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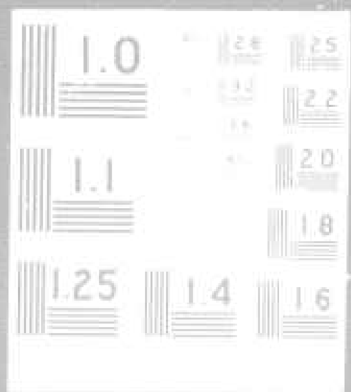

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INTRODUCTION

In this report we develop a systematic procedure for the design of seismic arrays. Existing arrays have been designed by a variety of methods. Among the first arrays were those built to specifications recommended by the Geneva Conference of Experts in 1958. The dominant noise on short-period surface vertical instruments in most systems existing then was caused by the wind, and studies showed that wind-generated noise was uncorrelated at a spacing of approximately 0.6 km. It was desired to cancel the noise by direct summation of the traces, therefore the instruments could not be spaced so widely that there was appreciable moveout of the compressional wave signal. A velocity of 12 km/sec with moveout less than one-quarter cycle at 1 Hz would imply an array 3 km in diameter. Thus, the Geneva arrays, e.g., WMO, BMO, UBO, and CPO shown in Figure 1a, have a diameter of 3 km or less and a minimum spacing on the order of 0.5 km. The spacing was somewhat greater than 0.5 km because when there was little wind the seismic noise, which remains correlated to greater distances, becomes an appreciable fraction of the total noise background.

The design of LASA is discussed by R. Price and P.E. Green (1964), by P.E. Green (1965) and by R.A. Frosh and P.E. Green (1966). Figure 1b shows the original design. The subarray design was constrained by the desire to reject coherent surface waves with velocities between 2.5 and 4.0 km/sec and frequencies between 0.2 and 5.0 Hz. To avoid spatial aliasing, a minimum spacing of 0.5 km was required. To make the subarray beam narrow enough that a teleseismic beam could reject Rayleigh waves at 0.2 Hz, it was necessary to have a diameter of 7 km. Assuming a geometrical layout of six radial arms of seismometers, approximately 25 instruments per subarray were needed. As slightly more than 500 seismometers were readily available, it was possible to have 21 subarrays. It had been found earlier that wind noise could be eliminated by burying the seismometers 200 feet, this was done at LASA. The maximum array diameter of 200 km was selected in order to give a reasonable teleseismic location capability. It was tentatively assumed that loss of signal amplitude due to spatial decorrelation could be neglected. The subarrays were placed on a logarithmic spiral so the beam width would be approximately constant with frequency. The constant for the spiral was chosen so there would be an approximately uniform density of subarrays at the center. Green (1965) recognized that if the logarithmic design were adopted and if the signal correlation were low, a reduced diameter array would still contain a large number of seismometers. With our present knowledge this appears to have been a valuable insight.

It is difficult to find an authoritative discussion of the design of the present 37-element TFO array depicted in Figure 1c. Some information is given in the Final Report of the Operation of TFO (1967) which cites as the design manuscript Project Recommendation P-688 (1966).

In the Project Recommendation, it was stated that two objectives of the array design were to increase the signal-to-noise ratio in the frequency range 0.5 to 2.0 Hz, and, a somewhat overlapping requirement, to make the main lobe of the array narrow enough that velocity filtering alone could reject a substantial portion of travelling wave noise.

Studies by Texas Instruments (1965a, b) were cited to the effect that in the 0.5 to 2.0 Hz band there was little low-velocity coherent energy at TFO. We may note that this obviates the requirement, imposed in the LASA design, for close spacing of seismometers. Also in the Project Recommendation were duplicated figures from Texas Instruments (1965a) showing all possible cross correlations of twenty minutes of data from two lines of instruments at the old TFO crossed array. One set of cross correlations was for data band-pass filtered 0.77 to 1.15 Hz, and from these plots we have made an interpretation that the correlation has mean zero at a spacing of 5 km. These data would therefore have been sufficient to justify the 5 km spacing suggested in P-688.

Subsequent reasoning in the array design might have been as follows. The absence of low-velocity noise would make it unnecessary to have a narrow main lobe on the array, because there would be less coherent noise to exclude. However, assuming the existence of a significant amount of coherent P-wave noise, one would nonetheless add seismometers to narrow the main lobe. One would also add more seismometers to increase signal-to-noise by averaging out the incoherent noise. The array should be regular to avoid large side-lobes, and the ultimate size presumably would be constrained by economics. With a 30 km diameter array, the teleseismic area could be covered at the 3 dB level with 30 beams at 1.0 Hz, implying roughly an attainable factor of $\sqrt{30}$ ~ 15 dB improvement of signal-to-noise due to velocity filtering of isotropic P waves.

This implication was checked theoretically in P-688 by a calculation which assumed isotropic P wave noise with constant power above 8 km/sec and zero noise power for the lower velocities. The resulting cross-spectral matrix for the 37-element array was calculated, and by making use of a formula similar to (1), below, a gain of approximately 16 dB was predicted at 1.2 Hz for a 10 km/sec beam. This is insignificantly different from the 15.7 dB predicted by $N^{1/2}$ arguments, ... and in P-688 for all frequencies higher than 1.4 Hz.

Thus in summary it appears that the TFO array was designed on the basis of correlation measurements which showed that 5-km spacing would give $N^{1/2}$ improvement in signal-to-noise ratio. In the design phase it was checked that good performance would be obtained for a particular isotropic P wave model.

A basic requirement in array design is to be able to predict signal-to-noise gain from any hypothetical array. Here we extend in a systematic way the "zero correlation distance" technique used in the design of the Geneva and TFO arrays. In these studies the results are based directly on field measurements and are independent of whatever physical process may underlie them. This is in contrast to the LASA array design in which limited measurements were used to deduce a physical model which was then used as the basis for array design.

The underlying assumption of our design procedure is that the principal data processing will be simple beamforming; if multichannel filtering is to be used, a different array design might be better.

The ability of multichannel filtering to perform more than 1 or 2 dB better on ambient noise than simple beamforming is still a subject of controversy. It has been generally agreed for some years, e.g., Flinn et al (1966), Capon et al (1968), that 1 or 2 dB is the maximum gain over LASA beamforming in the principal signal band around 1 Hz, and thus represents the gain available for detection purposes. However, from 0.2 to 0.8 Hz, Capon et al shows that for a LASA subarray multichannel filtering reduces noise approximately 10 dB more than does simple beamforming. Such an improvement would be of value for purposes of discrimination. To the authors' knowledge it has not, however, been definitely shown that the MCF passes a signal sufficiently undistorted such that this noise reduction yields an equal improvement in signal-to-noise ratio.

Haubrich (1968) has studied array design under the assumption that it is desired to narrow the main lobe and reduce the side lobes of a simple beam. If the noise is propagating, then this will improve the signal to noise ratio. If it is not propagating, then small weights applied to some elements will, in effect, reduce their contribution to cancellation of the incoherent noise.

