Geof. Int., Vol. 28-3, 1989, pp. 561-578

A DEDICATED SEISMIC ARRAY FOR NUCLEAR TEST BAN MONITORING AT REGIONAL DISTANCES

F. A. NAVA*
J. M. ESPINDOLA*
(Received: 19 September, 1988)
(Accepted: 9 May, 1989)

Contribución del IGF # A-6

RESUMEN

En vista de un posible acuerdo de prohibición de pruebas nucleares en el Campo de Pruebas de Nevada, USA, se consideran algunos aspectos técnicos para instalaciones sísmicas a fin de resolver el problema de monitoreo desde suelo mexicano. Se propone el uso de instalaciones especiales aplicadas aquí para el caso particular de México, como un medio para lograr la capacidad adecuada de monitoreo a distancias regionales con un mínimo de medios. Se propone la región alrededor de Tecate en Baja California Norte como sitio preferente para dichas instalaciones. Se presentan diseños preliminares para ilustrar la metodología propuesta, basada en el uso de operaciones en línea y un interruptor de rechazo azimutal.

ABSTRACT

In view of a possible nuclear test ban in the Nevada Test Site of the USA some technical aspects of seismic arrays are considered, in order to solve the problem of monitoring from Mexican territory. Dedicated arrays applied here to a particular case in Mexico, are proposed as a means for achieving adequate monitoring capabilities at regional distances with a minimum of means. The region around Tecate in Northern Baja California is proposed as the preferred site. Preliminary possible array designs are presented to illustrate the proposed methodology based on the use of minimal on-line operations and an azimuthal rejection switch.

* *Instituto de Geofísica, UNAM, MEXICO.*

INTRODUCTION

Present capabilities, including those of the Six Nation Initiative Group (Six Nation Declarations, 1986), for seismic worldwide monitoring of worldwide nuclear test activity and particularly of possible nuclear test ban agreements between the two nuclear superpowers, the USSR and the USA are, at present, unbalanced.

Due to the proximity of Mexico to the USA, and particularly to its most used test site, the Nevada Test Site (NTS), monitoring of NTS from Mexican territory should help redress such unbalance, thus contributing to set favorable conditions for a possible test ban treaty.

Hence, the present work considers the design of a possible array located within Mexico and dedicated to the monitoring of the Nevada Test Site. Such an array would be located at a regional distance from NTS, leading to the expectation of possible explosion discrimination down to a fairly low yield threshold. However, lithosphere variations and high local and regional seismicity introduce complications and strongly influence the design.

The main objective here is to present a first theoretical approach to the design of an array, which may serve as a basis for discussion leading to a better understanding of the problem and, eventually, to a working array design.

GEOLOGICAL AND SEISMOLOGICAL SETTING

The geological structures of the source and receiver sites and of the possible ray paths between them are an important factor to take into account for the design of a monitoring array.

The location of the source site, NTS, is a given parameter; unfortunately that does not mean that the effects of the source geological characteristics can be corrected for in an easy way for any explosion generated there. NTS is located in the Basin and Range Province (Fig. 1), which is tectonically quite active (Stewart, 1971). The lithology and seismic wave velocity vary greatly over the test site; geology goes from rhyolite to tuff to alluvium (Dahlman, 1974), and velocities vary over large ranges for any one depth (Priestley, 1974; Bache *et al.*, 1978). These variations cause corresponding differences in the explosion source functions which may change by a factor of more than 100 (Dahlman, 1974).

