needed to detect surface waves. The figure also has an axis labeled in values of m_b. The values of m_b and M_s are related by the Gutenberg-Richter relationship. The curves assume that all earthquakes obey this relationship exactly and shows the magnitude at which 100% will have detectable surface waves. Since in reality for a specified value of m_b only half of the events will have M_s as large as that predicted by the Gutenberg-Richter relationship, the values of m_b should be interpreted as the 50% incremental detection threshold.

V. DISCUSSION AND MODIFICATION OF INITIAL ASSUMPTIONS

Assumption 1 Discussion

The relative excitation of short-period body waves and of Rayleigh waves has been established as a powerful discriminant. In addition, Rayleigh waves tend to be received at teleseismic distances with larger amplitudes than other surface waves or than any long-period body phases. Thus it should be possible to use Rayleigh waves as a discriminant at lower magnitudes than any long-period discriminant based upon other phases.

Assumption 2 Discussion

It has been found that the LP horizontal, East-West (EW), North-South (NS), instruments at the Montana LASA are typically about 10 db noisier than the vertical (Z) components. This additional noise on the horizontals may be typical of LP installations in sedimentary regions. It is anticipated that instruments in Norway will be sited in granite and care taken to supply a good operating environment. In such a situation horizontals do not usually tend to be noisy relative to verticals. The noise survey currently underway will yield a definitive answer concerning the relative signal-to-noise ratios on vertical and horizontal instruments in Norway.

If the horizontal instruments are not noisy relative to the verticals, they should provide about 3 db additional gain and should be installed. The installation of N three component sites is no more costly than the installation of 2N vertical only sites and the horizontals allow the use of Love waves as discriminants.

If horizontal component noise is large, the possible installation of a large number of horizontal instruments should probably be reconsidered. In any case it is still desirable to include at least a few three-component instruments. These would be of general scientific value and allow the study of Love wave discriminants at least for large events. The three noise survey sites should constitute the minimum number of three-component sites in the array. If horizontal instruments are not installed initially but may be in the future, the initial installation should take this into account. The additional system cost to allow flexibility (three-component vaults and three channel amplifiers, for example) appears to be modest and would contribute significant savings if retrofitting of horizontal sensors were undertaken.

Assumption 3 Discussion

The signal band assumed in the preceding sections is in fact larger than that which has been found to be of greatest value when using Montana data for discrimination studies. Specifically, useful Rayleigh wave energy has been received only in the band from 0.025 Hz to 0.05 Hz. Thus the use of a 0.065 Hz upper frequency in the above sections rather than 0.05 Hz has constituted a built-in safety factor. That is, small changes in the Rayleigh phase velocity or the upper frequency of interest will not result in the introduction of undesirable sidelobes.

The passband of instruments installed in Montana (20 sec natural period adjusted to 0.64 critical damping) seems quite satisfactory for discrimination purposes.

The present narrow band filter characteristic with 80 db/decade attenuation should also be satisfactory. Some widening of the bandpass might be of interest for scientific studies.

Assumption 4 Discussion

Array processing need not be limited to delay and sum. Experiments using Montana data have indicated that maximum-likelihood processing can be used to get about 9 db additional gain against interfering events for example, as well as to obtain about 3 db for typical noise and perhaps more when the noise is highly organized. Experiments using Montana data have also indicated that the gain of maximum-likelihood processing above that of delay and sum does not vary greatly for a large range of separations above 10 km. It is anticipated that a similar situation will hold in Norway.

Assumption 5 Discussion

Analysis of long-period noise has indicated that it contains three basic types. These are fundamental Rayleigh and Love waves and noise which is independent between sensors. The independent noise, which normally constitutes at least 20% to 30% of the noise in the frequency band of interest and may constitute as much as 80% of the total noise, will be rejected by 10 log N as has been mentioned before. If only vertical instruments are under consideration, it is clear that they cannot record the Love wave noise. If, however, an array of horizontals is considered, then the Love noise must also be considered. The locus of such possible Love noise on Fig. 1 is interior to the locus of possible Rayleigh waves. It is thus clear that an array which rejects Rayleigh waves will also reject Love waves. If the array is steered for Love waves, the situation is a little more complex, but the array will still operate satisfactorily against both Love and Rayleigh noise.

Assumption 6 Discussion

The assumption of no dispersion across the array is approximately correct for the array apertures considered here. For example, an array 200 km in diameter steered by delay and sum to 25 sec Rayleigh waves would typically not introduce more than 0.5 db of signal attenuation at any point in the entire band from 0.025 Hz to 0.065 Hz.

Assumption 7 Discussion

Narrow angular resolvability is no more than an arbitrary design objective. The degree to which it can be met can be judged from Tables I and II which show the resolution of the various arrays considered.

VI. GENERAL COMMENTS OF AN ENGINEERING NATURE

Location of Seismometers

The LP vaults should be placed in granite whenever possible, with an overfill of about four feet. This type of installation tends to reduce the effects of ground motion due to wind and atmospheric pressure fluctuations on both the vertical and horizontal instruments. In addition, there is a reduction of the tilting motion of the vault, due to settling, which affects primarily the horizontal seismometers.

The LP vaults can generally be placed about a mile from the nearest road without obtaining interfering ground motion due to traffic on the road. Sites where water tables are near the surface should be avoided.

Long-Period Vaults

The LP seismometers should be isolated from environmental changes, especially temperature and pressure. This is best accomplished by deep burial in sealed tanks inside of a concrete LP vault.

Tank vaults just below the earth's surface usually do not provide adequate isolation from wind noise. Installations such as the LP LASA have a four-foot overfill and are generally 6 - 12 db better than vaults at the surface in the presence of high wind. Care must be taken to assure that seismometer piers are firmly coupled to underlying bedrock. Good drainage from vault area should be provided. The inside of the vaults should be treated to avoid accumulation of water vapor.

Amplifier

A solid-state amplifier is used at LASA as opposed to the usual phototube amplifier. The experience at LASA has been that the solid-state amplifier is superior to the phototube amplifier, since it is not subject to many of the problems of the phototube amplifier. Therefore, a solid-state amplifier is recommended for the Norway installation.

Communications and Telemetry

The sampling rate of the LP data should be 1 Hz, as this has been found to be adequate on the basis of the experience obtained with the LP data from the Montana LASA. It is typically desirable to be able to process events with surface-wave magnitudes ranging from 2.5 to 6.5, which implies an 80 db operating range for the system. If no compression were used, this would imply quantizing using 14 bits with one bit for sign. Ideally even larger events are of interest. This would mitigate in favor of an additional low gain channel from each instrument or the use of a floating point data format.

The problem of data transmission involves essentially a choice between FM analog and digital telemetry. The dynamic range of the FM analog system is not generally more than 50 db while that of the digital system can be better than 80 db. In addition, the drift, synchronization and maintenance problems are more severe for the FM analog than for the digital system. The implementation of the digital system is relatively simple due to the low data rates involved for the LP data. It is for these reasons that a digital telemetry system for the LP array is suggested rather than an FM system. More detailed analysis would of course be required to evaluate any specific system.

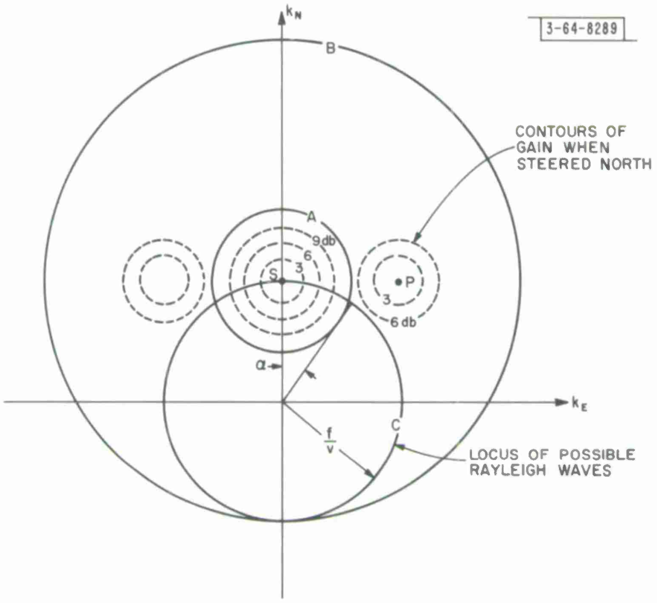

Fig. 1(a). Typical gain contours for an array steered to receive Rayleigh waves from the north.

