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A Scheme to Increase the Signal-to-noise Ratio of Teleseismic Records

by

R. Whitworth

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CONTENTS

ILLUSTRATIONS

SUMMARY

Various methods of increasing the signal-to-noise ratio of teleseisms are outlined. If improvement is defined as the ratio of the number of earthquakes detected before, to those detected after, applying a particular method, the corresponding improvements in the number of detected earthquakes are deduced as follows: by careful choice of site - up to 3.0; by frequency filtering - up to 1.7; by random noise reduction using uniformly effective arrays - about 4.0; by coherent noise cancellation using weighted arrays - about 10.0; and by use of shallow boreholes for reduction of wind noise - a maximum of 2.0.

It is suggested that resiting the seismographs and frequency-filtering should be carried out at the Australian Antarctic observatories. A combined improvement of up to 3.0 is feasible. Square arrays to reduce random noise could result in a further improvement of 4.0. The total improvement could then approach a theoretical limit of 20.0. The cost of such improvements would not exceed a few thousand dollars.

1. INTRODUCTION

Seismological observatories are usually placed in seismically noise-free areas so that maximum magnification may be used. Criteria influencing site selection are: low seismic noise level; homogeneous geology with few elastic discontinuities; good coupling of the seismometers to bedrock; a distance of at least five miles from a busy railway line, one mile from a busy road, 200 yards from the nearest tall trees; and a relatively flat area (Birtill & Whiteway, 1965).

In order to improve azimuth and epicentre determinations of earthquakes, particularly those occuring in the southern hemisphere, observatories have recently been built in areas falling far short of the criteria outlined above. Often the problems of adequate logistic support and lack of alternative sites preclude any better solution. This is especially true of Antarctica and the sub-Antarctic islands, where ice-free and accessible areas are rare.

The problem then becomes one of improving the observed signal-to-noise ratio (S/N) in order to bring the weaker teleseismic events above the background noise level. Before any attempt is made to improve S/N, the noise and signal characteristics of each site must be investigated. The general properties of seismic events and noise are outlined in Chapter 2. Work which has been carried out in Britain by the United Kingdom Atomic Energy Authority and in the USA under Project VELA UNIFORM, and which contributed towards a nuclear test detection system, has been drawn upon heavily.

2. THE CHARACTERISTICS OF SEISMIC SIGNALS AND NOISE

The seismic signal

At epicentral distances greater than 20 degrees, teleseismic events are only slightly affected by the peculiarities in transmission path or observing station (H.M.S.O., 1965). The dominant frequency of the signal depends upon its mode of transmission. Periods usually recorded are: P waves - one second; S waves - around four seconds; and surface waves - about ten seconds. The accurate determination of epicentres and depths relies upon P arrival times, and later events are used to confirm the interpretation.

Analysis of USCGS Earthquake Data Reports gives the following variation of dominant P-phase period (T) in relation to epicentral distance (Δ):

Δ, deg.	T, sec	Δ, deg.	T, sec	Δ, deg.	T, sec
10	0.9	40	0.85	70	0.8
20	1.0	50	0.85	80	0.85
30	0.9	60	0.75	90	0.9

A passband centred around one second would pass the P event almost unaltered. However, if a sharp commencement to the phase is wanted, the higher-frequency components must not be attenuated too severely. A band extending from 0.25 to 2.0 seconds would be more than ample for anything except local shocks.

The characteristics of seismic noise

Seismic noise originates from a variety of sources. It may or may not be coherent. There is a large peak in the spectrum around seven seconds which has not yet been satisfactorily explained. The total noise varies considerably from site to site and day to day in amplitude and other characteristics.

Multiple sedimentary layers usually produce more noise than crystalline rock. The quietest sites are found in the centres of continents, where the noise level can be below one nanometre (nm) in the 1 to 2 H_z band. For example, Yellowknife in Canada (in the centre of a Precambrian shield) has a noise level ranging from 0.2 to 2 nm; Eskdalemuir in Scotland (on extensive Silurian shale) has a noise level from 3 to 20 nm; and Macquarie Island (to the south-east of Australia) has a quiet-day noise level of about 100 nm. These correspond to very quiet, average, and very noisy sites respectively, according to Brune and Oliver (1959).

For periods longer than one second, noise is governed mainly by ocean microseisms, whereas below one second wind and cultural noise predominate. In general one would expect distant sources to generate coherent noise and local sources to produce random noise; the noise can thus be crudely separated into coherent noise above one second and incoherent noise below one second. (Toksoz's (1964) work partially confirms this hypothesis). This is unfortunate as the methods used to cancel coherent and random noise are different in principle, and the P wave is on the borderline of each. But, as mentioned before, the frequency spectrum and the type of noise vary from site to site, so that only a detailed site investigation can indicate the best method of improving S/N.

The major types of noise are outlined below:

Microseisms. Study of seismic noise on the ocean bottom and on land (Bradner & Dodds, 1964) indicates that most microseisms are generated by ocean storms. Coherence is high at long periods (greater than 8 seconds), but at short periods (less than 6 seconds) coherent microseisms occur only in short bursts (Toksoz, 1964). Rayleigh waves predominate at long periods, but there are differences of opinion about the type of wave present at short periods. Douze (1964) interprets the microseisms as fundamental, first, and third higher mode Rayleigh waves, while Gupta (1965) and Seriff et al. (1965) believe the noise could be standing waves of P type arriving at almost vertical incidence, especially in the band around and below one second. Bradner and Dodds (1964) also suggest the presence of leaking mode waves.

Cultural noise. This type of noise is of short period (less than 1 second) and is caused by industry, transport, and other human activities. Its amplitude varies greatly with time and place.

Wind noise. The wind blowing against hills and trees produces noise. The noise level depends upon local geology and wind velocity. Surf noise caused by waves breaking on a nearby beach could be included in this section. There can be a variation of ten to one in the noise level over a few kilometres, and a change of three to one can occur in a few tens of yards.

<u>Miscellaneous</u>. Low-magnitude events not identifiable as earthquakes produce noise at periods greater than one second. Local signal-generated noise due to multiple reflections and refractions within the surface layers can be considerable. Instrumental noise is always present, but can usually be kept below the general noise level.

3. METHODS OF IMPROVING S/N

There are many ways of increasing the efficiency of detection of teleseisms. Some of these are:

(1) Careful choice of site location.
(2) Frequency filtering.
(3) Arrays to reduce random noise.
(4) Arrays to cancel coherent noise.
(5) Arrays using azimuth and velocity filtering.
(6) Borehole seismometers.

Each of these will be discussed in turn, and an assessment will be made of how each one can improve the efficiency of earthquake detection. Only the order of magnitude of improvement can be assessed, because site peculiarities almost certainly have an effect.

Site location

As has been mentioned before, an improvement of ten to one in S/N can be otained by careful site selection. However, what we are basically interested in is the best possible location once the general site has been chosen. Local noise variation of three to one may occur, so a careful test of spatial noise variation needs to be carried out to find the quietest spot.

Weathering can create localised low-velocity layers, which enhance the noise level. Nearby hills, beaches, or rivers can result in high levels of wind and surf noise. The noise created by the observatory buildings themselves is frequently neglected. Much unnecessary noise is generated by badly designed and located huts. Buffeting of the huts in high winds can vibrate the piers if there is close coupling between hut and pier. Firmly grouting the piers into unweathered bedrock and the building of low-profile huts or vaults are obvious ways of reducing this type of noise.

If the local rock is poorly consolidated or too deeply weathered to allow the piers to be set in solid rock, use of multiple detectors to obtain more effective coupling with the earth suggests itself. This technique is common practice in seismic exploration, but seems to have been totally ignored in earthquake seismology.