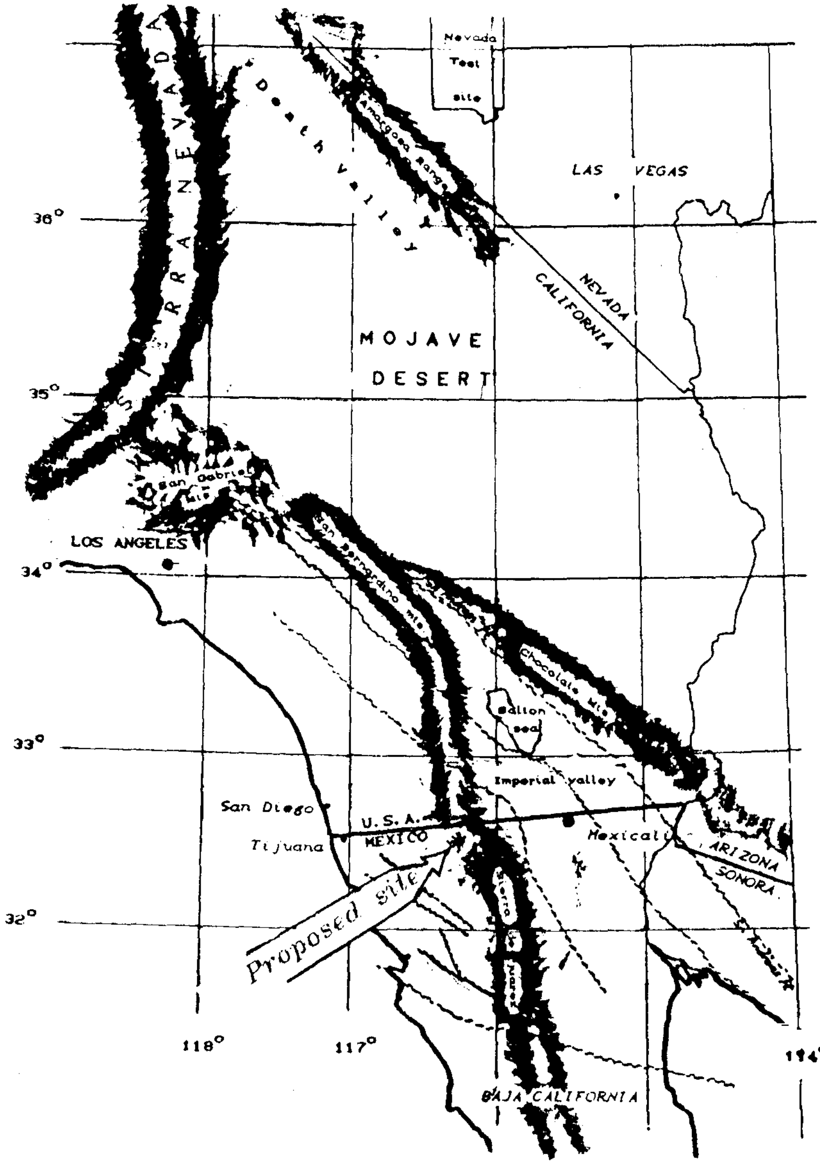

Fig. 1. Map showing the location of the Nevada Test Site, the preferred location of a possible array in northwestern Mexico (indicated by a cross, between Tijuana and Mexicali), and the principal tectonic features in the region.

The second part of the problem, the receiver array site characterization, depends of course on the problem of choosing the best possible site. Several aspects of this will be considered now.

The first decision to take is whether to set the array as near as possible to NTS or not. The rationale for a near location is, of course, to be able to sample the signal before its energy is greatly diminished by the many dissipative, refractive, etc., processes involved in seismic wave propagation, thus losing part of the signal information and resulting in a lower signal/noise level.

Against a near location is the fact that signals travelling mainly through the crust and upper mantle can be greatly complicated because of local and regional changes in structure, thus difficulting the interpretation of observed phases. However, once phases are correctly identified, recording at regional distances allows the use of many phases, such as Pg, Sg, Pn, Sn, S*, Lg, and others, for location purposes. These phases can also be used to simultaneously determine phase velocities along the trajectories (Blandford, 1982). The ratio of maximum amplitudes of some regional phases which arrive before and after Sn are valuable for discrimination (Blandford, 1982), and several regional discriminants between earthquakes and explosions that appear to be adequate for small magnitudes have been found (Peppin and McEvilly, 1974; Pomeroy *et al.,* 1982; Johansson and Åström, 1987).

Since for NTS the local deep structure is far from homogeneous, rays travelling mainly downwards from neighboring source locations will not necessarily sample equivalent paths, thus depriving a far receiver site of one of its main advantages. Since the northernmost parts of Mexico are not heavily populated, no advantage is to be gained with respect to the absence of cultural noise by choosing a site in some other sparsely inhabited region of Mexico.

An ideal solution would be to set up at least two arrays, one near NTS and the other, which could be also used for worldwide monitoring. somewhere in central Mexico. However, due to economic circumstances, a realistic solution must be based on one site only, and a near location is preferred.

The next step is to choose the actual site, as near as possible to NTS, taking into account the following factors: local geology, seismic and noise factors, ease of access, availability of electrical power and communication lines, and the probable source-receiver paths for the explosion seismic signals.

Local geology in northernmost Mexico changes rapidly from sedimentary deposits near the Pacific coast, to andesitic batholiths in the Peninsular Ranges (locally called the Juárez and San Pedro Mártir ranges), then to alluvial deposits in the Salton-Mexicali trough, and continues over the sediments of the Altar desert of Sonora to the East. Thus, good, large adequate rock outcrops are found almost exclusively in the highlands of Northern Baja California. Sites east of the trough are discarded on the grounds of being farther from NTS than other points in Mexico, of not having good outcrops on which to install the array without going to the trouble of boring fairly deep, and on the lack of easy access, power, etc., at most places.

The point within Mexican territory closest to NTS lies near the city of Mexicali (Fig. 1), which is located within the Salton-Mexicali trough. This trough shares many characteristics with the Basin and Range province, from which it is separated by the Transverse Ranges of southern California. This suggests the possibility of having a (somewhat) homogeneous medium along the ray paths between NTS and an array in this region. However, ray paths through the Basin and Range province itself traverse a medium which is hardly homogeneous; different media are encountered when the paths enter the Transverse ranges, and finally when they pass through the Salton-Imperial inland dispersion centers (*e.g.* Hill *et al.*, 1975), where structure is fairly complicated and where the effect of the hot material on the ray trajectories and the seismic signal shapes are unknown.