Noise correlation calculations

A well-known formula e.g., Hartenberger and Shumway (1967), for the noise reduction obtainable by simple beamforming of an array is

$$dB = - 10 \log_{10} \frac{N}{1 + (N-1) \hat{\rho}_n} \qquad (1)$$

where N is the number of seismometers and $\hat{\rho}_n$ is the average zero-lag noise cross correlation between elements of the array after the data have been time-shifted and filtered as appropriate for the beam and frequency band under consideration. This formula is valid for noise that has low or high velocity, that is propagating or non-propagating, isotropic or anisotropic.

The noise correlations must, of course, be stationary in time, since otherwise they have no predictive value. It is usually assumed in array design that the correlations are space stationary: that is, two seismometers separated by the same distance and with the same relative azimuth will have the same average cross correlation. However, even this assumption can be relaxed if one is willing to undertake a more extensive field measurement program.

We note also that the signal reduction is given by an identical formula except that the correlation is the average signal cross correlation. Thus, taking the difference, the signal-to-noise ratio gain for an array over an individual channel is given by

$$dB = 10 \log_{10} \frac{1 + (N-1)\,\hat{\rho}_s}{1 + (N-1)\,\hat{\rho}_n} \tag{2}$$

It is important to have correlation measurements of both the signal and noise if one is to be able to predict the performance of an array. Most authors, e.g., Dean (1965), and Capon et al (1968) have calculated coherence instead of correlation. (Because coherence is not an estimate of correlation, it is difficult to make use of these calculations. For the spectral representation of correlation one replaces the cross-spectrum amplitude in the numerator of the coherence estimate by the co-spectrum. For most of the purposes of this paper, the seismometer spacing available to Dean was too large. As mentioned in the Introduction, Texas Instruments (1965b) calculated the cross correlation functions for 20 minutes of noise data at TFO. The results were presented only as plots. Their variance is unsatisfactorily large, and it is difficult to be certain of the accuracy of the plotted scales. However, as we will see below, their results are fairly consistent with ours, which were calculated from LASA data.

The correlation as a function of distance in the band pass of interest is the basic function needed for our study. We assume here that the noise is isotropic as well as space stationary, so we will average correlations between seismometers separated by equal distances but with different relative azimuths. Our data base is 150 seconds of data from LASA subarrays B1, 3, 4; C4; D2; E1, 2, 3, 4; and F1, 2, 3, 4, beginning at 04:03:20.0

on 10 November 1965. Unfortunately, data from other time periods available at SDL did not have data from seismometers spaced at 0.5 km.

The cross correlations were calculated using program CORLALL which prefilters and time-shifts the data as desired and then calculates the zero-lag correlation coefficient. We first calculated correlations using identical noise data for an infinite velocity beam and for northern and eastern 12 km/sec beams, and plotted them as a function of one another.

In Figure 2, we see that a slope of 1.0 is a good fit to the data, and that there is no substantial bias for northern or eastern beams, or for spacings near 1.0 km or greater than 1.5 km. Therefore, for the remainder of this study we shall calculate noise correlations only for infinite-velocity beams.

Figure 3 is a plot of a typical LASA subarray together with the correlation as a function of distance for the frequency range 0.8-2.0 Hz. This curve was calculated using data from all subarrays in the data base. The number of 150-second estimates in each average is noted. We see that our estimate of the true correlation function, drawn by hand, passes substantially outside many of the 95% confidence error bars. One possible cause for this could be nonisotropic noise. Figure 4 shows f-k plots at 1.0 Hz from the D2 and E4 subarrays. We see that the structure of the noise changes whether it is considered as a function of time or a function of the subarray. Thus if our averages were extended over a long enough time, we might expect convergence to a correct isotropic correlation function. It is possible that temporary anisotropy, different in each subarray, is enough to invalidate our estimates of the variance.

Much of the same data as used for Figure 3 was band-pass filtered to the range 0.4 to 3.0 Hz and used to produce Figure 5. This frequency range might be called the discrimination bandpass, in contrast to the 0.8 to 2.0 Hz bandpass which is more suitable for detection.

ANALYSIS OF EXISTING ARRAYS

LASA

A program was written to accept the locations of all seismometers in an array, calculate the distances between all possible pairs, enter a table determined either by Figure 3 or 5, and calculate the average correlation. Then (1) is used to determine the noise reduction in dB.

In Figure 6, the upper and lower curves give the predicted noise reduction for arrays determined by including increasing numbers of seismometers in the LASA subarray depicted in Figure 3. The seismometers are introduced in the order in which they are numbered in Figure 3. This is done in such a way as to decrease the minimum spacing as slowly as possible. The minimum spacing for each partial array is also plotted in Figure 6. A delay-and-sum calculation on noise from subarray B1 was performed by Capon et al (1968), using a 0.6-2.0 Hz bandpass. They calculated the noise reduction as first the inner 7, then the inner 6, then the inner 5, rings of three seismometers were excluded from the array. The resulting sequence of partial arrays is similar to that discussed above, and so their curve, reproduced in Figure 6, may be compared to ours. Hartenberger and Van Nostrand (1970) have also reported calculations for partial arrays identical to some of ours. They averaged over all LASA subarrays, and over eight time periods and they used the frequency range 0.4 to 3.0 Hz. The results of their calculations are also plotted in Figure 6, together with their plot for the bandpass 0.7-2.0 Hz averaged over all subarrays for only one time period. To plot their results, we assumed that the points could be plotted at the same number of dB below $N^{1/2}$ as in their figures.

We see that the theoretical calculations are in as good agreement with observation as could be desired.

Geneva arrays

In Figure 1a we saw the positions of the seismometers of the BMO, CPO, UBO, and WMO arrays. We remember that these arrays were designed to eliminate wind noise. Here we calculate the array gain if each of the seismometers were buried 200 feet to eliminate the wind noise, assuming the noise correlation structure to be the same as at LASA. By using the same procedures as for LASA we find (Table I) that because of their close spacing the arrays would have a gain equivalent to only 2 or 3 seismometers.

TABLE I

Array Noise Reduction in dB for two Bandpasses

Array	Number of Seismometers	0.4 - 3.0 Hz	0.8 - 2.0 Hz
BMO	10	2.33 dB	4.01 dB
CPO	19	2.37 dB	4.13 dB
UBO	10	2.17 dB	3.42 dB
WMO	13	2.51 dB	4.87 dB

TFO, 37-elements

Finally, we analyze the TFO array and project some of the possible improvements in its capability if it were enlarged, again under the assumption that its correlation structure is similar to that of the LASA. As a partial indication that this is the case, in Figure 3 we have superimposed on the LASA data our best analysis of the Texas Instrument (1965b) correlation data for the frequency range 0.77 - 1.15 Hz. Our variance estimates for the TI data are also indicated on the figure. There appears to be a possibility that the correlation falls off more slowly with distance at TFO than at LASA. However, considering the apparent unreliability of the variance estimates, the higher frequency limit on the LASA bandpass, and the fact that these data are from one time period at a single site equal in area to one LASA subarray, it seems difficult to reject the hypothesis that the correlation structures are the same.