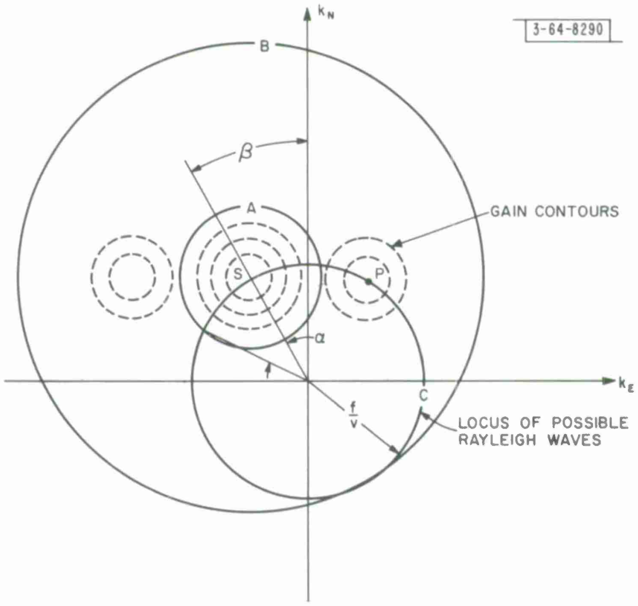

Fig. 1(b). Gain contours for an array steered to receive Rayleigh waves from azimuth - β.

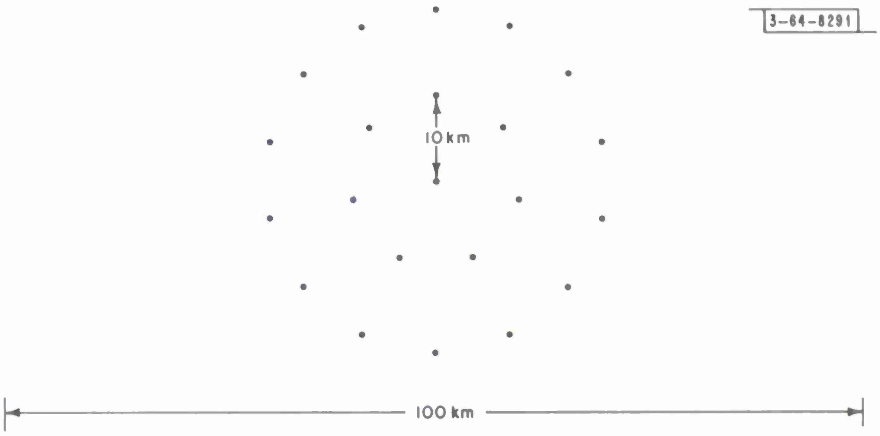

Fig. 2(a). Array geometry.

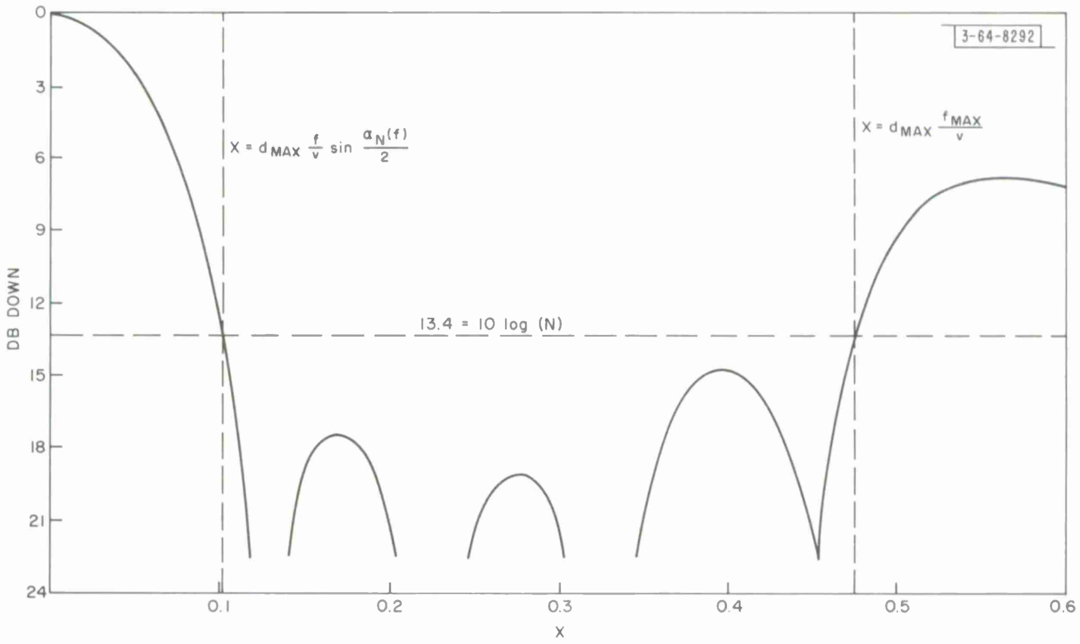

Fig. 2(b). Narrow-band minimum noise rejection.

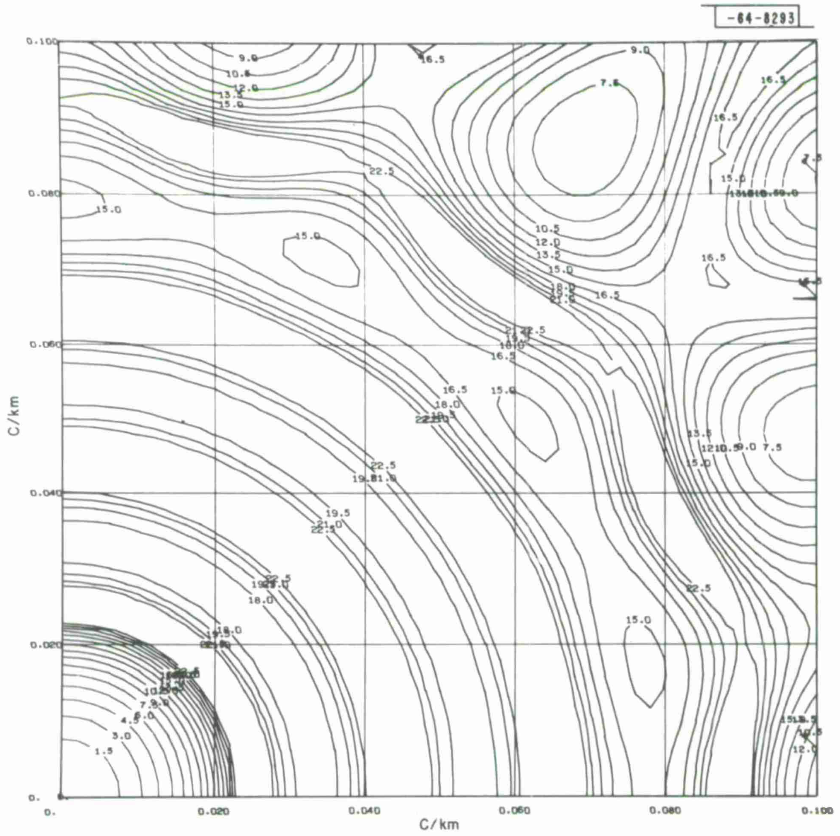

Fig. 2(c). Narrow-band wavenumber pattern (d = 10 km).

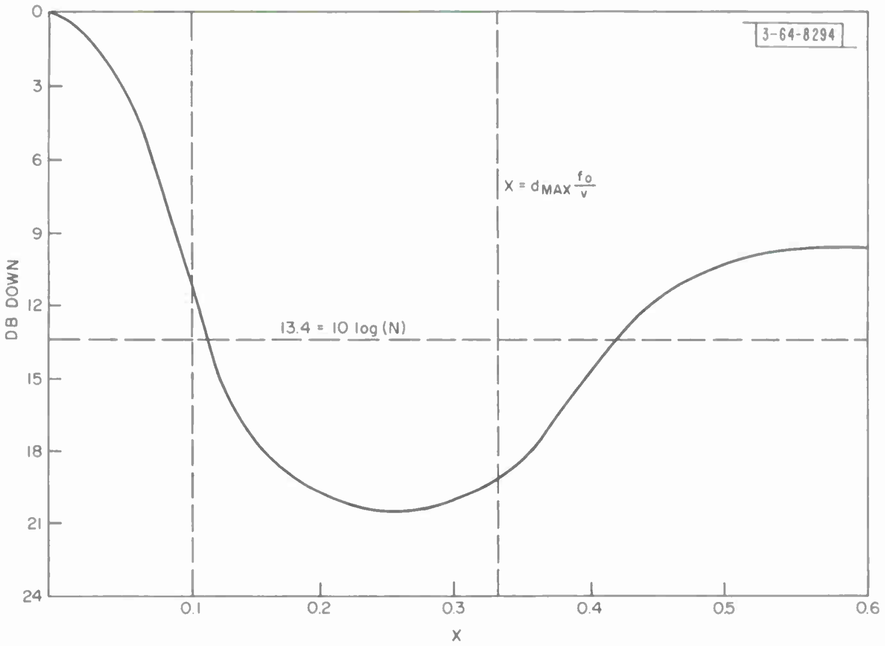

Fig. 2(d). Wide-band minimum noise rejection.