Other disadvantages of a site within the trough are the local extreme climatic conditions, which difficult instrument operation, and large agricultural activity, which causes a large amount of cultural noise.

From the previous analysis it was decided that the best possible site for the array would be close to the international border near the town of Tecate, around 32.57^{O}N and 116.25^{O}W, almost directly south of NTS (Fig. 1). There is good highway access to the site, electrical power is available nearby and it is not far from a federal microwave network station, which could be used for data transmission. Local population is not very dense and the main noise sources would be wind and seasonal variations in the water flow through the Rumorosa canyon.

The velocity structure through the ranges is reasonably homogeneous, so that complications in the ray paths and signal shape will be due mostly to the travel through the source region and to the transition into the Peninsular Ranges structure. These effects may be determined empirically once the array is working.

Contrary to the case of most other arrays, this one would be operating in a highly seismic environment. The array site lies among the main branch of the San Andreas fault system and other important branches.

In this region the main branch goes from the Gulf of Baja California, through the Mexicali (Cerro Prieto and Laguna Salada faults) and Imperial Valleys (Imperial, Brawley, Sand Hills, Elsinore, San Jacinto, Banning-Mission Creek faults (Hill *et al.*, 1975)), where it gives rise to dispersion centers (*e.g.* Elders *et al.*, 1972), to the Transverse Ranges where it bends to the East, and then continues in an approximate NW direction.

South of the site there are two important fault branches: the San Miguel, currently very active, and the Agua Blanca fault systems. Seismicity is also observed offshore, from the SW to the NW of the site and from other possible ramifications of the Agua Blanca fault.

Seismicity is spread all over the whole 360^{o} of azimuth from the proposed array site (*e.g.* Brune and Allen, 1967). In this region, except in and around the spreading centers along the eastern flank of the Sierra Juárez where earthquakes with normal mechanisms are observed, most earthquakes have dextral strike-slip mechanisms, concordant with the transcurrent motion between the North American and Pacific plates.

Natural seismicity is also fairly large in the NTS region, especially to the SW and WSW. In this region most earthquakes exhibit source mechanisms with a normal component (with the extension axis bearing roughly S) as would be expected due to the extensional stresses in this province (Priestley, 1974; Dahlman and Israelson, 1977).

DEDICATED ARRAY DESIGN

The desired array should have the capability to discriminate explosions originating at NTS from among the plethora of seismic signals originating all around it. This discrimination may be based on several criteria, some of which do not depend on the characteristics of the array itself, while others will be very much dependent on them.

Many earthquakes will be easily distinguishable based on their signature alone, since most events (especially large ones) originating in or near the dispersion centers have low apparent stresses ($\eta\bar{\sigma}$) and are usually not very impulsive. On the other hand, some events originating in the ranges have much larger $\eta\bar{\sigma}$ values, lie sometimes quite close to the explosion population in m^b/M^o diagrams (Thatcher, 1972; Nava and Brune, 1983), and may not be reliably discriminated through this criterion.

Some of these high $\eta\bar{\sigma}$ events could be discriminated on the basis of first motion polarity alone, since the radiation pattern of the dominant strike-slip earthquake mechanism along the San Andreas north of the array would cause dilatational first motion at the chosen array site.

Thus, the array must have a large degree of directionality to discriminate high $\eta\bar{\sigma}$ seismic signals not originating in the direction of NTS (or thereabouts) and to eliminate all signals not arriving from the desired direction, in order to raise the signal/noise ratio to the level necessary for reliable first motion determination in suspect signals.

Directionality can be achieved through the physical configuration of the array, through numerical processing of the data, such as filtering, time shifting, summing, cross-correlating, etc. (implemented and modified most easily by software), or through a combination of both.

To achieve unambiguous discrimination of explosions, the array must have the capability to store selected time series for further processing. To achieve reliability, the system should be as simple as possible, and in order to have a larger probability of existence it should be, as far as possible, inexpensive to install, maintain and operate.

Thus, the proposed array would consist of a small number of one-component sensors, located over a few square kilometers and operated by one or two PC type minicomputers. A high sampling rate of up to 80 samples/s (40 Hz Nyquist frequency) would be desirable (Evernden *et al.*, 1986), so the real time chores of delaying, filtering, summing, averaging, etc. should be kept as simple as possible.

The array is to be a dedicated one, *i.e.* the stored time series could be processed to extract signals coming from any direction, and a parallel triggering system could be implemented to accept signals from, say, some region of particular seismological interest, but the main objective of the system is to detect and store signals from NTS. The following tentative array designs, which also try to satisfy the needs outlined above, are based on this premise.