Frequency filtering

A seismograph is a wide-band recorder with a low rate of cutoff. The bandwidth of a short-period recorder is typically 4 Hz. If white noise is present, then the noise power in unit bandwidth is constant. Narrowing the bandwidth to one-half or one-third of the original value should reduce the noise power in the same ratio. If the signal is not affected by the reduced bandwidth, the S/N should be improved by a factor of 2 to 3, as amplitude is proportional to the square root of the power. This would increase the number of earthquakes detected by 1.41 to 1.73 times respectively (see Appendix B). A short-period Benioff seismograph has a 1.0-second seismometer and 0.2-second galvanometer; these result in a 4-H_z bandwidth as defined by the 3-dB-down points. If the galvanometer period is increased to 0.4 second, the bandwidth reduces to 2 Hz; if increased to 1.0 second, the bandwidth reduces to 1.3 Hz (see Plate 1).

Narrowing the bandwidth in this way will attenuate the higher frequencies such that the start of a P phase will be harder to detect. As the dominant frequency of all teleseismic P waves is around one second, the high-frequency component is fairly small, but not necessarily unimportant. However, the primary aim of filtering is to detect signals that would otherwise be lost in the noise. 'Cleaning-up' the signal often makes the first cycle identifiable even though its start may not be very clear. Once the first cycle is identified, the start can be predicted to within a fraction of a second. It is all too often forgotten that an observer frequently cannot tell whether he has identified the first cycle of an event. As the second cycle is characteristically twice as large as the first, there seems little doubt that many small-amplitude P phases are wrongly associated with the second cycle, the first being submerged in the background noise.

If 'monochromatic' noise is present, use of a notch filter can greatly enhance the quality of the records obtained. A galvanometer with natural period of oscillation equal to that of the noise will reduce the noise by at least an order of magnitude when placed in series with the recording galvanometer (Pomeroy & Sutton, 1960). This technique is particularly suitable for removing the seven-second microseisms from long-period instrument records. Also, as noted by Birtill and Whiteway (1965), there are long-period events that are not identifiable earthquakes. If the records could be cleaned up sufficiently, sufficient detail could possibly be seen to determine epicentral distances. A notch filter could also be used to give higher cut-off rates at the edges of the passband to remove troublesome microseisms.

Many different types of filtering can be applied. Narrow passband, higher cut-off rates, and notch filtering are just a few of the possibilities. With electronic amplifiers, these methods could easily be used. Inverse filtering to make the background noise white would become possible, and then the optimum S/N could be obtained with frequency filtering. Recording on magnetic tape would become a worthwhile proposition and observatory seismology would take a large step forward.

Arrays to reduce random noise

Much of the noise at periods of less than one second is incoherent. This is especially true of wind and surf noise. A detector array of comparatively small dimensions can be used to reduce such noise. The dimensions of the array would depend upon the predominant frequency and velocity of the noise. The seismic noise in the one-second band, as given by Brune and Oliver (1959), is not isotropic. As the optimum S/N is obtained with white noise, inverse filtering could be used.

A study of the improvement in S/N obtainable using multiple detectors when random noise is present has been made by Denham (1963). He assumed the noise was isotropic. As long as the bandwidth of the seismograph is not too large, the assuming of the noise to be white will enable us to get an approximate idea of the improvement possible. Denham derived the correlation between detectors at various bandwidths for two cases: white noise with a rectangular spectrum, and noise after passage through a tuned circuit (Plate 2). A seismograph is equivalent to a high-gain, low-Q, tuned circuit rather than a rectangular passband detector. However, both cases give low correlation when d/λ_0 is greater than 0.5 (where d is the detector spacing and λ_0 the wavelength of the noise at the central frequency of the passband), so the exact equivalent is not very important.

If the bandwidth is increased or the Q decreased, the amplitudes of secondary maxima of correlation are reduced. Further, it is better to use a few detectors separated sufficiently to obtain random noise rather than many detectors with only a small positive correlation coefficient. Then, with the individual detectors weighted to give optimum S/N output, the familiar $\sqrt{N}$ improvement is obtained. The optimum weighting may be determined using Birtill and Whiteway's formulae (1965, p. 477).

A square array of 16 detectors with optimum weighting will improve the S/N by four to one as long as the signal is in phase at all points, and will thus increase the number of detectable earthquakes by about four times. If the dimensions of the array are small compared with the signal wavelength, there will be only small signal phase differences across the array, and the S/N improvement will be close to the theoretical maximum. However, the apparent P wavelength along the Earth's surface varies with epicentral distance; the Jeffreys-Bullen travel-time tables show that it varies from 8 km at the epicentre to 25 km at large distances for periods around one second (see Plate 3). The variation of S/N with distance for detector spacings of 0.25, 0.5, and 1.0 km is given in Plate 4.

The optimum dimensions of the array can be determined only by a field investigation such as that described by Denham (1963). Tomoda (1956) gives a method for calculating the correlation coefficient that is good enough for the accuracy required, so little peripheral equipment is required besides a low-frequency seismic exploration instrument.

<u>Arrays to cancel coherent noise</u>

Wavelength filters may be used to reduce coherent noise. Noise with wavelengths ranging from twice the dimensions of the array down to the order of separation of the detectors is greatly attenuated, the degree of attenuation depending upon the number and weighting of the detectors and their spatial arrangement.

That noise is coherent implies that it is coming from a discrete source, and hence a fixed direction. The noise source may move with time, or there may be several sources, so an array with omni-directional attenuation is needed. A square array with uniformly effective detectors is a rough approximation to such an array and, as its properties are simple to derive, this type will be used as an example. The attenuation of a square array depends on the direction of approach of the noise, but for simplicity the response to noise travelling parallel to a side of the square will be taken as representative. The problem then reduces to that of a line of uniformly effective detectors with noise travelling along the line.

The relative response of 4, 6, and 8 detectors is shown in Plate 5, where λ is the wavelength of the disturbance and d is the detector spacing. Average response curves give a better idea of the array response because both signal and noise have wavelength distributions rather than single values (Graebner, 1960). The law of diminishing returns with increase in number of detectors rapidly sets in. The limiting case of a continuous detector still has an average response in the attenuation band of about 0.1. If a square array is being used, the number of detectors increases greatly for little increase in attenuation. A four-square to six-square array would be the best compromise, with an average response of 0.2 to 0.15 in the attenuation band.

The amplitude of subsidiary peaks can be equalised and reduced to any required value by suitable weighting of the detector outputs, such as Tchebyscheff polynomial weighting (Holtzman, 1963). Tchebyscheff polynomial weighting has the advantage of increasing the uniformity of azimuthal response as well as improving S/N. The average response of a four-square array can be reduced to less than 0.1 in the rejection band, but the rejection bandwidth would be narrowed as a result (Parr & Mayne, 1955). For large attenuations the sensitivities of the central detectors become very high compared with those of the outer detectors. This would make the array prone to disturbance by any random noise crossing the array. As random noise is always present, variation of detector sensitivities by more than two to one should be avoided.

The type of noise present has a great influence on the dimensions of the array. As mentioned in Chapter 2, there is disagreement on this point. Let us assume that the coherent noise is predominantly fundamental Rayleigh waves, in order to obtain an idea of the probable improvement. At short periods (around one second), Rayleigh waves have a velocity of about 3.5 km/s for continental sites, and about 2.0 km/s for oceanic sites. Adopting a passband of 0.25 to 2.0 seconds, and a noise velocity range of 2.0 to 4.0 km/s, the noise wavelength may range from 0.5 to 8.0 km. Setting the upper limit of the noise wavelength at the rejection band half-power point $\lambda/d = 8$ for a four-square array (from Plate 5), the spacing of the elements must be one kilometre, making the array 3 x 3 km. The higher-frequency noise will tend to be more incoherent, and so will be reduced owing to the spacing of the detectors. In other words, the array output is not likely to be saturated by wind and surf noise with wavelengths shorter than the minimum wavelength of the rejection band.