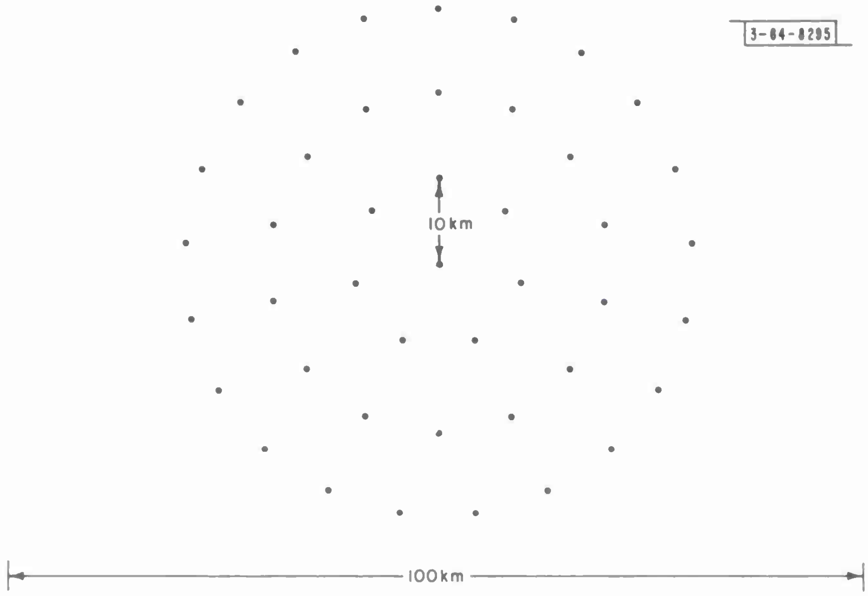

Fig. 3(a). Array geometry.

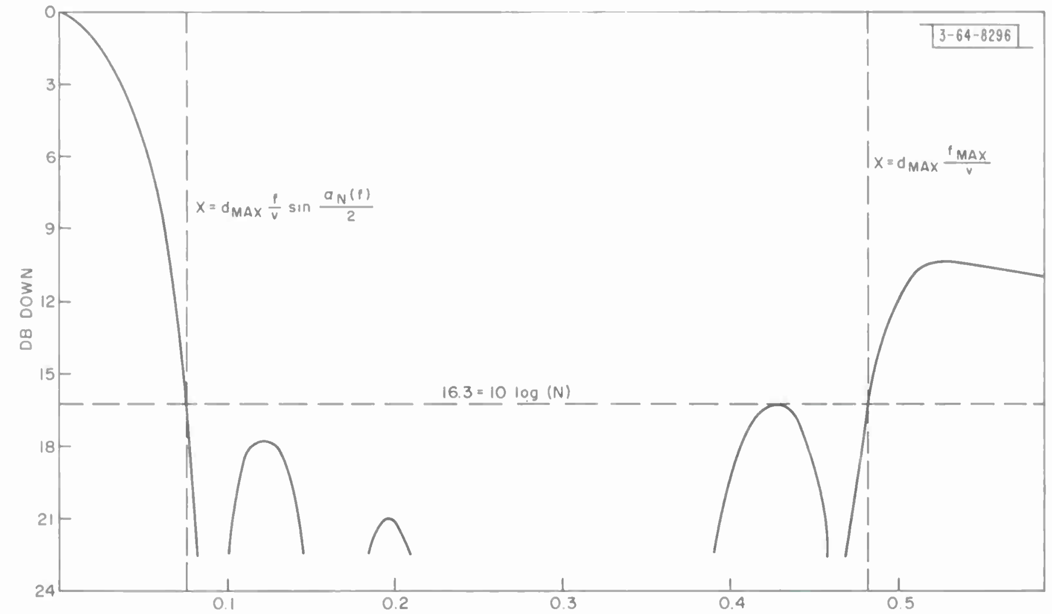

Fig. 3(b). Narrow-band minimum noise rejection.

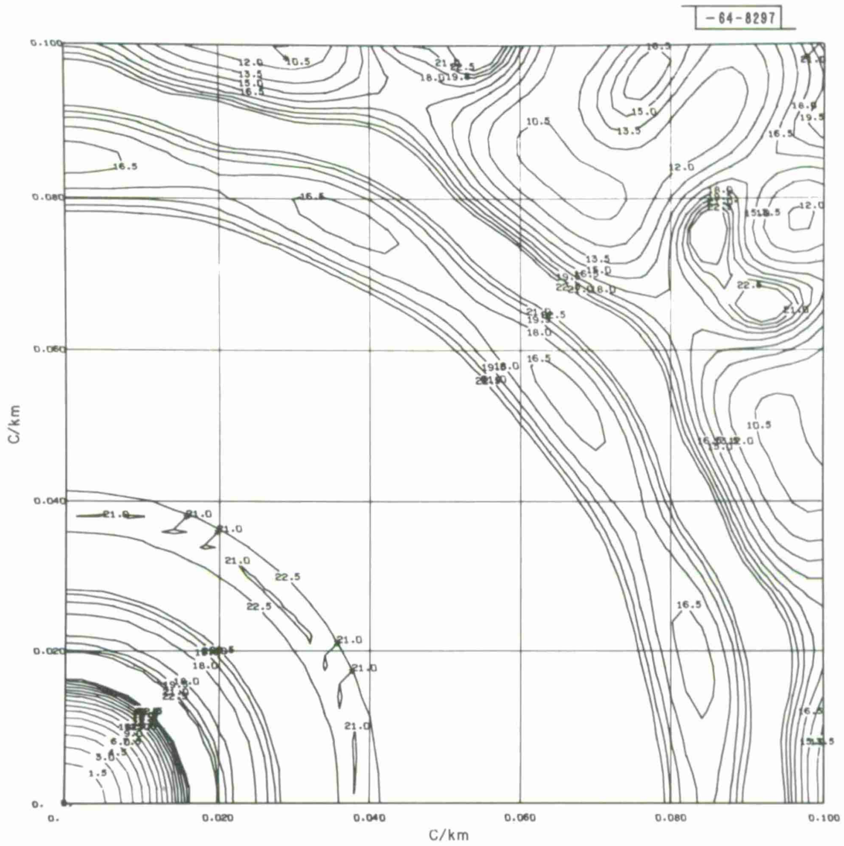

Fig. 3(c). Narrow-band wavenumber pattern (d = 10 km).

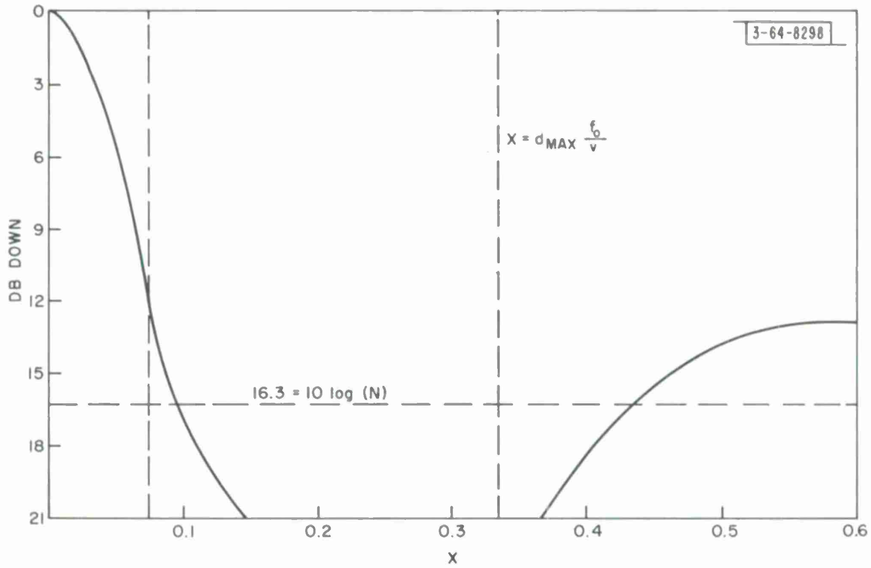

Fig. 3(d). Wide-band minimum noise rejection.

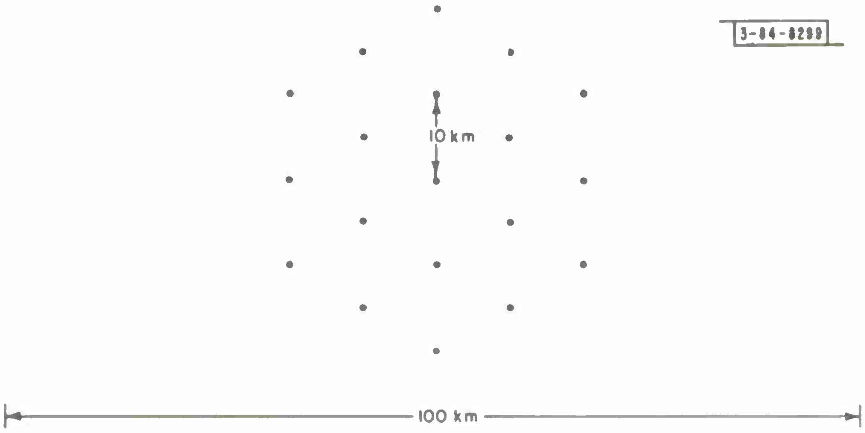

Fig. 4(a). Array geometry.