The first task was to check whether a plane wave approximation at the distances in question would be valid for the treatment of the problem. Since a considerable part of the path would be through the Peninsular Ranges structure, wavelengths for different frequencies of the probable phases of interest were computed using the velocity model shown in figure 2 (Nava and Brune, 1982). Typical apparent wave velocities in the 500 km range (the distance from the center of gravity of the latest explosions at NTS to the proposed site is about 509 km) are some 8 km/s for Pn, 4.6 km/s for Sn, $\gtrsim$5.6 km/s for Pg, $\gtrsim$3.2 km/s for Sg, some 4 km/s for S*, and around 3.53 km/s for Lg (Pomeroy *et al.*, 1982). Thus, for a frequency of 1 Hz the wavelength range of interest is from 3.5 to 8 km, approximately; for 10 Hz, the wavelength range is from 0.35 to 0.8 km.

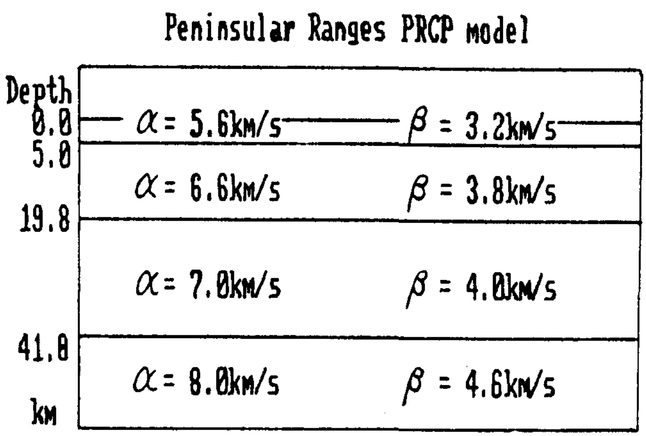

Fig. 2. Velocity model for the Peninsular Ranges from Nava and Brune (1982).

For the plane wave approximation to be valid, the difference, shown in figure 3 as **d**, between the position of the spherical wavefront, with radius **R**, and the plane one at a distance **D** from the source, should be much smaller than (say, less than about one tenth of) the wavelength. For frequencies around one Hz (the "natural" frequencies of many widely used short period seismometers (Herrin, 1982)) this condition is easily met for array dimensions perpendicular to the direction of propagation of up to some 20 km for Lg and some 35 km for Pn. In the 10 to 40 Hz signal range this approximation is no longer valid for perpendicular dimensions above 2 and 3.5 km, respectively; but, since the present work is a first approximation, and since empirical station delays will be certainly needed by any real array, the plane wave approximation and a treatment based around 1 Hz signals will be used. The modifications for the treatment of curved wavefronts can be easily implemented if and when needed.

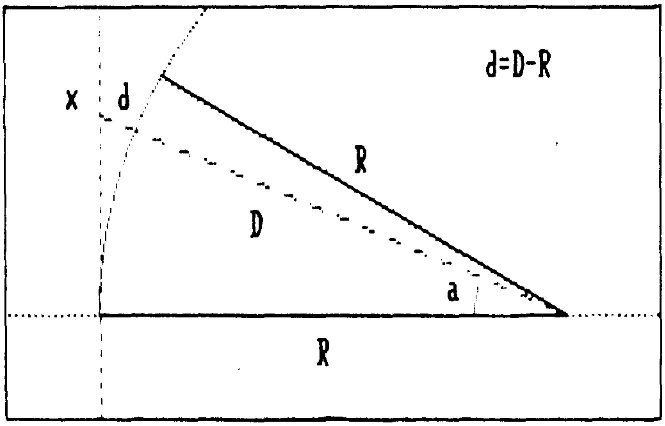

Fig. 3. Circular vs. plane wavefront approximation. R is the distance between source and array, X is a point (within the array) located on the perpendicular to the line joining source and array center at an angle a to it, D is the distance from source to X, d is the difference between R and D.

STRAIGHT SUMMATION ARRAYS

The first rough design, named MEXAR-1 is shown in figure 4. It was obtained by trying to minimize the number of operations necessary to emphasize a signal arriving from some particular azimuth, in this case straight from the north (the array can be tilted to accommodate any other preferred direction). Straight summation of the signals from the seismometers located on the base E-W line (X axis) will emphasize the arrival of a plane wave with any apparent velocity, arriving from an azimuth of 0^{o} (or 180^{o}) onto it. On the other hand, signals coming from the E or W directions, with an average typical wavelength of interest of around 4.4 km will be suppressed by the 2.2 km spacing between sensors.