At one Hz, the P-phase apparent wavelength ranges from 8 to 25 km (Plate 3). Therefore, the higher-frequency components at short distances will be removed, but the effect at normal teleseismic distances will be small. For example, at 5^{o}, the lower half-amplitude point for P waves will be 0.8 s, at 20^{o} about 0.6 s, and at 50^{o} about 0.4 s (Plate 6). By decreasing the size of the array, the higher-frequency content of the P waves may be retained.

The 3 x 3-km array will reduce the noise within a wide bandwidth. However, it is unlikely that the full range of Rayleigh wave velocities will be present at any one site. For example, at oceanic sites noise velocities are unlikely to exceed 2.5 km/s at P-wave periods. Adopting the same pass band as before, the greatest noise wavelength would be about 5 km. A detector spacing of about 0.5 km would be needed to set the upper limit of the noise wavelength at the half-power point. P-phase periods above 0.4 s would be passed for local quakes, and periods above 0.2 s for teleseisms (Plate 6). The small dimensions of the array and the high noise level usually present at island sites would make the method most attractive.

Improvements in S/N of 5:1 for uniformly effective arrays and 10:1 for Tchebyscheff polynomial weighted arrays are feasible without the arrays becoming excessively large or requiring any very sophisticated peripheral equipment. A d.c. amplifier is about the only piece of equipment needed that is not at present in use at most observatories, so costs could be kept low. The number of earthquakes detected would then go up by 4 to 8 times the present level.

Arrays for azimuth and velocity filtering

If the output of each detector is recorded separately, the outputs can later have variable time delays introduced. This allows one to search for events of specified velocities and direction of approach. Very large improvements in signal detection capability may be obtained by using cross-correlation techniques. Such a method requires that the azimuth and distance of each event are known, or the outputs are swept for velocity and azimuth. Considerable peripheral equipment such as multi-channel magnetic tape recorders, time delay units, cross-correlators, and possibly a computer are required to take full advantage of this technique (Birtill & Whiteway 1965).

An observatory in a populated area could possibly use a phased array on line, but a station in a more isolated area would need to carry several weeks' or months' records on tape for analysis elsewhere, such as a computer centre. The present procedures of observatory seismology require rapid reduction and transmission of data. We are mainly interested in improving S/N at noisy, and usually isolated, sites so phased arrays need not be considered further.

Borehole seismometers

The amplitude of fundamental Rayleigh waves decreases with depth below the Earth's surface. Therefore, Rayleigh wave effects can be reduced by placing the detector down a borehole. The problem is whether seismic noise is made up predominantly of Rayleigh waves. As mentioned before, there is still lack of agreement on this point. Work by Gupta (1965) and Seriff et al. (1965) certainly shows that the noise level passes through several minima with increase in depth. The depths of the minima depend upon the period of the noise. At a period of one second, the first minimum occurs at about 1.5 km.

Unless the detector is placed at a depth carefully determined from a study of the noise variation down the hole within the passband, little improvement could result. By placing detectors at depth and on the surface, mixing could be used to reduce the noise. By applying a fraction of the surface noise with a complete reversal of phase to the output obtained down the hole, a very large increase in S/N could be obtained. Theoretically, the noise could be totally eliminated. However, as more than one mode of noise certainly exists, only partial cancellation could be obtained.

Phase reversals also take place with increase in depth, so great care must be taken in siting the borehole detector to prevent destructive cancellation of the signal also.

Wind noise is usually in the 0.2-second period range, so is mainly confined to the near-surface layers. In areas with high wind noise, improvements of ten to one in S/N can be obtained with boreholes only a few hundred feet deep (Thirlaway, pers. comm.). It must be remembered that shallow holes will improve S/N only on days of high wind, so the average increase in S/N will be much less. At Wilkes about one-fifth of the days may be termed windy, so the average improvement in earthquake detection would be perhaps 1.2. At Mawson about half the days are affected by katabatic winds, and the improvement would be about 2.0.

4. CONCLUSIONS

(1) By careful choice of the detector sites within the local area, by the grouting of detectors to bedrock, or by use of multiple detectors if necessary, the number of detected earthquakes may be increased by a factor of about 3. At observatories with instrument vaults, moving to a better site would be expensive and time consuming; but where huts are used, the removal would present comparatively few problems. Furthermore, the observatories using huts are in the Antarctic, an area critical to improved azimuth and epicentre determination, and the improvement possible would be more significant than elsewhere.

(2) Increasing the galvanometer period to one second should result in an improvement of 1.7 or so. This alteration would give the greatest single improvement for the effort involved. Using notch filter galvanometers at places such as Wilkes would improve the quality of long-period records considerably, again with little effort involved.

(3) If incoherent noise is the major part of the noise spectrum, improvements of 4.0 to 6.0 are possible with four-to six-square arrays. To keep the cost low, low-frequency geophones and d.c. amplifiers should be used.

(4) An improvement of 5.0 may be achieved with a uniformly effective four-square array when coherent noise is present. The technique would be most suitable at oceanic island sites as the dimensions of the array may be kept small and the effect of signal phase differences over the array thus kept at a low level.

(5) Assuming that considerable peripheral equipment is available (multi-channel tape recorders and possibly a computer) improvements of 10.0 are possible. This is feasible only at a large station on the Australian mainland, and the necessary finance would run into hundreds of thousands of dollars.

(6) At sites suffering from almost continuous high winds, shallow boreholes could give improvements of up to 3.0 or so. Mawson, with its daily katabatic wind, would be a suitable test site. At our present state of knowledge, deep boreholes would not be justified, particularly as a similar order of improvement could be obtained by other techniques (see 1 to 5 above) at about one-tenth of the cost.

5. RECOMMENDATIONS

(1) Thorough investigations of noise should be carried out at Macquarie Island, Mawson, and Wilkes.

(2) The seismograph huts should be relocated at the quietest points, and the short-period galvanometers should be replaced by one-second galvanometers. These two stops alone would increase the number of detectable earthquakes by a factor of about 5.

(3) The use of arrays to reduce incoherent noise, particularly that due to high winds and surf, should be seriously considered. The number of detectable earthquakes could be increased by up to five times.

(4) The possible use of shallow borehole seismometers at Mawson should be investigated further. However, if the above recommendations are adopted, a borehole would probably prove to be an uneconomic proposition.

The combination of recommendations 1 to 3 could result in a maximum improvement of 20. As the various techniques tend to have conflicting requirements e.g., narrow passband for frequency filtering but a wide passband reduces secondary maximums in random noise cancellation, possibly 10 to 15 would be the maximum achievable improvement. This corresponds to a reduction in magnitude of the smallest detectable earthquake of 1.2 to 1.5.

6. REFERENCES

BIRTILL, J.W. and WHITEWAY, F.E., 1965 - The application of phased array to the analysis of seismic body waves. Phil. Trans. Roy. Soc. (Lond.), 258, p. 421.

BRADNER, H. and DODDS, J.G., 1964 - Comparative seismic noise on the ocean bottom and on land. J. geophys. Res., 69, p. 4339.

BRUNE, J. and OLIVER, J., 1959 - The seismic noise of the Earth's surface. Bull. Seismol. Soc. Am., 49 p. 349.

DENHAM, D., 1963 - The use of geophone groups to improve the signal-to-noise ratio of the first arrival in refraction shooting. Geophys. Prosp., 11, p. 299.

DOUZE, E.J., 1964 - Rayleigh waves in short-period microseismic noise. Bull. Seismol. Soc. Am., 54, p. 1197.

GRAEBNER, R.J., 1960 - Seismic data enhancement - a case history. Geophysics, 25, p. 283.

GUPTA, I.N., 1965 - Standing wave phenomena in short-period seismic noise. Geophysics, 30 p. 1179.

H.M.S.O., 1965 - The detection and recognition of underground explosions. London.

HOLTZMANN, M., 1963 - Chebyshev optimized geophone arrays. Geophysics, 28 p. 145.

PARR, J.O. and MAYNE, W.H., 1955 - A new method of pattern shooting. Geophysics, 20, p. 539.