In Figure 7 the noise reduction is predicted for filled hexagonal arrays as a function of the greatest array diameter. We see, of course, that the present 37-element array is well inside the diameter at which one obtains an $N^{1/2}$ gain of 15.7 dB for the 0.8 - 2.0 Hz frequency range. However, for the 0.4 - 3.0 Hz frequency range, the gain is only 11.5 dB. With a diameter of 49 km, packing in 169 seismometers, one could have an additional gain of 6.6 dB or 0.33 m_b in the 0.8-2.0 Hz frequency range. However, in the 0.4-3.0 Hz frequency range one would gain only 3.8 dB or 0.19 m_b. The geological environment of TFO is such that one might hope to find an area 50 km in diameter with the same noise characteristics as the present 30 km diameter array. Dean's (1965) signal coherence studies suggest that the signal coherence at 1.0 Hz decreases from 0.8 to 0.65 between 10 and 30 km, and is constant at 0.65 between 30 and 300 km. Thus the full $N^{1/2}$ gain would not be obtained by adding these extra seismometers. A quantitative evaluation of the actual gain to be expected will be presented in a following report which will make use of equation (2).

ARRAY DESIGN TECHNIQUES AND SUGGESTIONS FOR FURTHER RESEARCH

If the array elements are to be buried 200 feet, as at LASA, it is important to gather field data only when the winds are light, or to drill 200-foot test holes. Some of these holes, of course, might be used for the final array. A 20-minute noise sample would be more than adequate at any one time; however, ideally one would want several such samples spaced throughout the year. The distance range 0.5 to 10 km should be adequately sampled, and if anisotropy is suspected measurements should be taken at more than one relative azimuth.

In the design procedure, the first task is to generate figures similar to Figures 3 and 5 for any frequency ranges desired, and perhaps also for several very narrow bands at particular frequencies of interest. If the noise is anisotropic there will be different figures for different azimuths, and perhaps for different beam velocities. Once an appropriate set of curves has been established, the signal-to-noise ratio gain may be calculated for any beam and for any array geometry. At this point, if the noise structure is not simple the design procedure becomes more art than science. A program might be written to perturb an initial array geometry in order to seek minima in the signal-to-noise ratio for a particular beam. In another approach, the designer might specify a set of arrays, evaluate each of them for several beams, and make an overall judgement as to the best single array.

If data on signal correlation is available, equation (2) can be used in place of (1). In this respect, follow-on work from this study will include an example of array design using (2). We would also like to design an array for a site near the ocean where the noise is anisotropic. Finally, it would be worthwhile to gather a truly representative suite of noise data, perhaps from the old TFO short-period array, and deduce accurate correlation-distance functions, together with accurate estimates of their variance.

ACKNOWLEDGEMENTS

We are grateful to Carl F. Romney for the historical background of the design of Geneva-type arrays (personal communication).

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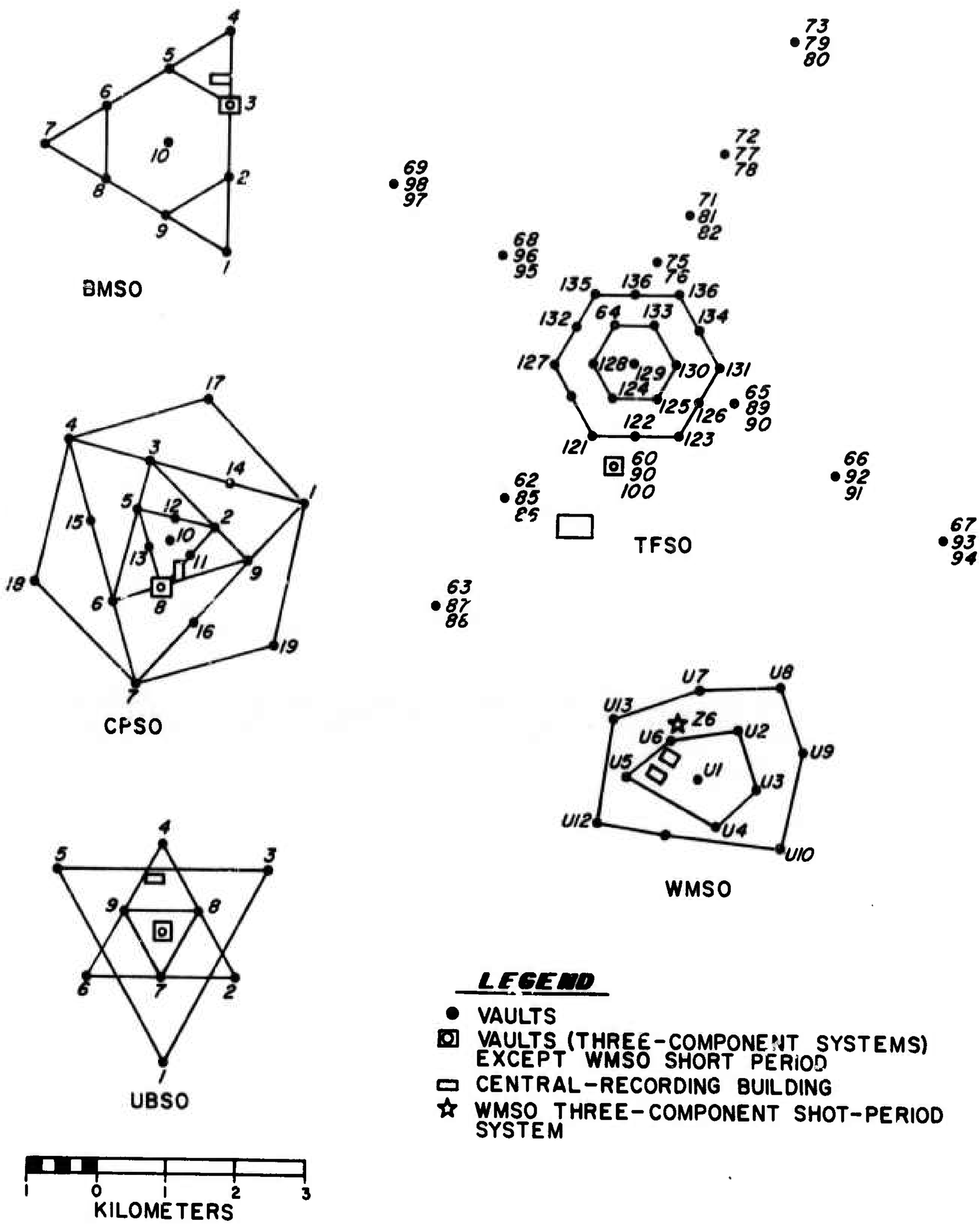

Figure 1a. Configuration of the early Geneva-type Observatories.