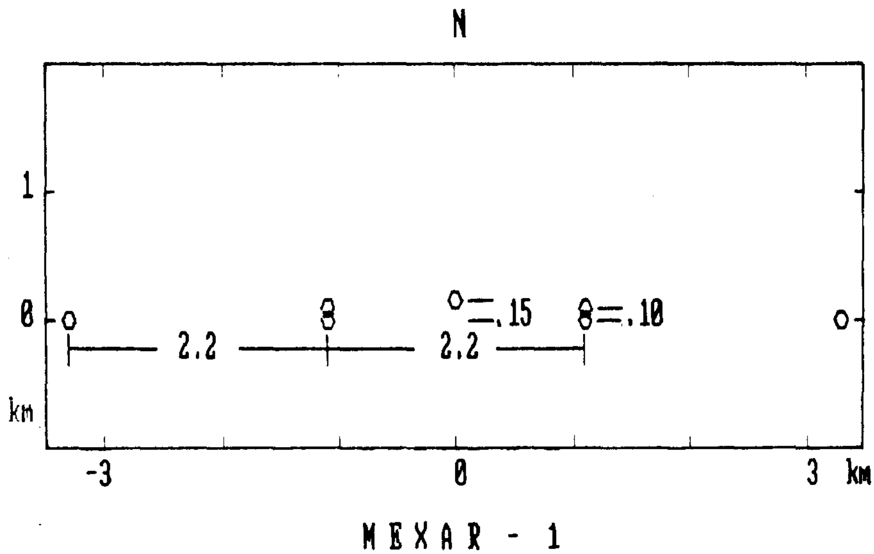

Fig. 4. Array MEXAR-1. Sensors are represented by circles and the distances between them are in km.

A single line array can be used to reliably determine the azimuth of a plane wave arriving from a direction almost perpendicular to the line. Thus, azimuths for the desired signals can be well determined by this array.

A single line array, however, will respond equally to signals arriving symmetrically from the N or the S directions (±Y axis). To eliminate the unwanted signals arriving from the S, a second and third line of sensors (with two and one sensors, respectively) were added; these sensors are close enough to the main line (.10 km and .15 km, respectively) to interfere constructively through a direct summation scheme (separations are a fraction of about .02 and .03 of a reference 5 km wavelength); but their main use is that of a switch to detect whether the provenance azimuth is acceptable.

Figure 5 shows a sampling of NTS shot locations, including a recent one of explosions detected in 1987 (Six Nation Initiative, 1988) and a long-term one of shots from 1962 to 1970 reported by Basham and Horner (1973). This sampling indicates that signals originated from NTS should arrive at the proposed array site from azimuths between ±2.6°, and the separations between stations in the N-S direction were designed so that any signal that reaches the main E-W line before reaching some of the other stations can be rejected forthwith (Fig. 6a). The MEXAR-1 array is a simple straight summation plus on/off switch scheme. Maximum and minimum separations for MEXAR-1 are 0.100 and 6.600 km, respectively, with average of 2.526 km and standard deviation of 0.345 km.

Figures 6b and c illustrate the power response *vs.* wavenumber k diagram (*e.g.* Harjes and Henger, 1973) for the proposed MEXAR-1 array. X is positive to the E, Y is positive to the N, and k range is ±7.2 km^{-1} in each direction. The surface representation (Fig. 6c) is viewed from an azimuth of 35° and an elevation of 50°.

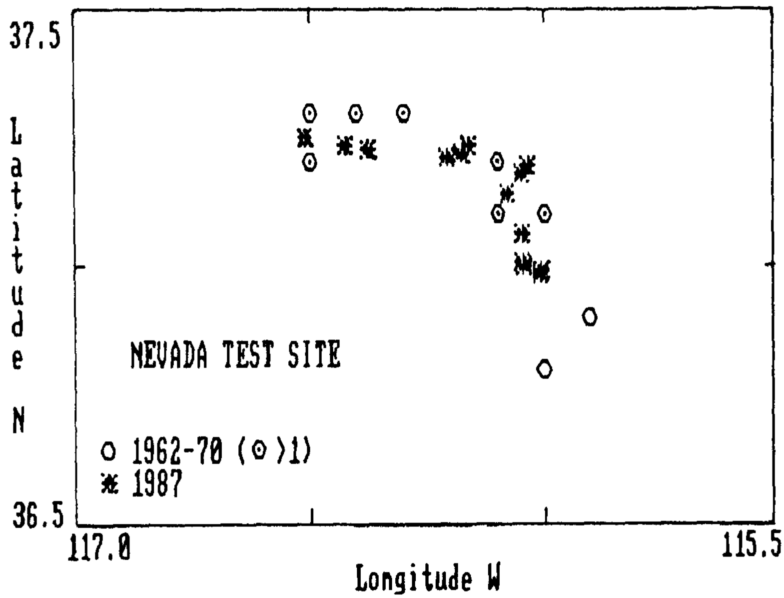

Fig. 5. Location of a sample of nuclear tests at NTS.