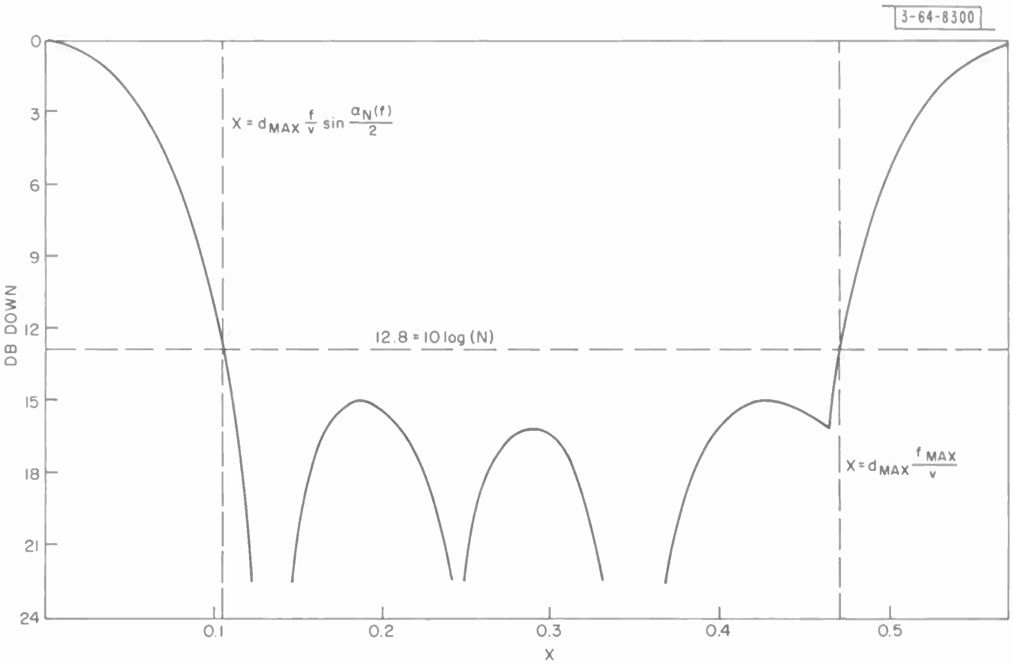

Fig. 4(b). Narrow-band minimum noise rejection.

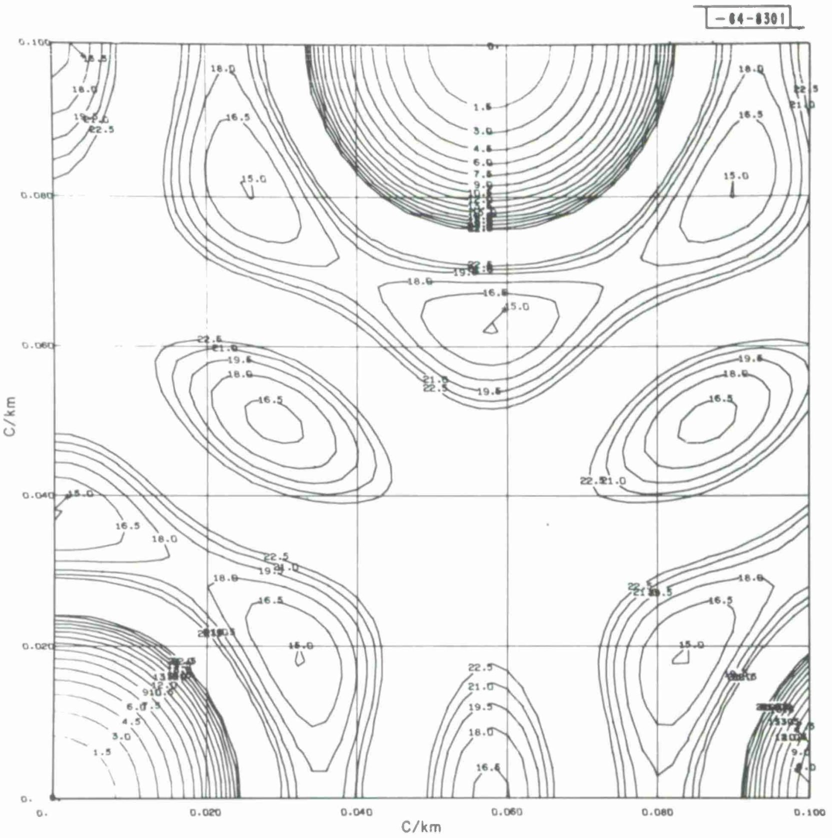

Fig. 4(c). Narrow-band wavenumber pattern (d = 10 km).

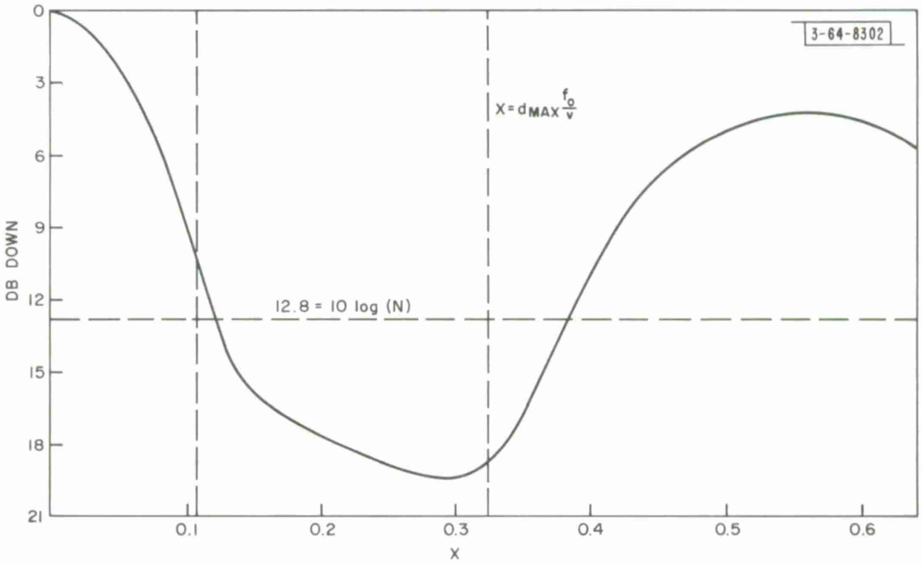

Fig. 4(d). Wide-band minimum noise rejection.

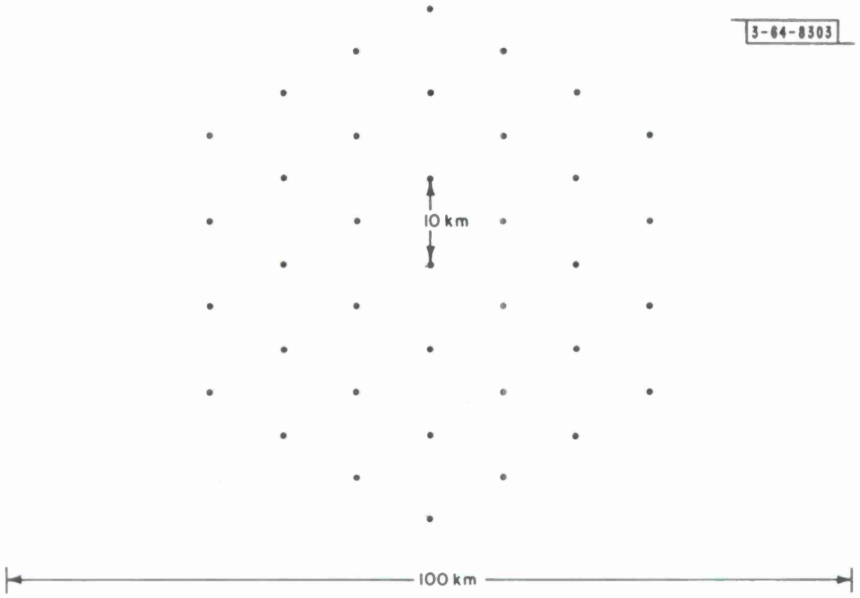

Fig. 5(a). Array geometry.

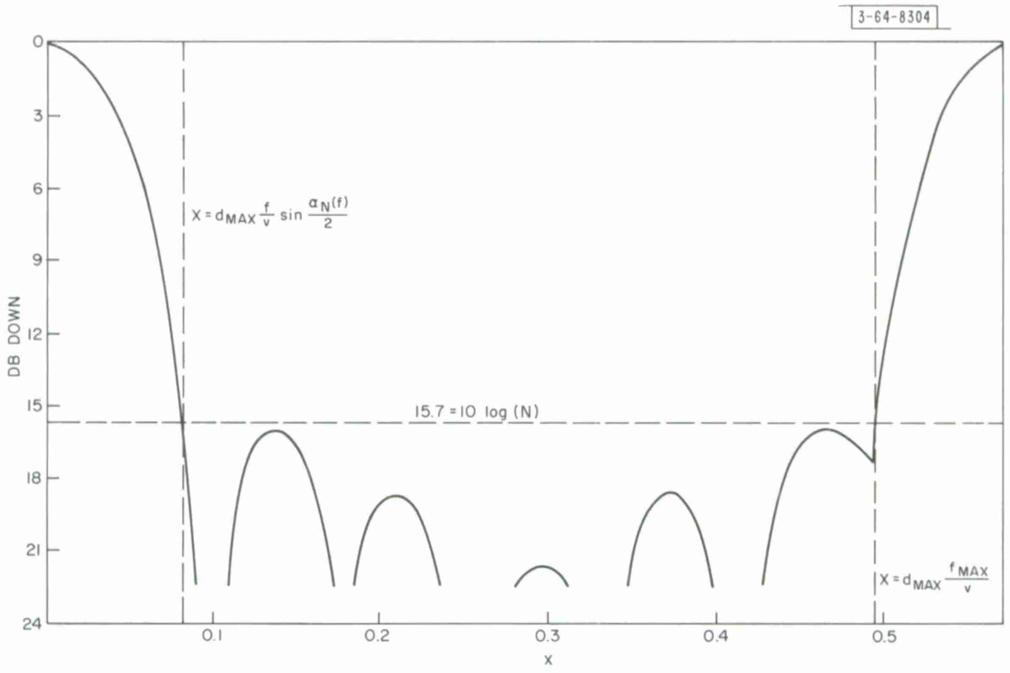

Fig. 5(b). Narrow-band minimum noise rejection.