POMEROY, P.A. and SUTTON, G.H., 1960 - The use of galvanometers as band rejection filters in electromagnetic seismographs. Bull. Seismol. Soc. Am., 50, p. 135.

RICHTER, C.F., 1958 - ELEMENTARY SEISMOLOGY. San Francisco, W.H. Freeman and Co.

SERIFF, A.J., VOLGEBOAR, C.J., and HAASE, R.J., 1965 - Possible P-wave observations in short-period seismic noise. Geophysics, 30, p. 1187.

TOMODA, Y., 1965 - A simple method of calculating the correlation coefficients. J. Phys. Earth, 4, p. 67.

TOKSOZ, M.N., 1964 - Microseisms and an attempted application to exploration. Geophysics, 29, p. 154.

APPENDIX A

TECHNICAL DETAILS CONCERNING RECOMMENDATIONS

The cost of resiting seismograph huts is difficult to determine. However, Wilkes is being moved to a new camp site and new huts are being provided, the Macquarie Island seismograph hut is scheduled for replacement within the next few years, and ANARE would be prepared to resite the Mawson observatory if required (Brown, pers. comm.). Of course, if arrays are used, seismometer huts are not strictly necessary. In the first few years of a test array, it would be best to obtain comparisons between normal observatory seismographs and array results.

Frequency filtering can be arried out by replacing the present galvanometers with one-second period galvanometers. The cost of such galvanometers is not likely to exceed $350.

A square array of 16 detectors at 0.5 km and 1.0 km spacings would require 7.5 and 15 km of wire respectively. If simple twinflex wire was suitable, this would cost $400 to $750. Twinflex wire could only be used if there were no pick-up from magnetic disturbances, lightning, and radio transmissions; i.e., the wire must be laid in such a way that there are no inductive effects. At Macquarie Island, rodent-resistant wiring would probably be required. A preamplifier at the array would reduce any pick-up effects.

There are two possible methods of instrumentation for the array:

(1) Normal seismometers summed and fed into the usual type of galvanometer, i.e. a slight variation of the usual seismograph layout where the single seismometer is replaced by a group.

(2) Seismic prospecting geophones summed, possibly after preamplification, and fed into a d.c. or v.l.f. amplifier followed by a suitable galvanometer. Any necessary filtering could be carried out in the amplification stage.

Technique 1 could prove very expensive. The cheapest seismometers available are Willmores, costing about $800 each. The 16-detector array would cost $13,000 for the seismometers alone. Geophones, on the other hand, are comparatively cheap, prices ranging from $10 for the subminiature type to about $200 for the more sensitive low-frequency type. It is obvious that geophones plus an amplifier costing perhaps $400 would be a far more economical proposition. The decision then rests upon whether the geophones are sufficiently sensitive in the 1-Hz band to give output voltages above the amplifier noise level.

The relation between earthquake magnitude M and ground amplitude A is

$$M = \log_{10}(A/T) + Q(\Delta, h)$$

where T is the P-wave period (here assumed 1 second) and Q is the distance-depth factor defined by Gutenberg (Richter, 1958). Plate 7 shows the variation of P-phase ground amplitude (in nanometres) with distance for a magnitude 5 earthquake at normal depth (33 km), derived from Richter's Fig. VIII-b. An average amplitude of 10 nm could be adopted at teleseismic distances. The approximate ground amplitude and number of earthquakes occurring (H.M.S.O., 1965, Fig. 13) are tabulated below as a function of magnitude.

Magnitude	Approximate P amplitude	No. of earthquakes ≥ M
4	1 nm	12,000
5	10 nm	1,400
6	100 nm	160
7	1000 nm	20

If an earthquake can just be detected when S/N = 1, then the approximate noise levels at an observatory can be deduced from the number of teleseisms detected each year (See Appendix B). The noise level varies considerably during the year, reaching a maximum in summer and a minimum in winter. At Wilkes for example, the number of earthquakes detected each month ranges from 25 to 100 associated with a noise level range from 10 to 50 nm; i.e. ratios of roughly half to twice the average level.

Observatory	No. of earthquakes	Noise level (nm)		
		Average	Maximum	Minimum
Macquarie Island	100	160	320	80
Mawson	600	26	50	10
Wilkes	600	25	50	10

A well designed transistor amplifier will have a noise level at the input of the order of 1 microvolt, while a valve amplifier can usually be built to give a noise level of 0.1 microvolts. For convenience, let us adopt an amplifier noise figure of 1 microvolt. Some representative geophone sensitivities are given bleow.

Geophone	Resonant freq. (Hz)	Sensitivity (Volt/cm/s)	Sensitivity at 1 Hz	
			Amplitude	Voltage
HS-10-1) EV-17)	1	1	500	2
HS-10	2	1	150	7
TIC	5	1	20	50
EVS-10	10	0.6	3	300

It can be seen that under average conditions for all Antarctic observatories, the TIC geophone would be sufficiently sensitive. Only on quiet days at Wilkes and Mawson when the noise level drops to 10 nm will the amplifier noise become significant. If the noise is random, the array output would then be 4 x 0.2 microvolts or about 1 microvolt, the same order as the amplifier noise. An individual geophone signal of 0.1 microvolts would then just be detectable (signal output of 1.6 microvolts compared with a total noise figure of 1.4 microvolts). This minimum signal level corresponds to a ground movement of 5 nm, or about 2500 observable earthquakes per year.

It should be noted that six or so EVS-10 miniature geophones could be substituted for each TIC to give the same results. Problems of impedance matching might then arise, but by choosing series-parallel connexions in the right fashion, a reasonable impedance could be maintained. The cost of miniature geophones is so low that this may be a more economical solution. With 5-or 10-Hz geophones, a passband of 1 to 5 Hz would be obtained if a one-second galvanometer is used. Filters to narrow the bandwidth for reasons given in Chapter 3 should therefore be used. The amplifier might possibly be saturated by high-frequency noise, so input filters may be necessary.

If lower-noise-level sites are found, higher-sensitivity geophones, more geophones, or lower-noise-figure amplifiers would be called for. With sufficient power, a valve amplifier would be the cheapest solution by far. It might then, however, be difficult to use preamplification, as the power requirements would rise rapidly with the number of geophones.

The cost of a 3 x 3-km array would then be about \$800 for wiring, \$200 for the amplifier, perhaps \$1600 for the geophones, and \$400 for the galvanometer: a total of \$3000. To test the effectiveness of such an array only about \$1000 would be required, as the geophones could be borrowed from B.M.R.'s seismic section and an available galvanometer used. For 0.5-km spacing a test array would cost only \$500.

APPENDIX B

RELATION BETWEEN IMPROVEMENT AND S/N

Let us assume that the smallest earthquake that can be detected has a signal-to-noise ratio of unity. Using the subscripts u and i for unimproved and improved detector arrangements respectively, S/N for signal-to-noise ratio, A for amplitude of smallest earthquake detectable, and n for number of earthquakes detected,

$$\frac{(S/N)_i}{(S/N)_u} = \frac{A_u}{A_i}$$

The number of earthquakes n occurring per year of magnitude $\geq$ M over the whole Earth has been determined empirically as

$$\log n = J - b\,M \qquad \text{(H.M.S.O., 1965, Fig. 13)}$$

where the magnitude M is defined in terms of ground amplitude A as

$$M = K + \log A \qquad \text{(Richter, 1958, p. 359)}$$

and where J, b, and K are constants. The constant b is approximately equal to unity. Because there is not much variation in the level of the graph in Plate 7 from 30° onwards, the number of teleseisms recorded down to a certain magnitude may be taken as n for a station not in an active seismic belt.