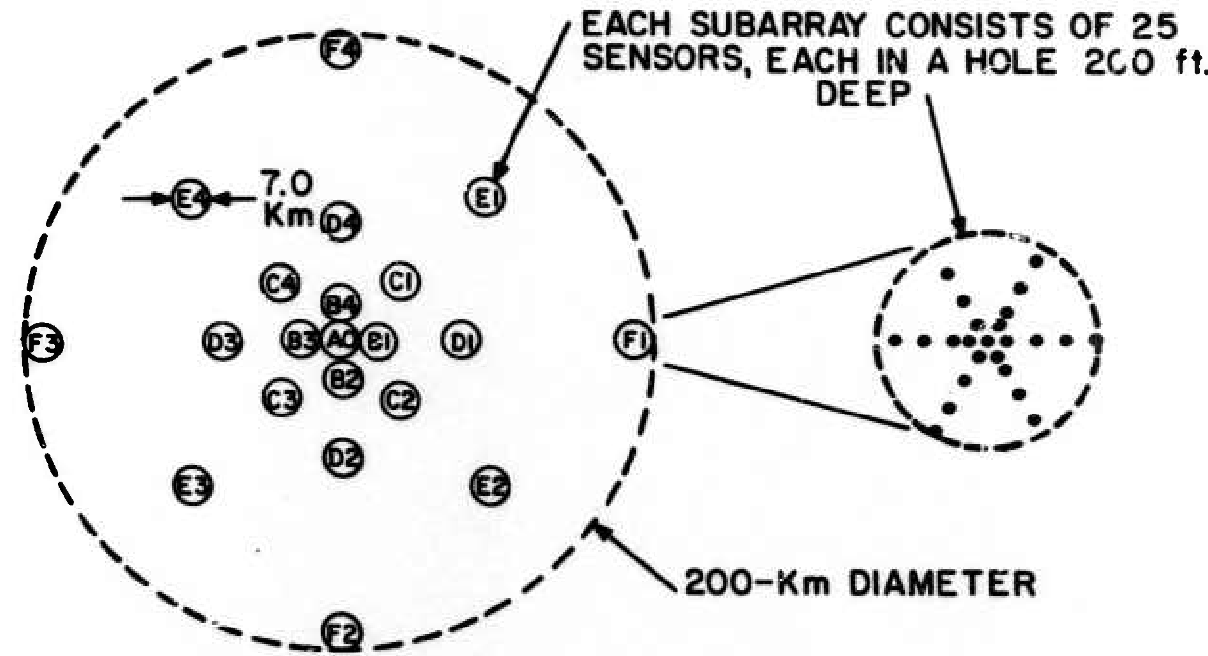

Figure 1b. Configuration of early LASA design.

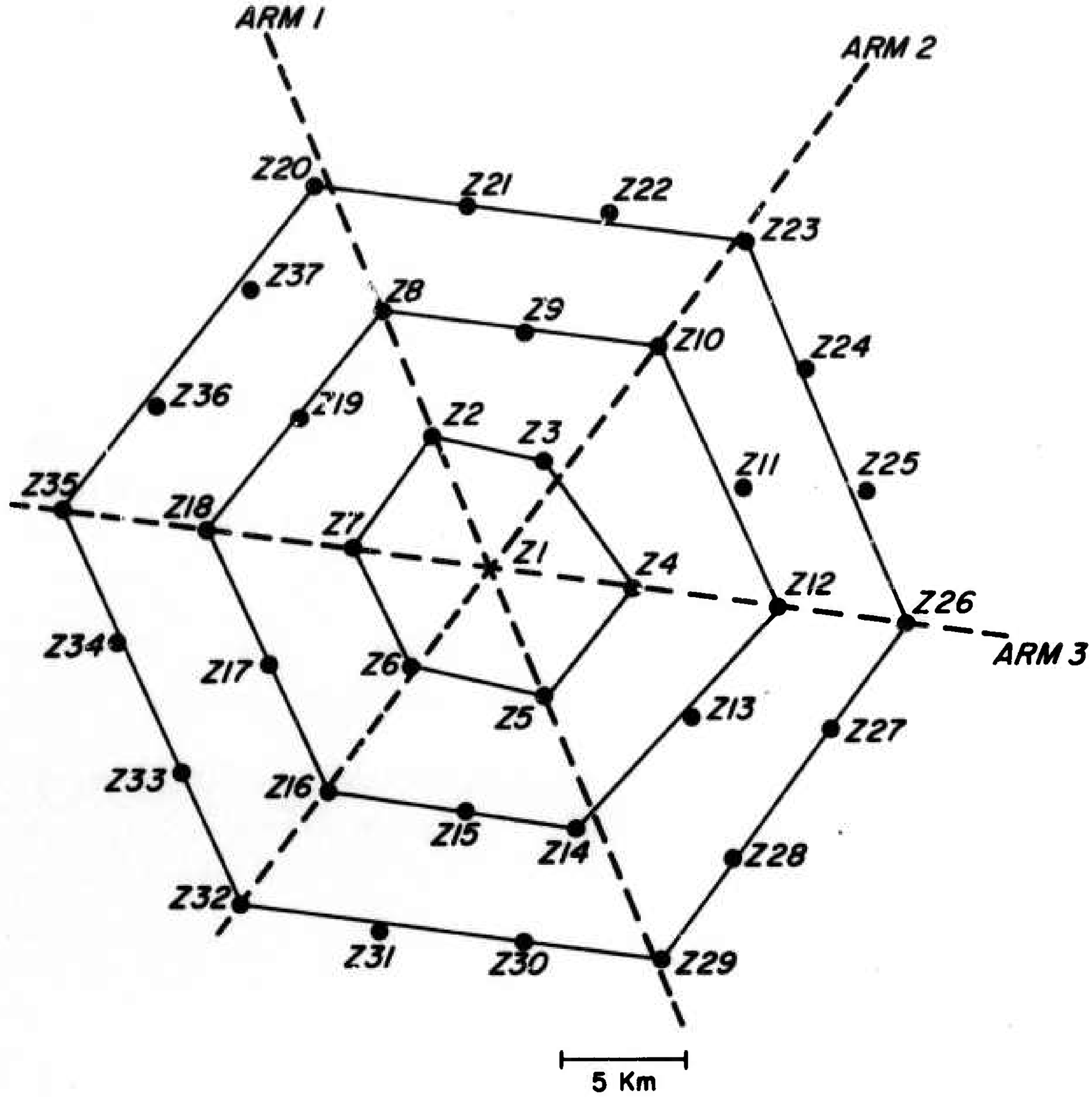

Figure 1c. Configuration of the extended 37 element short period TFO array.