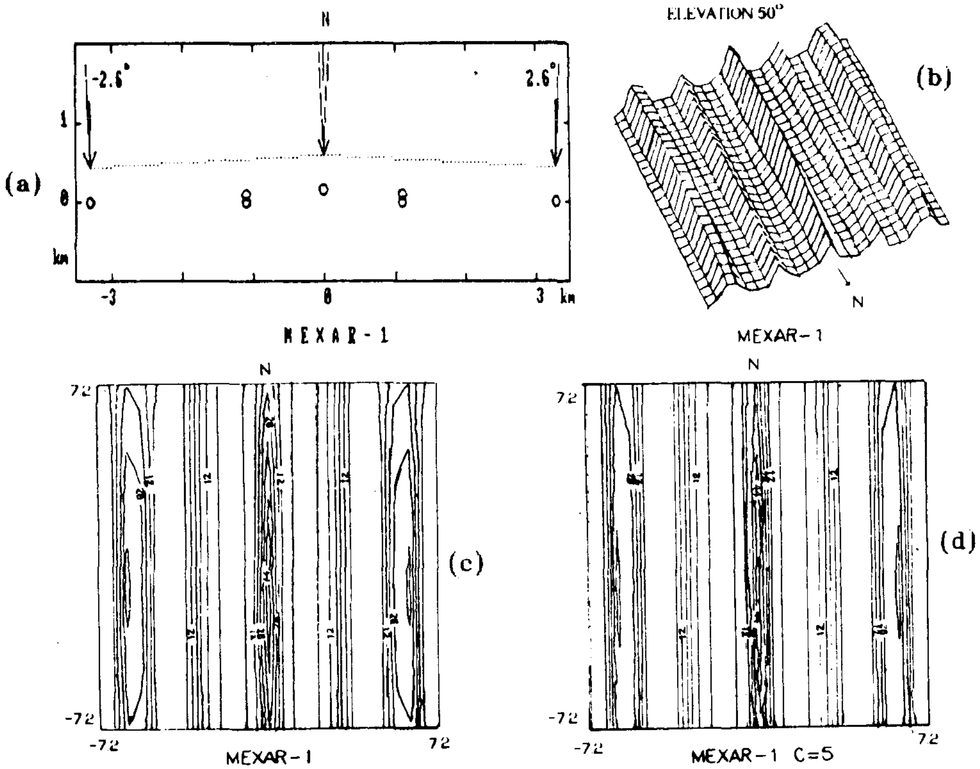

Fig. 6. a) Array MEXAR-1. The arrows and the dotted lines joining their heads represent possible rays and wave fronts, respectively, from seismic signals originating at NTS. b) Power response vs. wavenumber for array MEXAR-1. N-S axis corresponds to ky, positive towards N; E-W axis to kx, positive towards E; both wavenumber components range from -7.2 to 7.2 km^{-1}. c) MEXAR-1 power response after 5km/s, azimuth= 0^{o}, apparent velocity delaying of off-line sensor signals. Conventions as in Fig. 7.

The response is completely symmetrical with respect to the N-S axis and slightly asymmetrical with respect to the E-W one. Use of the azimuth discrimination switch can reject all wavenumbers shown in the power response except those within the large ridge along the negative ky axis, which represents acceptance of signals incident from the desired azimuths, and sharp rejection of everything else. Rejection is very good for wavenumbers located between the sidelobes; response along the main ridge never drops below 0.75 of the maximum, and is typically $\gtrsim 0.9$ of it, while for the wavenumbers adjacent to the main ridge response is always $\lesssim 0.23$ of the maximum.

Large sidelobes are due to the constant spacing of sensors in the E-W direction. While these sidelobes are effectively rejected from the triggering process, they do contribute to the noise level in the array. The energy content of these sidelobes may be important because of very strong wind (Dahlman and Israelson, 1977) and local and regional earthquake activity.

Application of a delay-summation scheme to emphasize a signal with dominant $k = (0., -1.2566)\text{km}^{-1}$ (which could correspond to a wave with a 1s period coming in from the N with an apparent velocity of 5 km/s, say), helps to diminish slightly the contribution from the positive central ridge (Fig. 6d). The main point here is that only the signals from the three non baseline stations need be delayed, and in this case by very small amounts (.02s and .03s) that require very little memory and processing.

An array of the HAGFORS mini type (Fig. 7a) is presented for comparison. Its response, shown in figures 7b and 7c, shows a large degree of axial symmetry; its advantage lies in that it can respond equally well to signals arriving from a large variety of azimuths, and is thus suitable for global monitoring. An elementary delay-summation scheme necessary to orient this type of array in some particular direction (Figs. 7d and 7e), requires time shifting of essentially all signals. Rejection is not very sharp outside the desired azimuth and different delays are required to sample different wavenumbers along the preferred azimuth; these are all disadvantages for its use as a dedicated array.

Array MEXAR-2 (Fig. 8a) was developed as an exercise in sidelobe modification; it is essentially the same as MEXAR-1, except that the X spacing of each pair of stations has been slightly changed, and the Y spacing has been kept so as to maintain the same azimuthal on/off switching properties. Minimum, maximum, average and standard deviation for the MEXAR-2 seismometer spacings are 0.224, 6.600, 2.595 and 0.343 km, respectively.