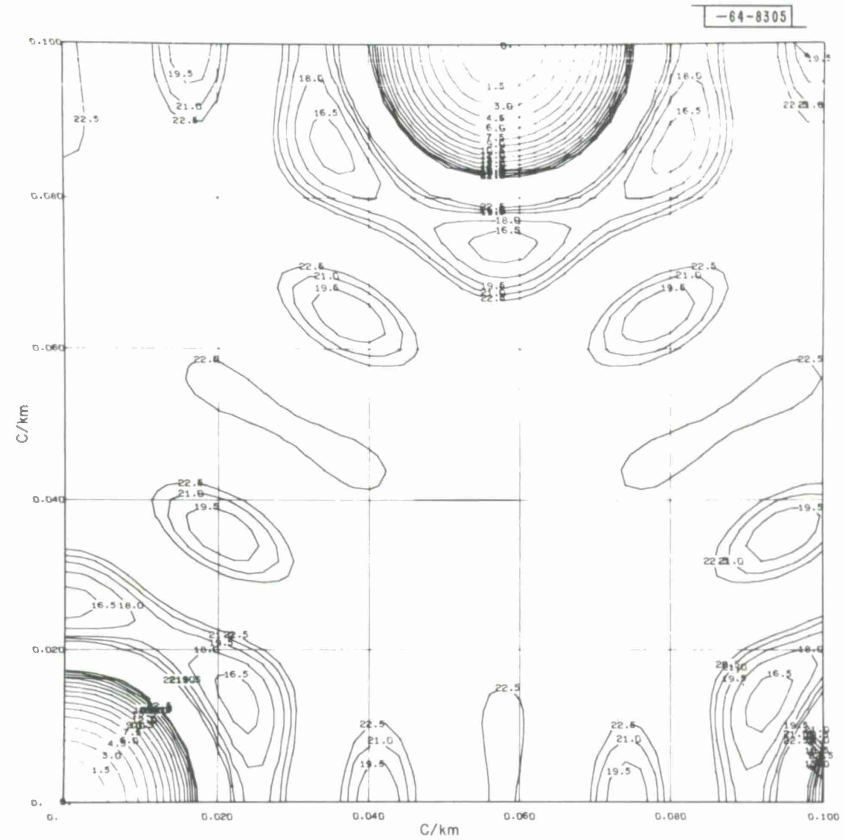

Fig. 5(c). Narrow-band wavenumber pattern (d = 10 km).

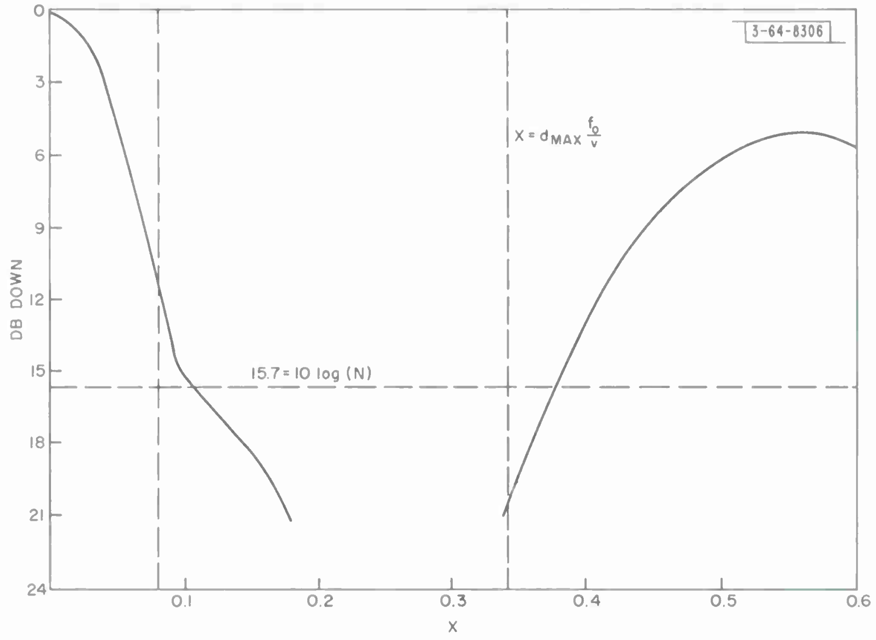

Fig. 5(d). Wide-band minimum noise rejection.

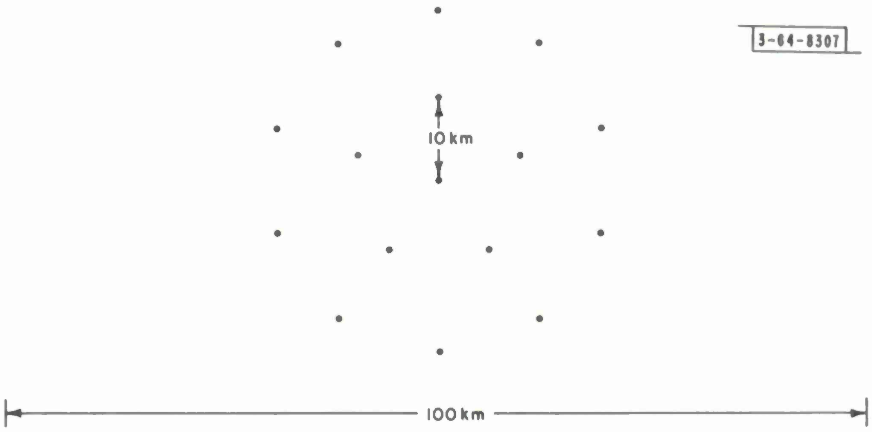

Fig. 6(a). Array geometry.

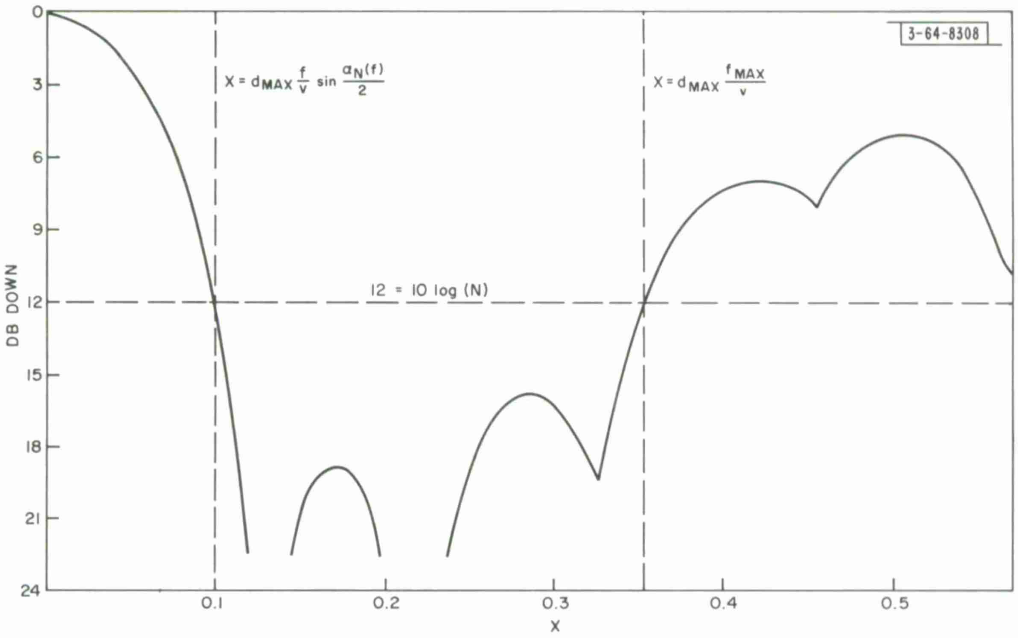

Fig. 6(b). Narrow-band minimum noise rejection.