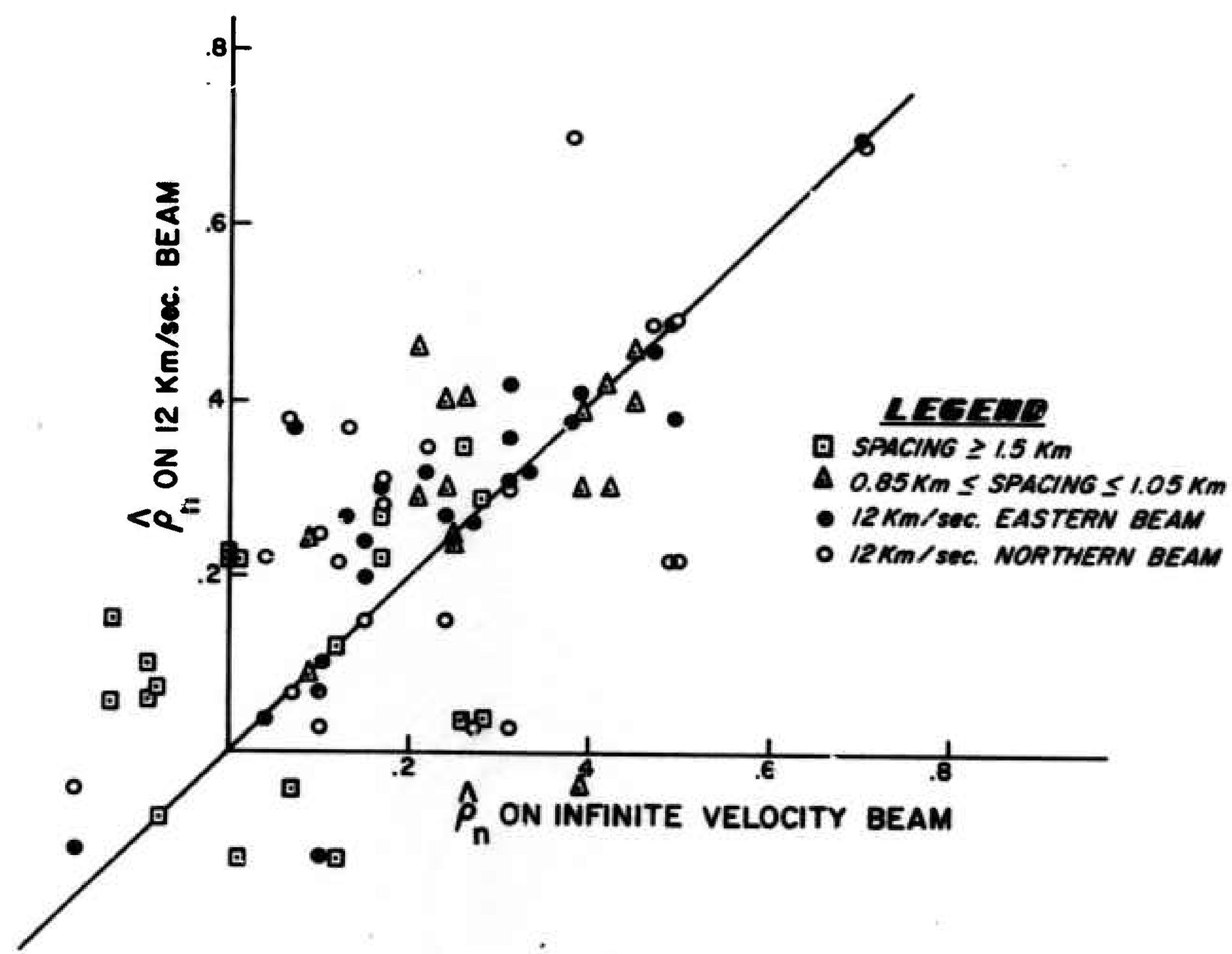

Figure 2. Correlations from 12 km/sec beams as a function of those from an infinite velocity beam on common data.