Figures 8b and 8c show the power response of array MEXAR-2, using the same conventions as in figure 6. It can be readily appreciated that sidelobes have diminished and shifted. A final choice of spacings for a MEXAR-2 type of array would

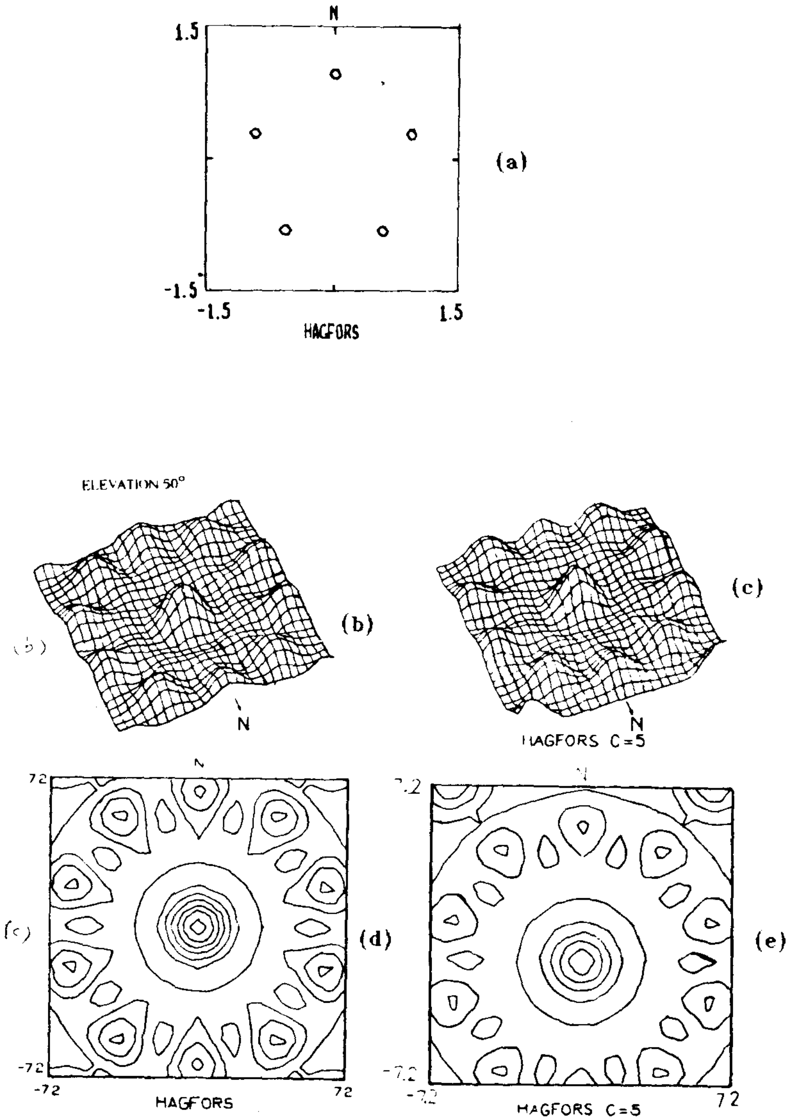

Fig. 7. a) HAGFORS type array. Conventions as in Fig. 4. b) and c) HAGFORS type array power response vs. wavenumber. d) and e) HAGFORS type array power response after 5 km/s, azimuth = 0°, apparent velocity beamforming. Conventions as in Fig. 6.