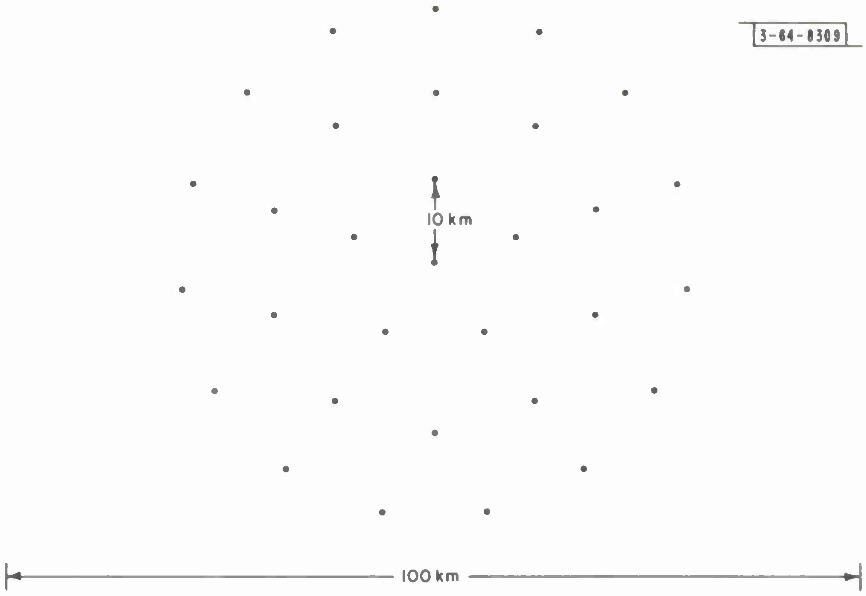

Fig. 7(a). Array geometry.

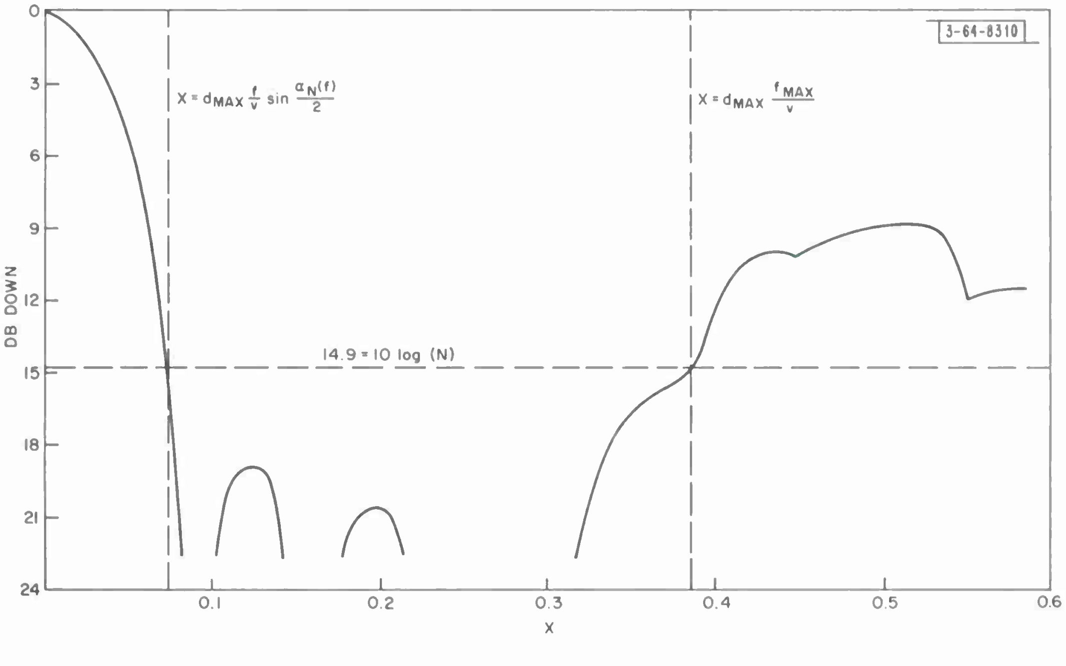

Fig. 7(b). Narrow-band minimum noise rejection.

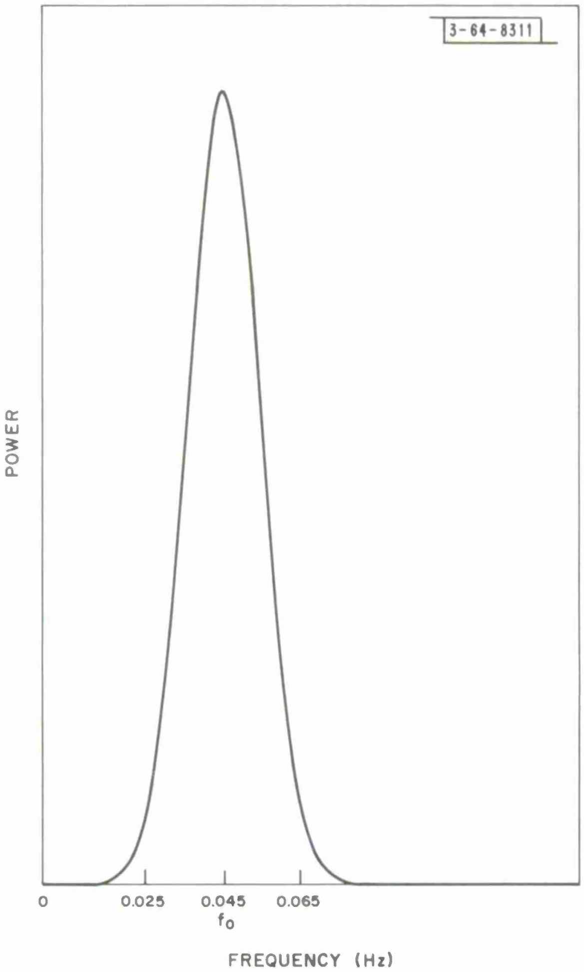

Fig. 8. Assumed wide-band power spectral density.

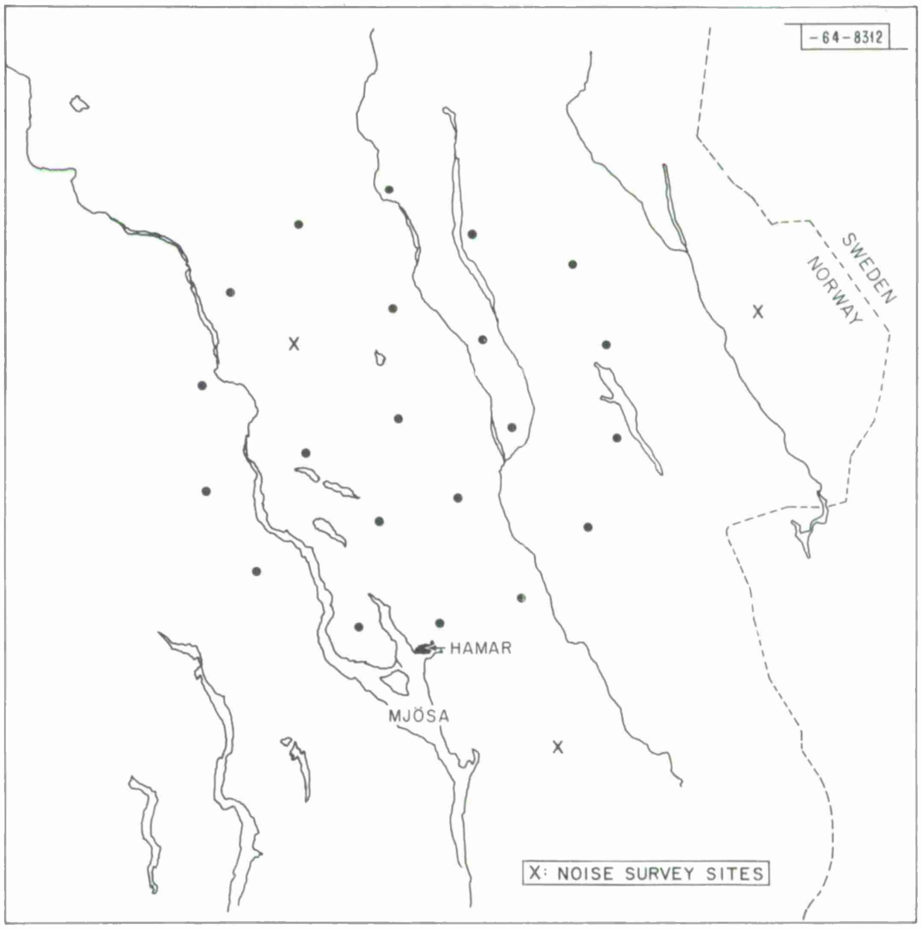

Fig. 9(a). Possible 24-element Norway array.