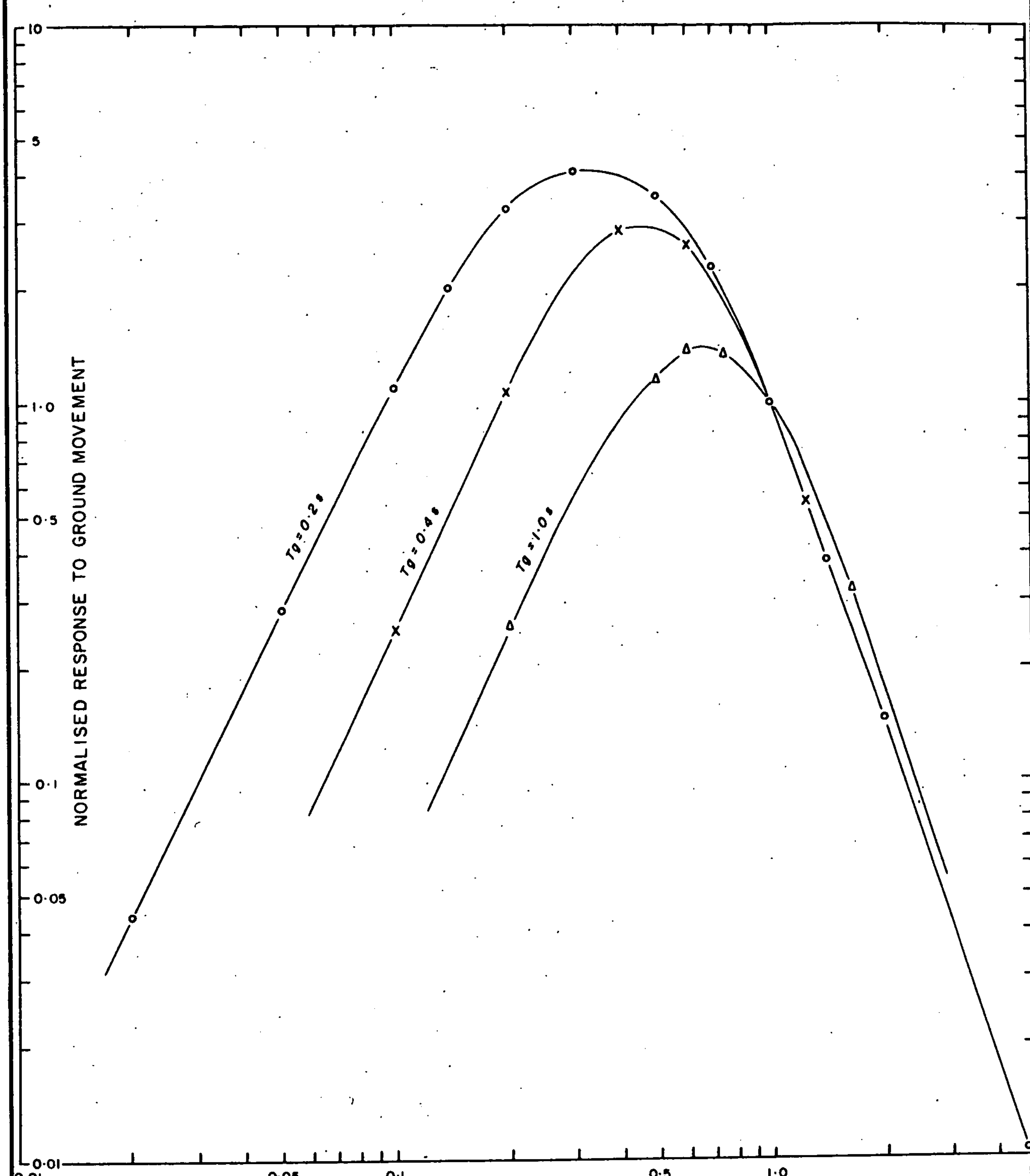
Hence $n \propto 1/A$

Hence $$\frac{(S/N)i}{(S/N)u} \simeq \frac{Ni}{Nu}$$

and as improvement is defined as ni/nu

$$\text{Improvement} = \frac{(S/N)i}{(S/N)u}$$

PLATE I



BENIOFF CALIBRATION CURVES FOR GALVANOMETERS WITH DIFFERENT PERIODS

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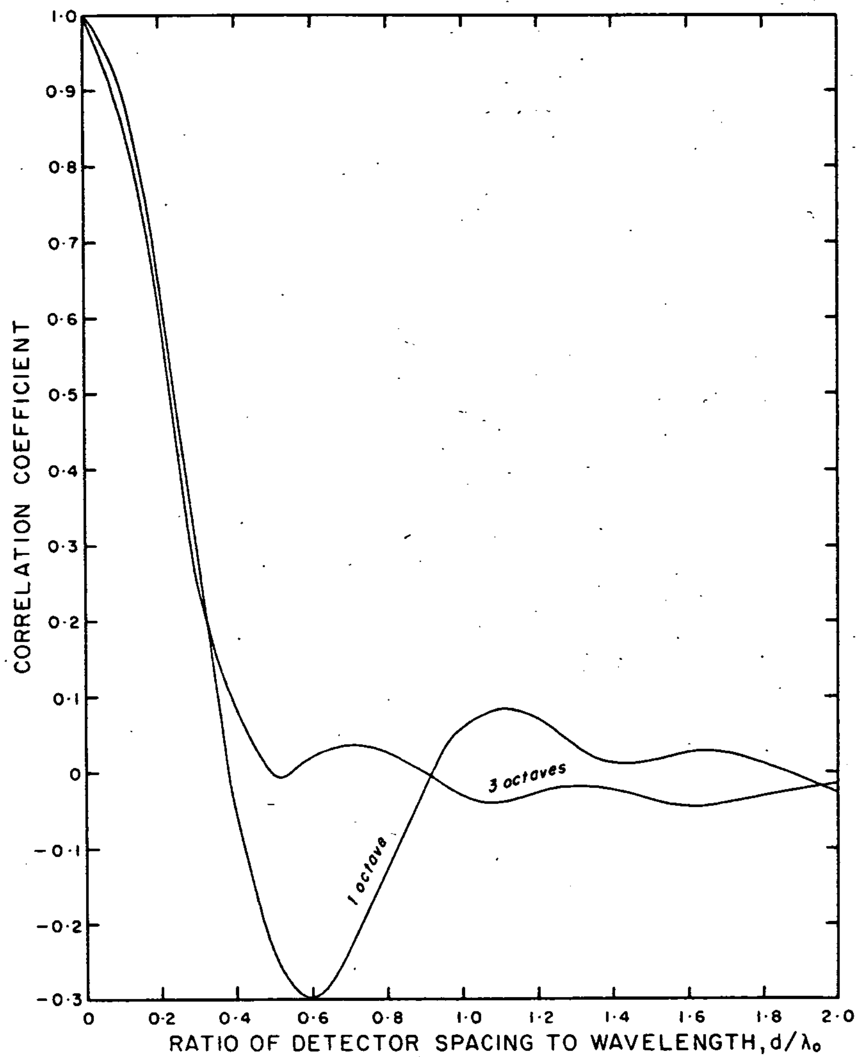