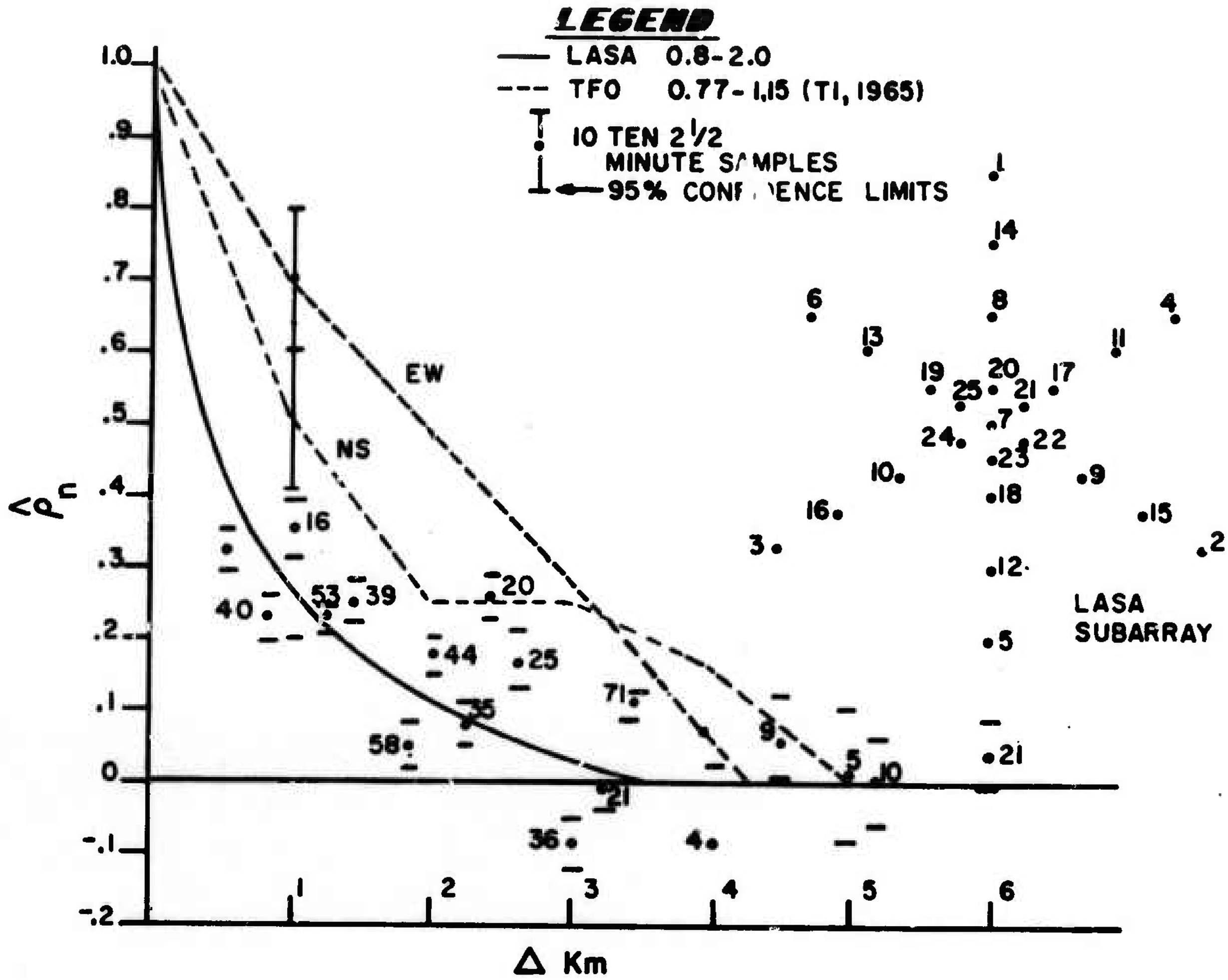

Figure 3. Solid line gives the correlation as a function of distance at LASA in the 0.8-2.0 Hz bandpass. Dashed lines give correlation at TFO for a North-South and East-West beam in the 0.77-1.15 Hz bandpass.as determined by Texas Instruments (1965a, b).

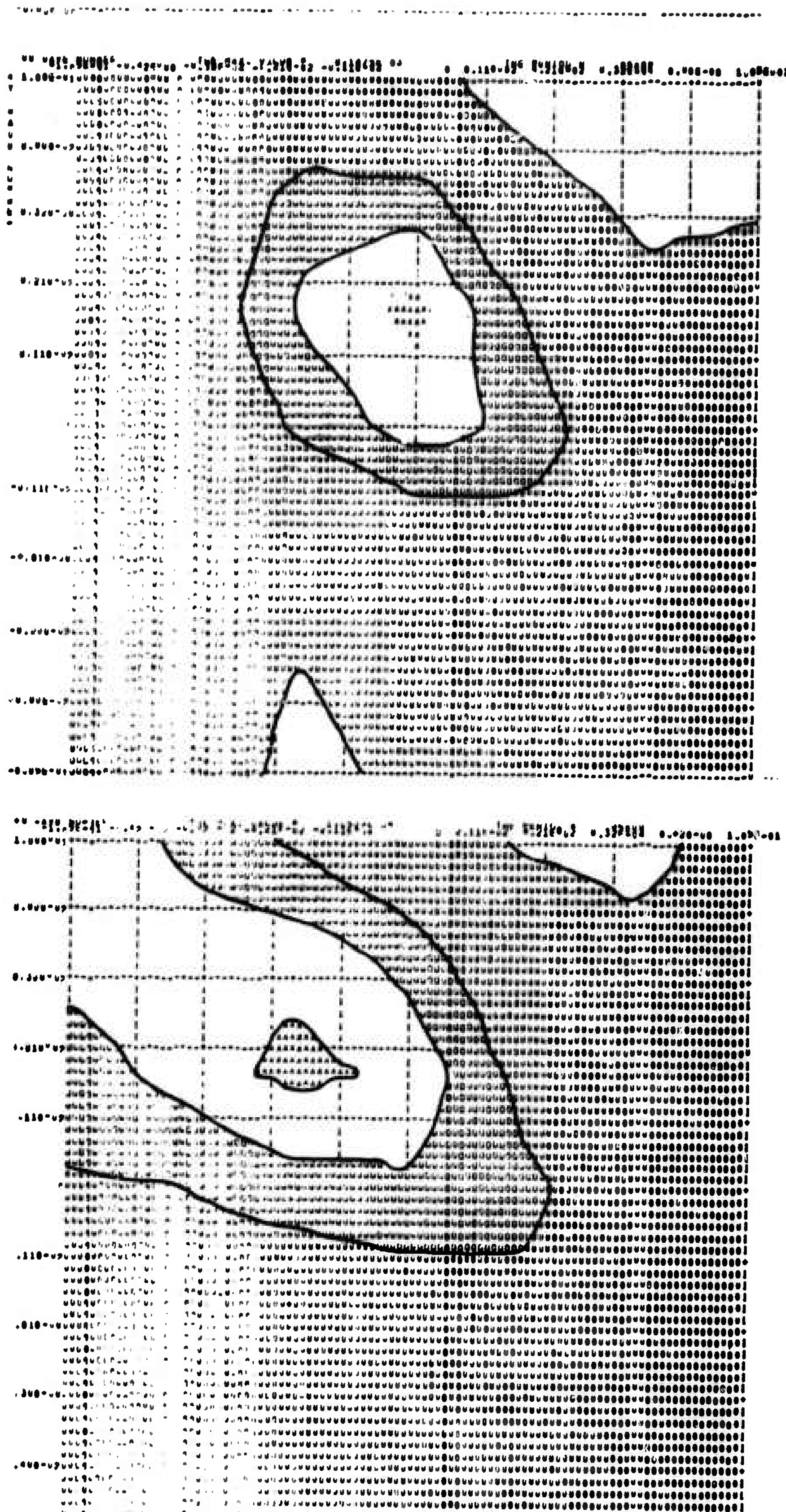

Figure 4a. Frequency-wavenumber plots at 1.0 Hz from the first 75 and the first 150 seconds at LASA subarray D2 on 10 November 1965.