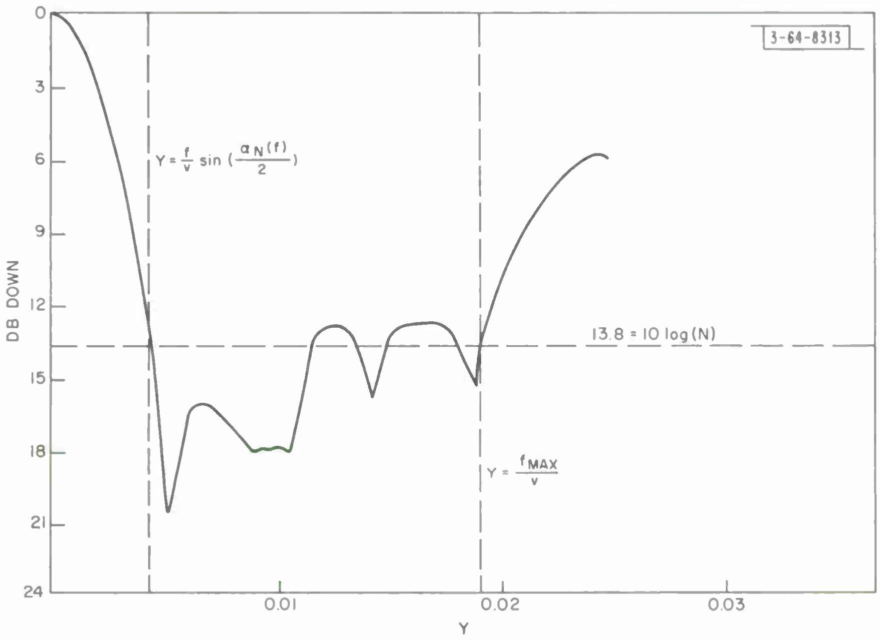

Fig. 9(b). Narrow-band minimum noise rejection.

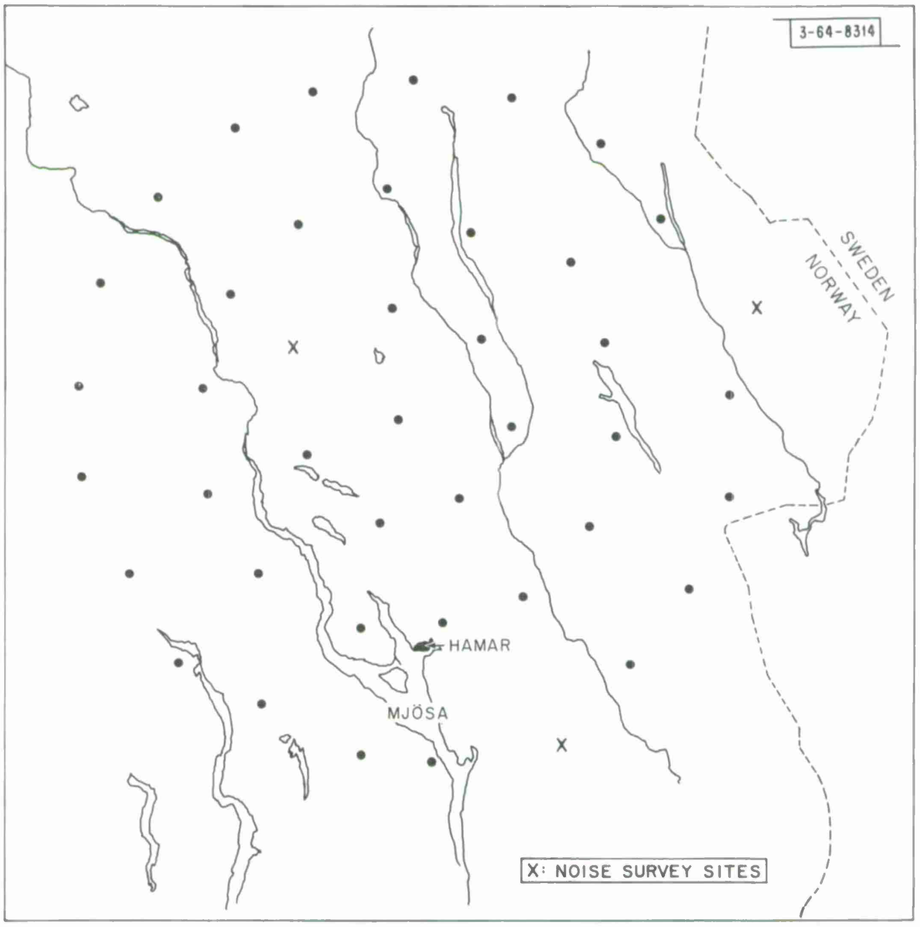

Fig. 10(a). Possible 43-element Norway array.

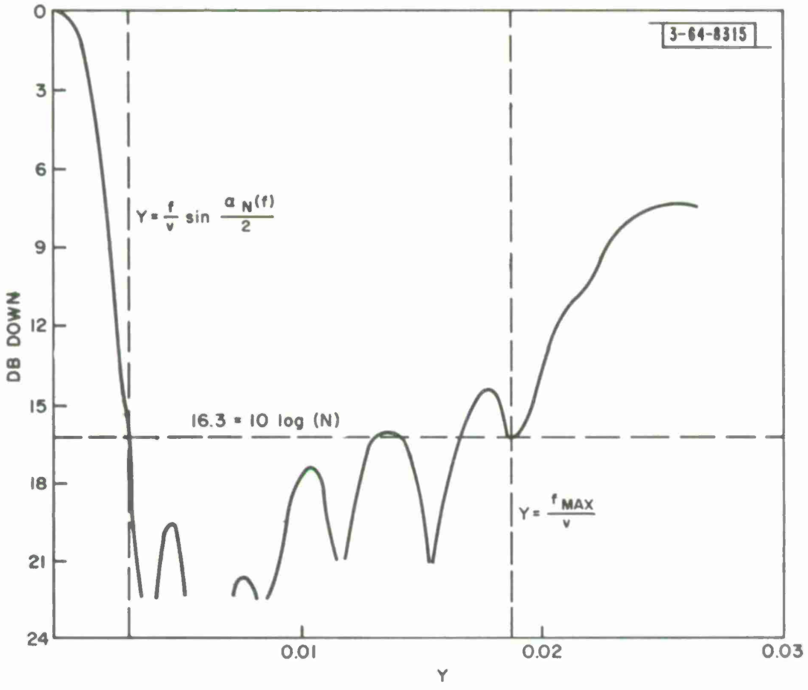

Fig. 10(b). Narrow-band minimum noise rejection.

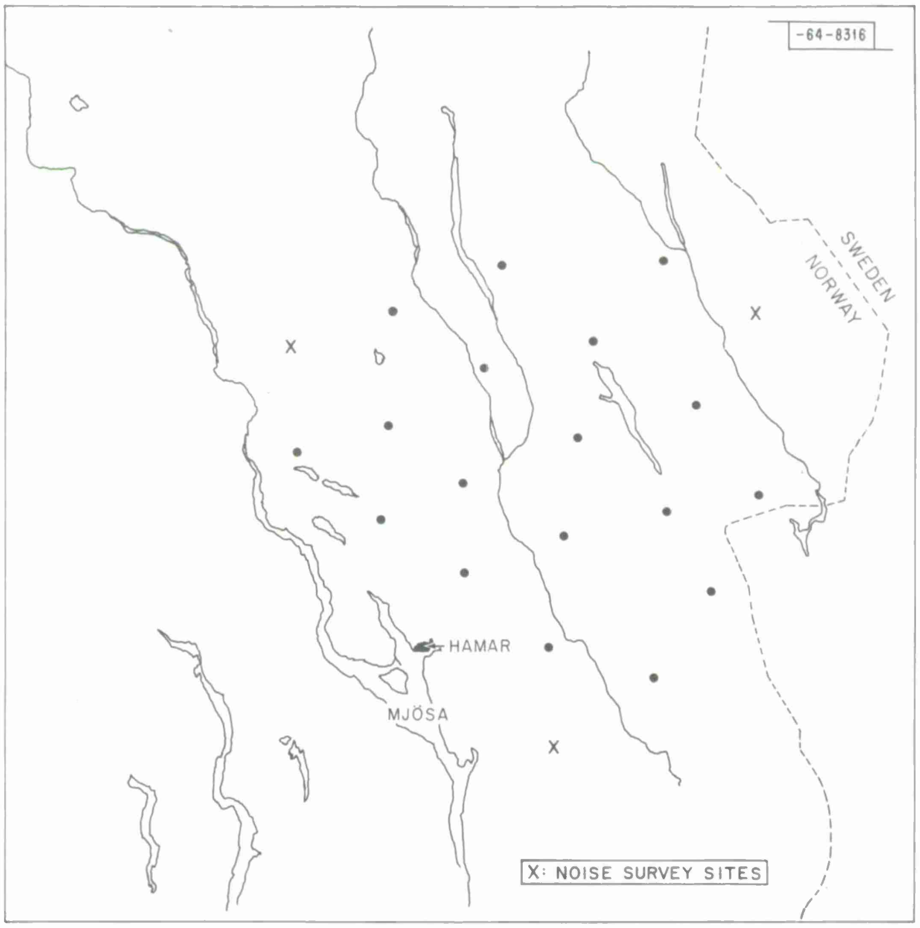

Fig. 11(a). Possible random 21-element Norway array.