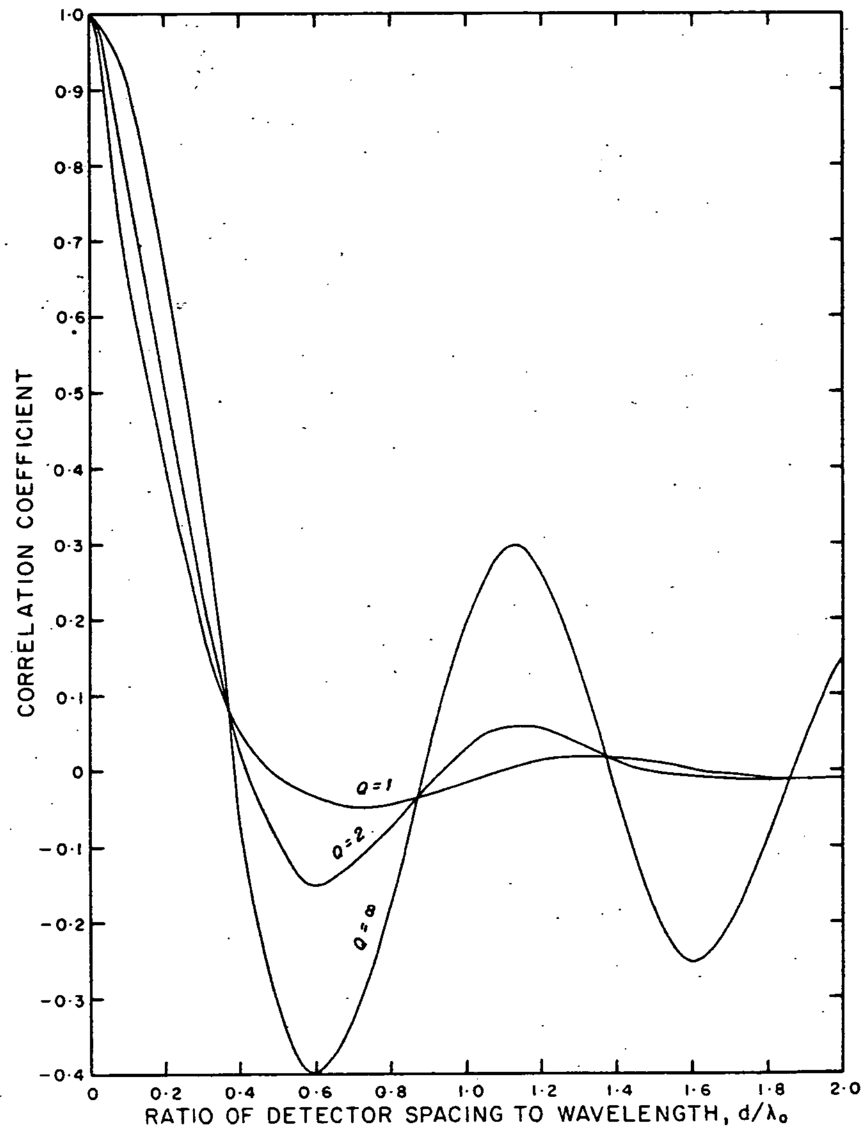
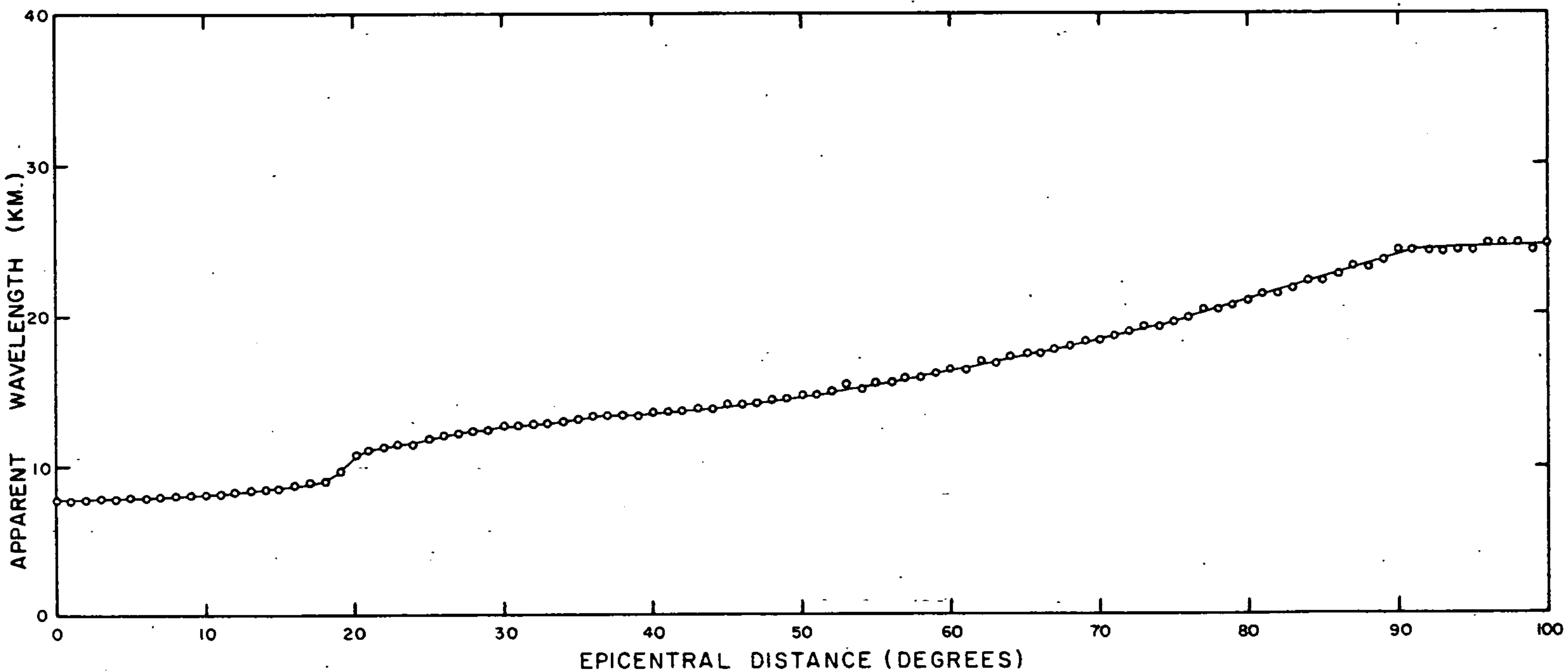


CORRELATION COEFFICIENT FOR RECTANGULAR SPECTRA



CORRELATION COEFFICIENT FOR TUNED—CIRCUIT SPECTRA

PLATE 2



P–PHASE APPARENT WAVELENGTH AT ONE–SECOND PERIOD

PLATE 3

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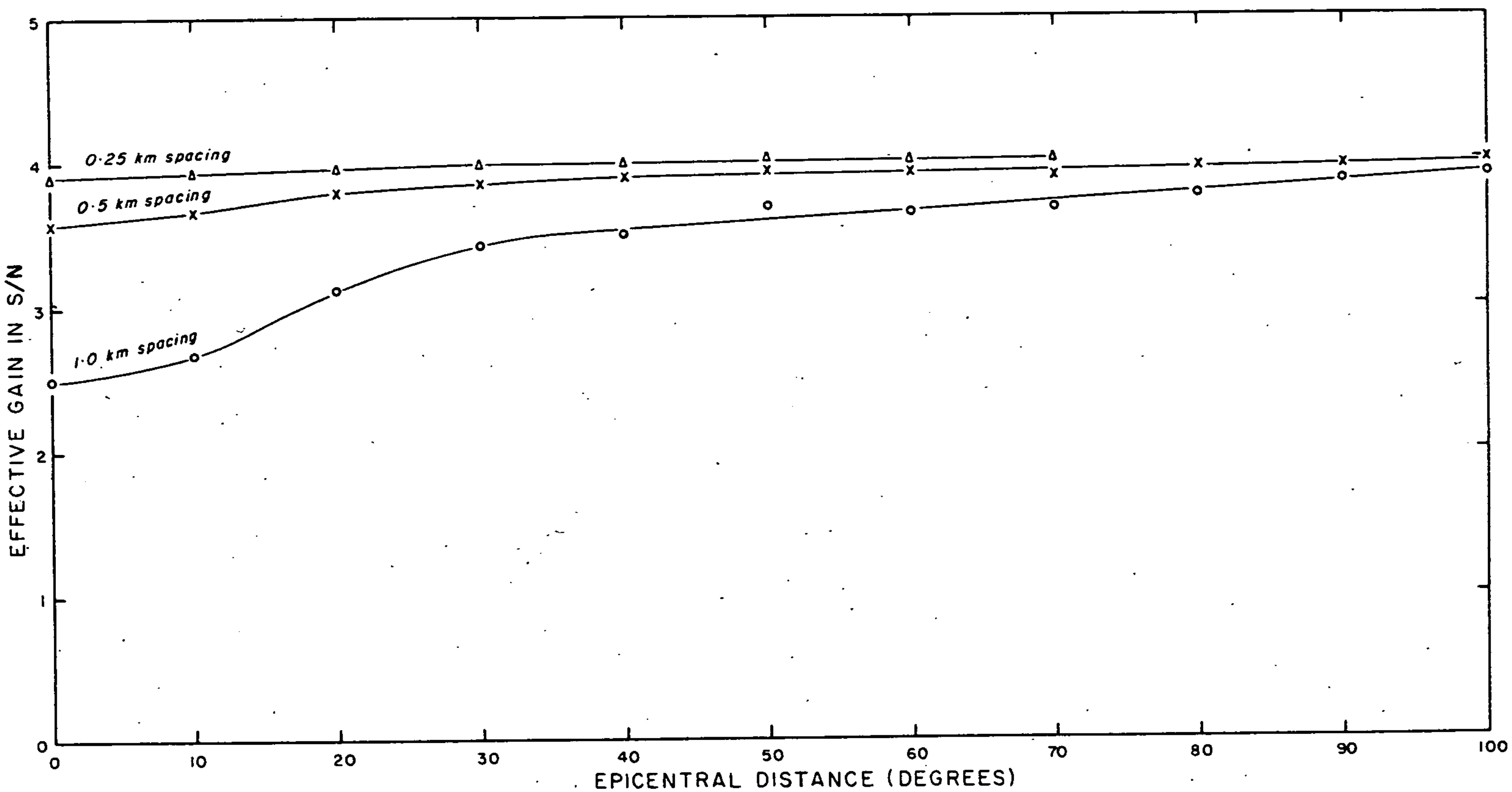
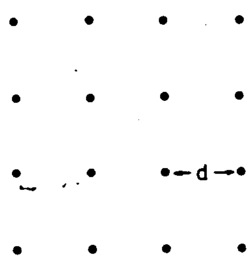
PLATE 4