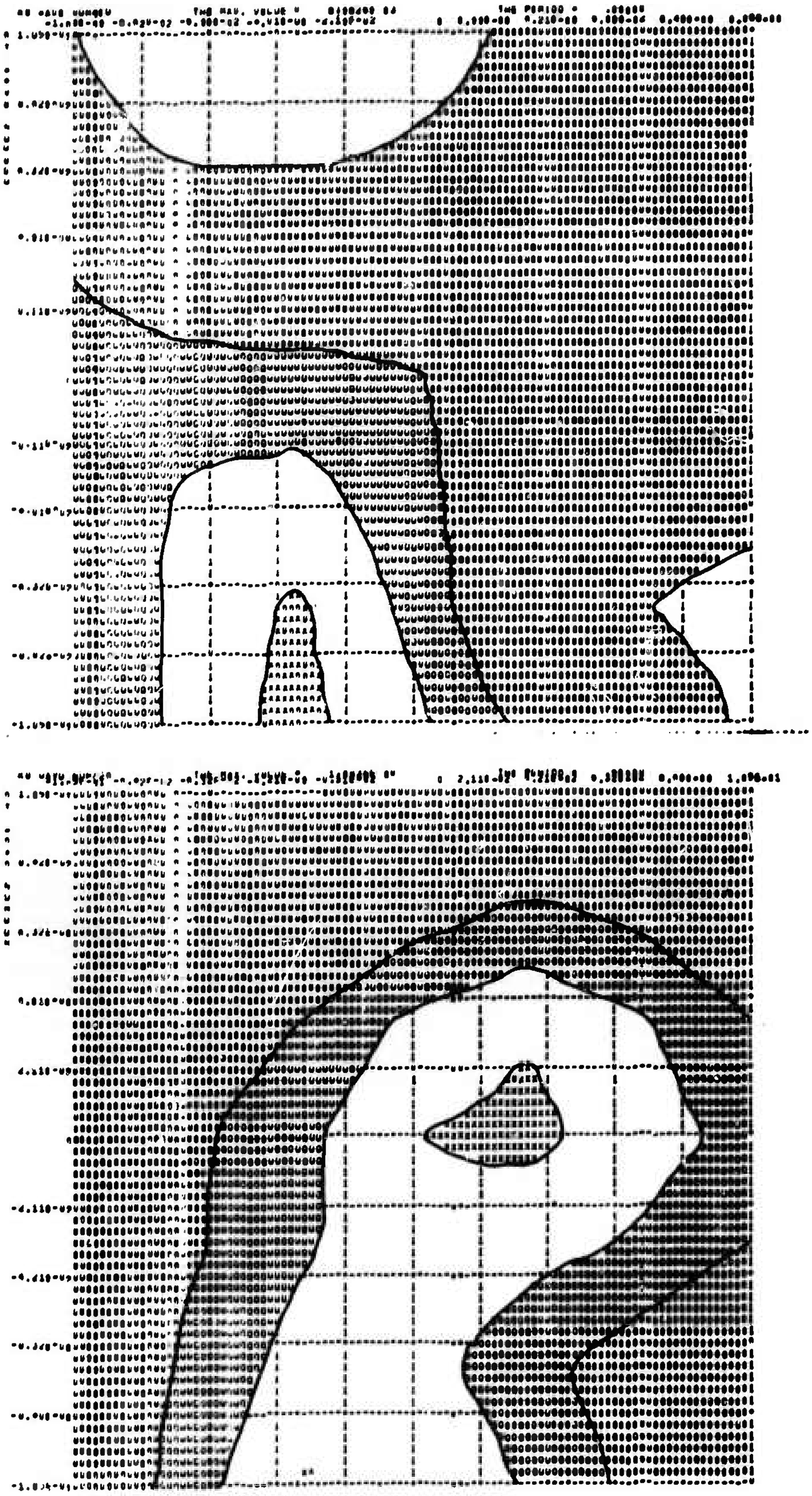

Figure 4b. Frequency-wavenumber plots at 1.0 Hz from the first 75 and the first 150 seconds at LASA subarray E4 on 10 November 1965.

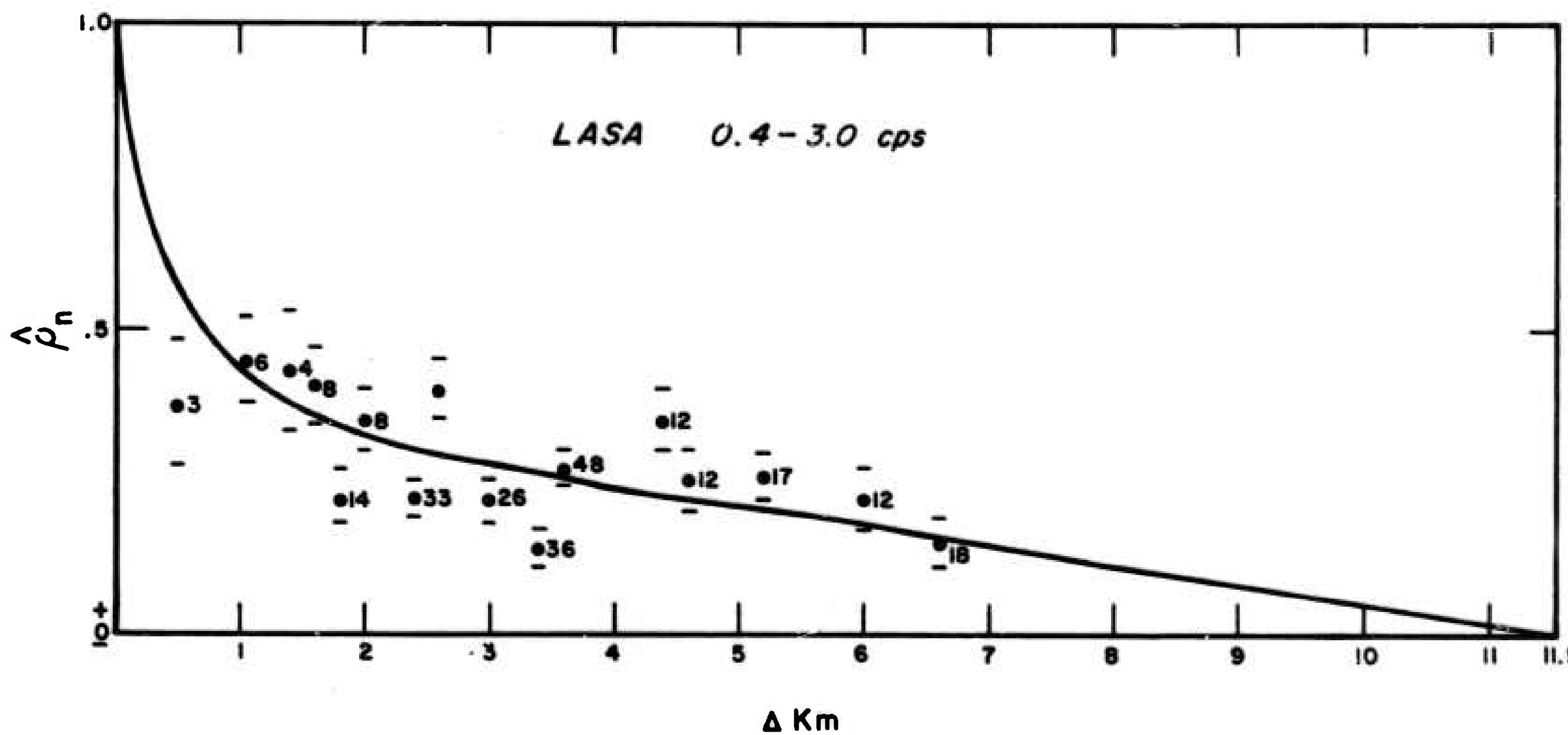

Figure 5. Correlation as a function of distance at LASA in the 0.4-3.0 Hz bandpass.