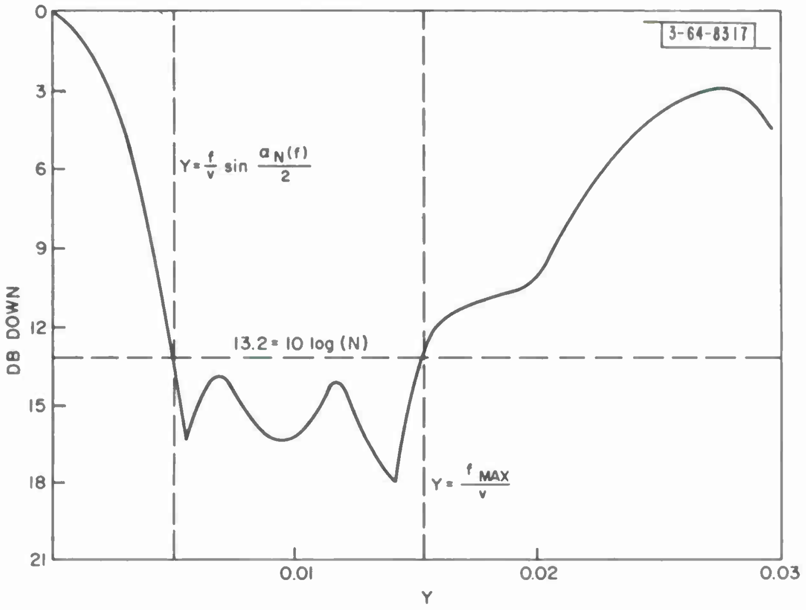

Fig. 11(b). Narrow-band minimum noise rejection.

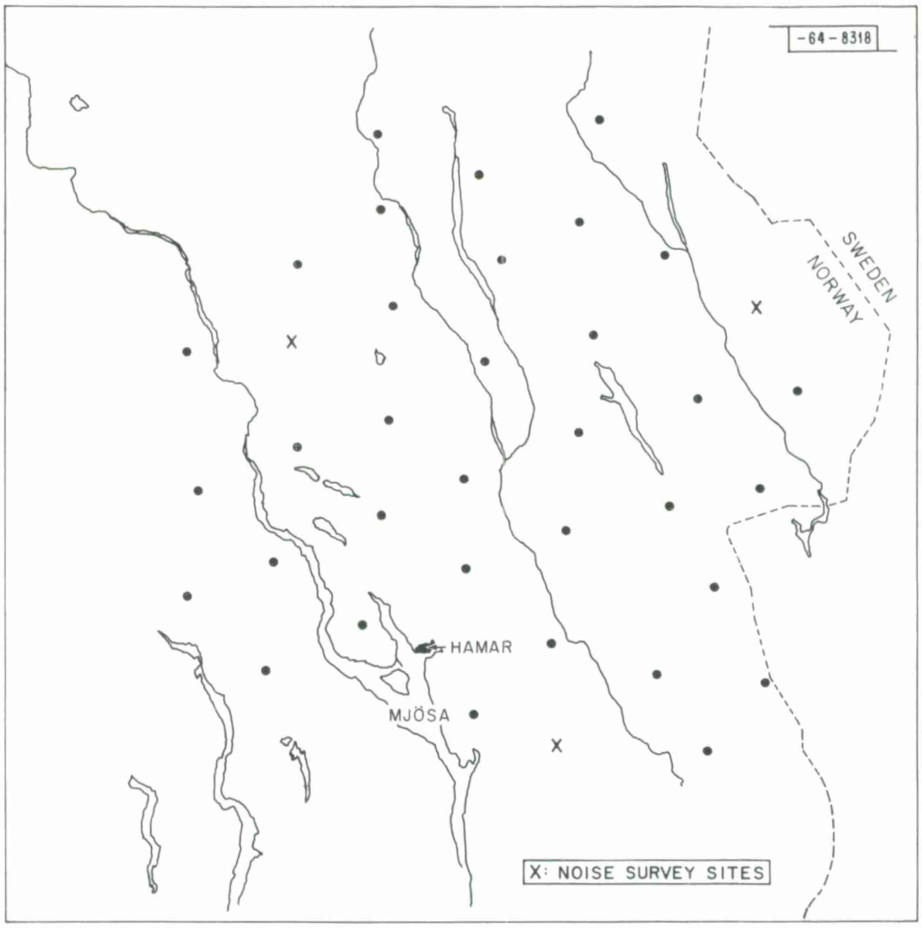

Fig. 12(a). Possible random 37-element Norway array.

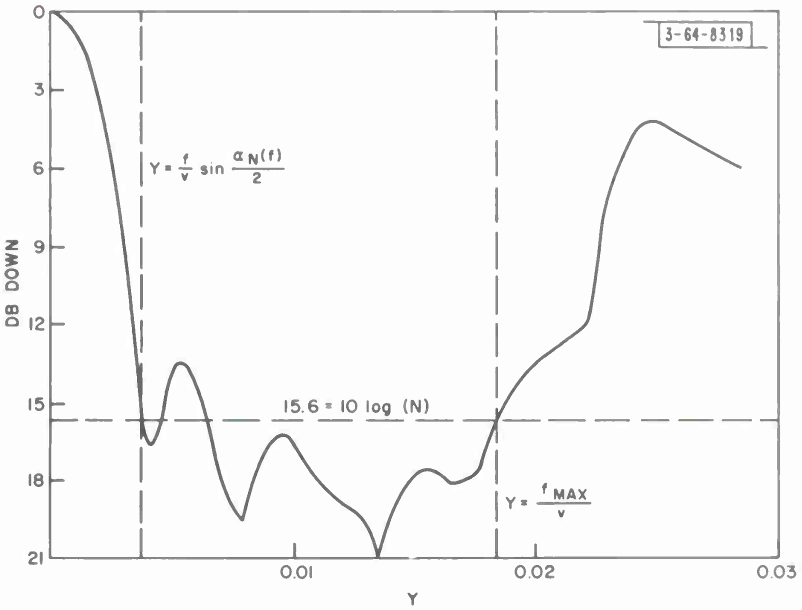

Fig. 12(b). Narrow-band minimum noise rejection.

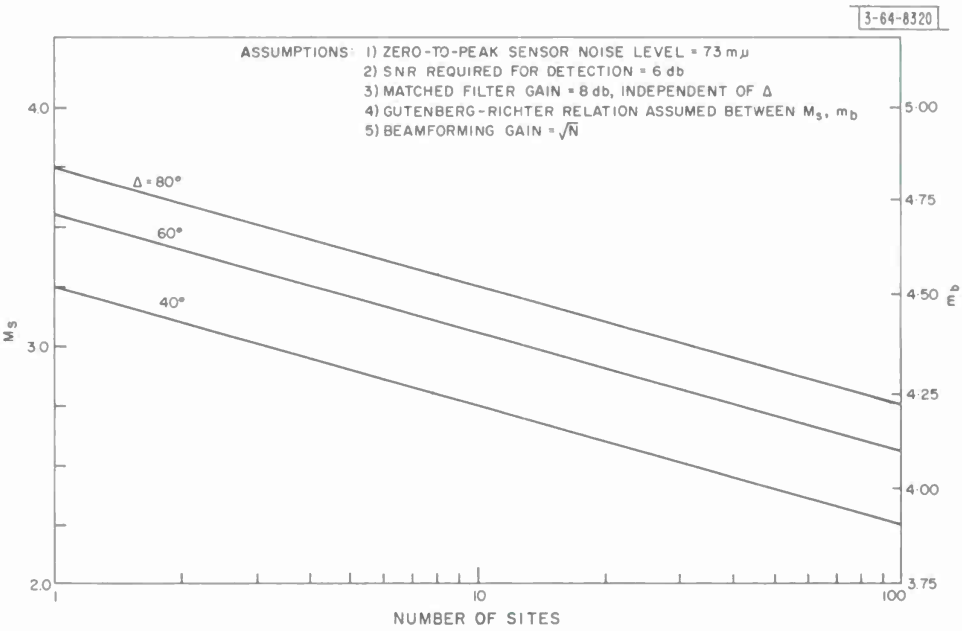

Fig. 13. Surface wave detection threshold vs number of sites.

DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None

3. REPORT TITLE

Preliminary Design of a Long-Period Seismic Array for Norway

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Note

5. AUTHOR(S) *(Last name, first name, initial)*

Lacoss, Richard T.
Capon, Jack
Greenfield, Roy J.

6. REPORT DATE 24 January 1968	7a. TOTAL NO. OF PAGES 48	7b. NO. OF REFS None

8a. CONTRACT OR GRANT NO. AF 19(628)-5167 b. PROJECT NO. ARPA Order 512 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TN-1968-4 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TR-68-7

10. AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency, Department of Defense

13. ABSTRACT

A preliminary design study for a long-period seismic array in Norway has been completed. It has been shown that if the array contains more or less uniformly distributed seismometers over a disc then the spacings between adjacent elements should be between 20 and 25 km. Larger spacings would result in spacial aliasing of organized noise and signals. Smaller spacings would decrease the array resolving power. Properties of specific array configurations are given.

A brief discussion of some engineering considerations is also included.

14. KEY WORDS

seismic array
array configurations
long-period seismic array
Norway

Printed by
United States Air Force
L. G. Hanscom Field
Bedford, Massachusetts