d = detector spacing

Maximum possible gain in S/N = $\sqrt{N}$ = 4

EFFECTIVE GAIN IN SIGNAL—TO—NOISE RATIO OF P—PHASE USING A FOUR-BY-FOUR DETECTOR ARRAY WHEN RANDOM NOISE PRESENT, FOR VARIOUS DETECTOR SPACINGS

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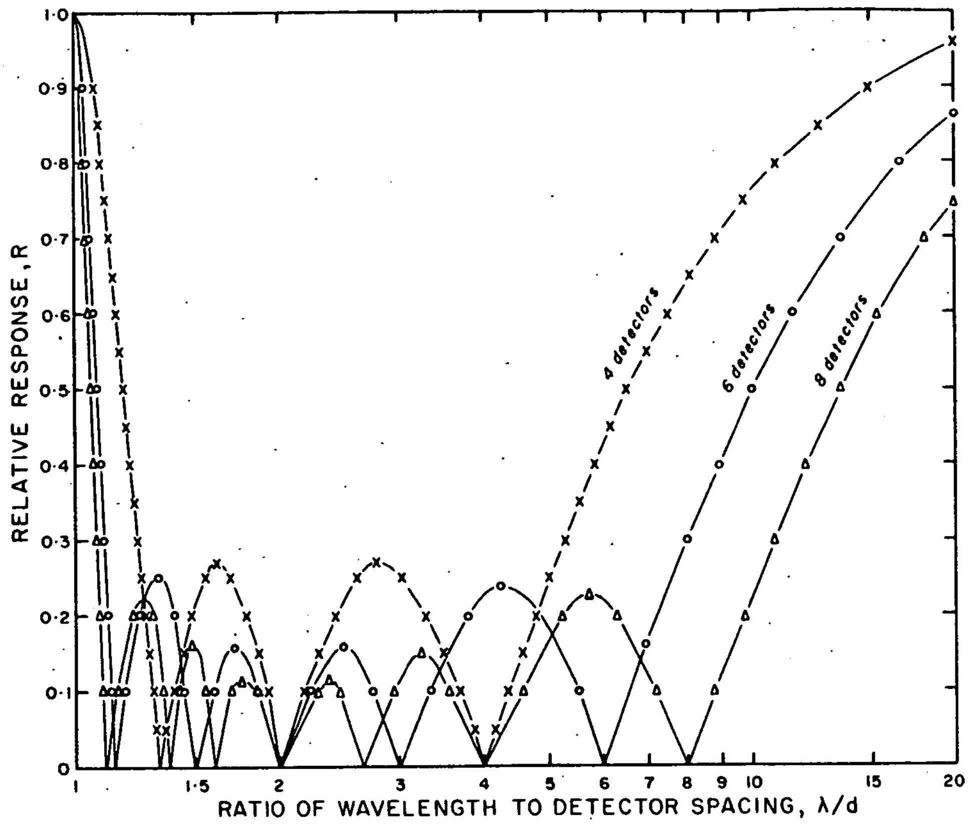
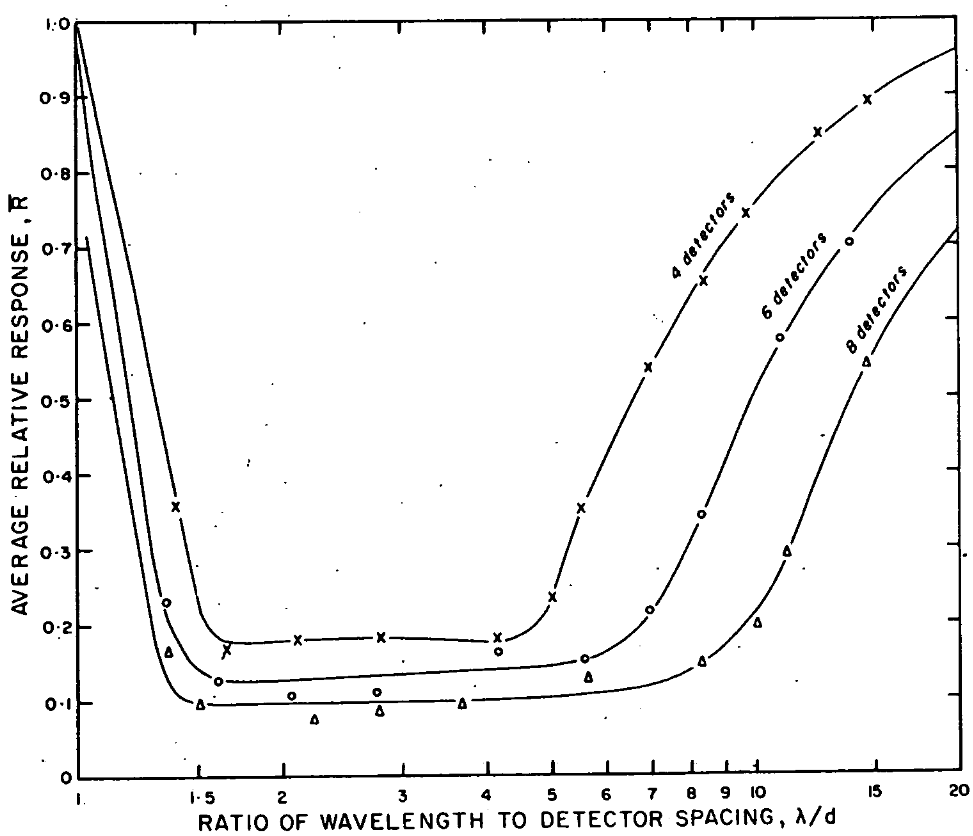