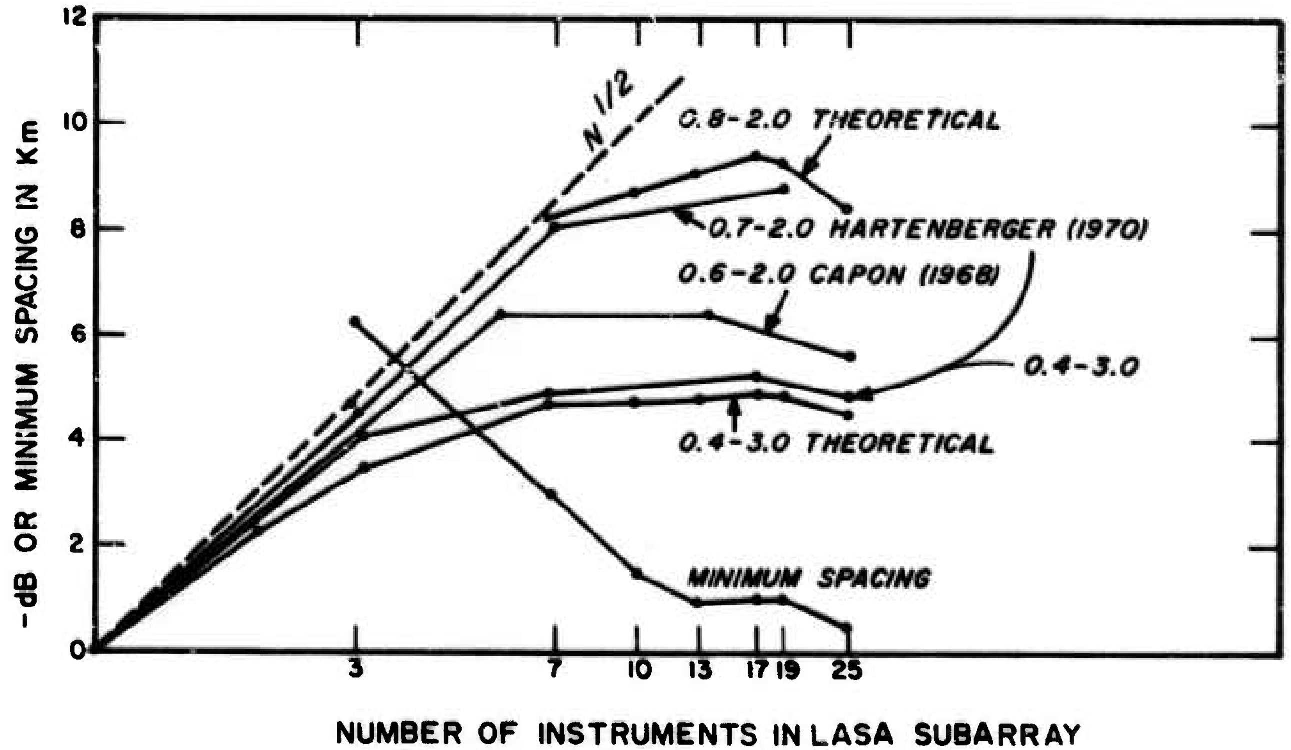

Figure 6. Noise reduction in dB as a function of number of instruments in a LASA subarray. The theoretical curves are derived from equation (1) and from Figures 3 and 5. The other curves are experimentally determined by other authors. The minimum spacing of each partial array is also plotted.

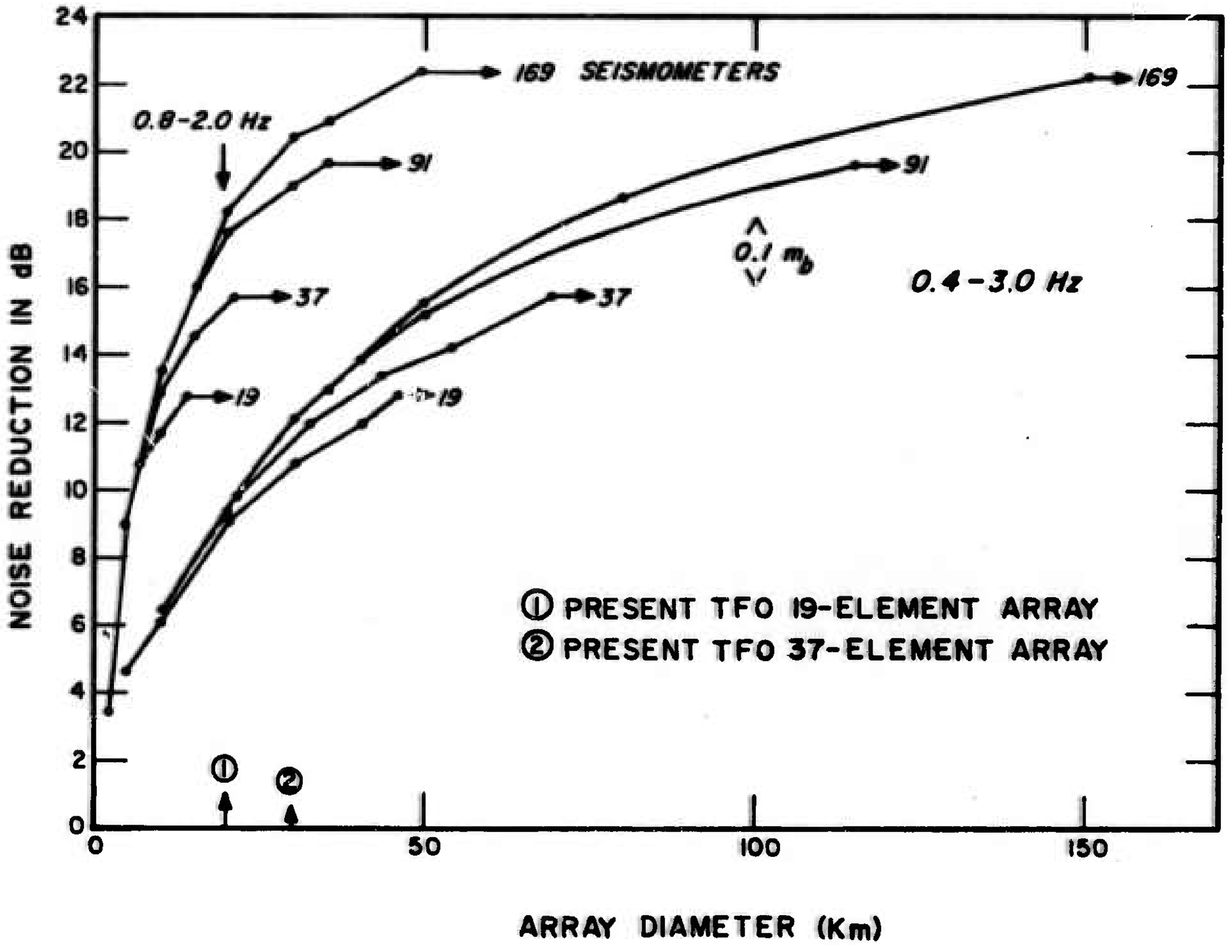

Figure 7. Predicted noise reduction for filled hexagonal arrays as a function of maximum array diameter for two bandpasses.