RELATIVE RESPONSE OF A LINEAR GROUP OF UNIFORMLY SPACED DETECTORS



AVERAGE RELATIVE RESPONSE OF A LINEAR GROUP OF UNIFORMLY SPACED DETECTORS

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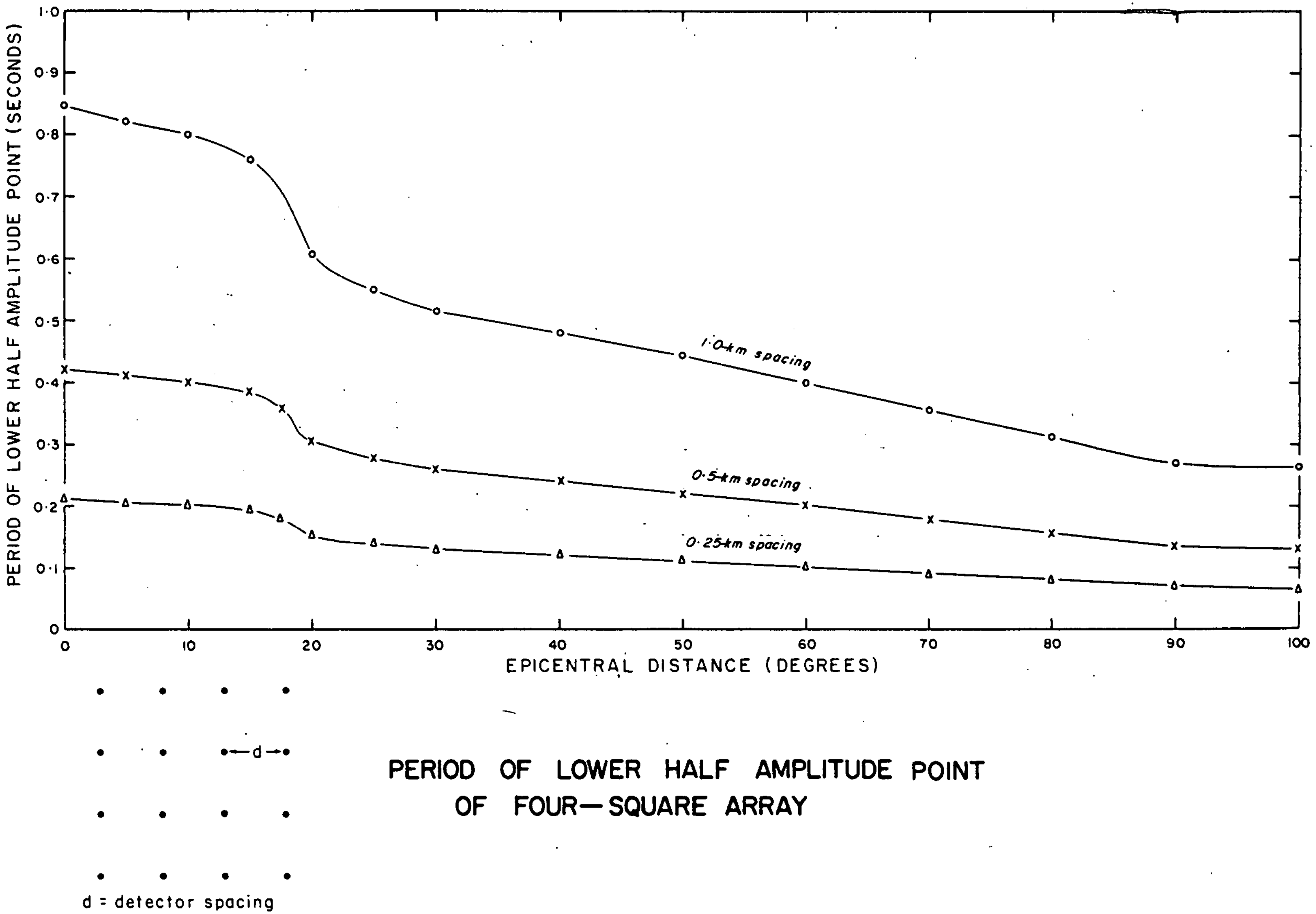

PERIOD OF LOWER HALF AMPLITUDE POINT
OF FOUR—SQUARE ARRAY

PLATE 6

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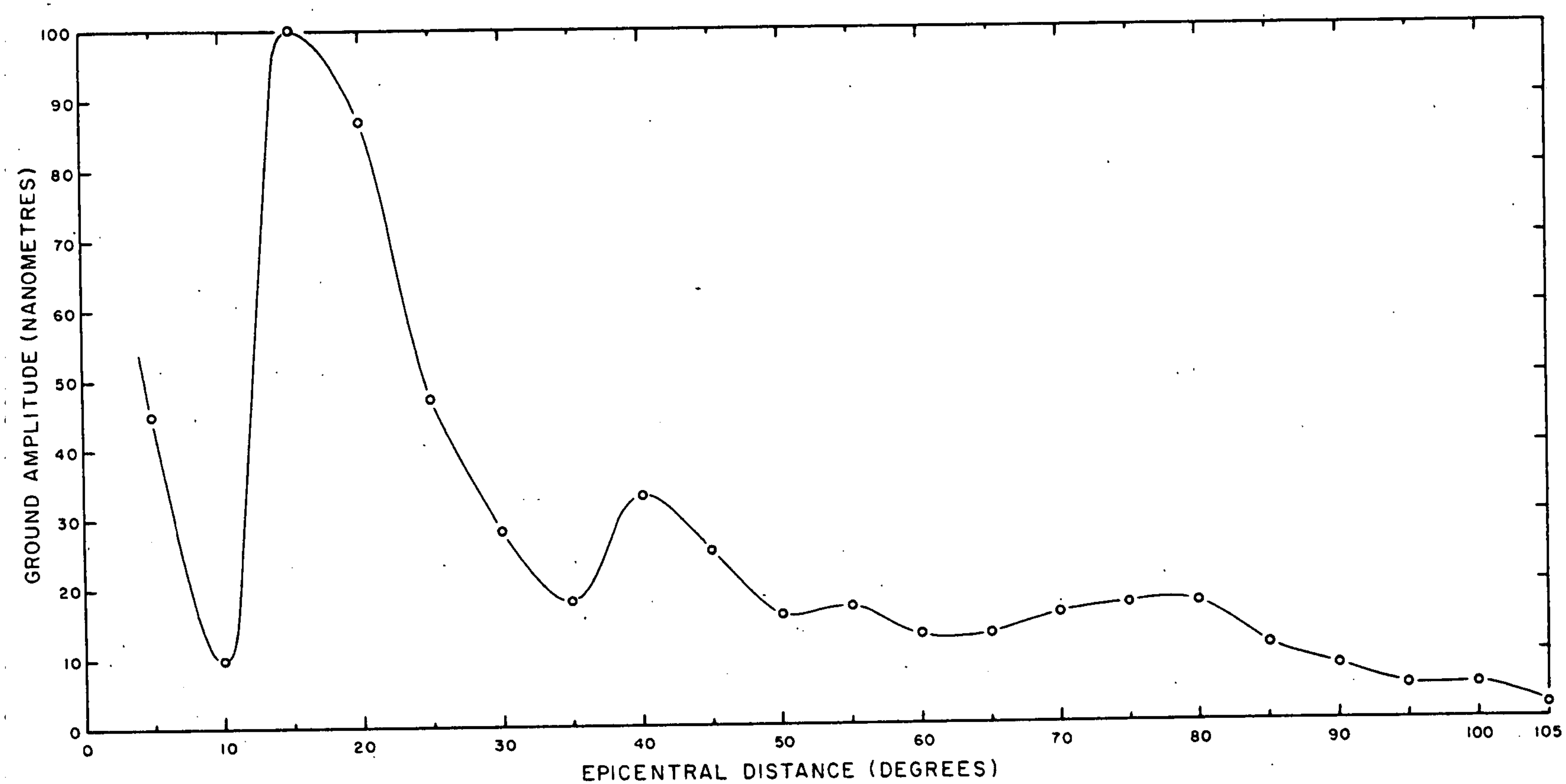

P-PHASE GROUND AMPLITUDE IN NANOMETRES FOR A MAGNITUDE 5 EARTHQUAKE

PLATE 7

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