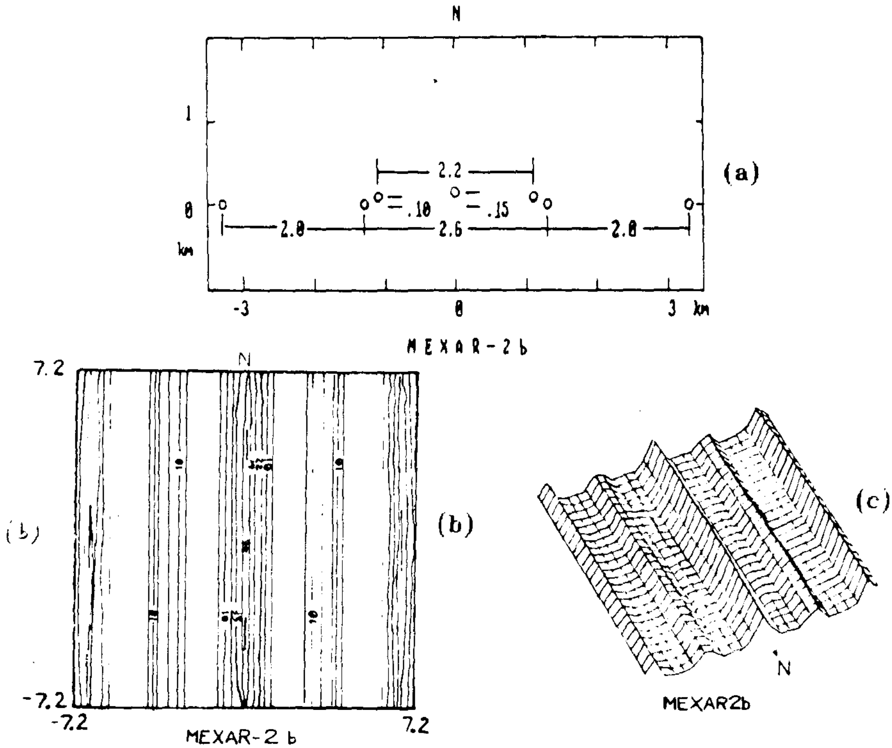

Fig. 8. a) MEXAR-2 array. Conventions as in Fig. 4. b) and c) MEXAR-2 power response vs. wavenumber. Conventions as in Fig. 6.

depend on actual field measurements of on-site noise characteristics.

PARTIAL DELAYED SUMMATION ARRAYS

While signal delaying was possible but not essential to the functioning of the MEXAR-1 and 2 arrays, array MEXAR-3 (Fig. 9a) was designed to employ partial delaying as a simple method of introducing more directionality (*i.e.* rejection of unwanted signals, especially those mapping on or near the positive ky axis). To introduce space rejection on the ky axis, the off-baseline sensors were significantly separated from the baseline, so that now the signals from these sensors need to be delayed if they are to interfere constructively with those from the baseline for the desired wavenumbers. Partial delaying means that signals were not delayed back to the baseline, but only to the azimuth switching line, thus maintaining the triggering azimuth cutoff capability.

Minimum, maximum, average and standard deviation for MEXAR-3 spacings are 0.776, 6.600, 2.689 and 0.326, respectively. Again, actual separations will have to be determined based on analysis of actual seismicity and site data.

Figures 9b and 9c show the power response of array MEXAR-3, illustrating the very considerable rejection effect of the partial delaying scheme. Maximum response is concentrated along the negative Y axis around k = (0, − 1.0)km^{-1}, and sidelobes have been drastically diminished, especially for positive ky. The total noise power (power at undesired wavenumbers) has been significantly reduced. Again, only signals from the three off-baseline sensors need be delayed, and those for small times (0.130, 0.130 and 0.070s, respectively) which place small demands on the on-line processing capabilities of the system.

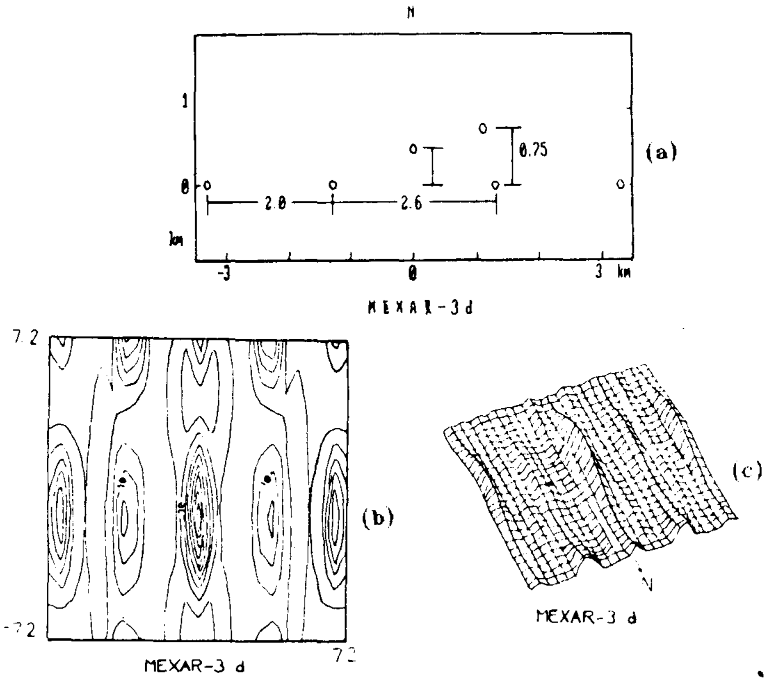

Fig. 9. a) MEXAR-3 array. Conventions as in Fig. 4. b) and c) MEXAR-3 power response after 5km/s, azimuth = 0^{0}. apparent velocity partial delaying of off-line sensor signals. Conventions as in Fig. 7.

Further time delaying, done as a separate step after evaluation of the switch, can perfectly be done to shift everything to the baseline.

DISCUSSION

Depending on the actual resources available, if and when it is decided to build such a dedicated array, and on the real conditions of noise, signal propagation, logistics, etc., the actual project may contemplate introducing sophisticated online signal processing schemes, larger numbers of sensors, complicated triggering, and so on. Unless some serious defect is found with the concepts embodied in the models presented here, the actual array may be an adaptation of one of them, probably of MEXAR-3.

Surely the capability of such an array for high probability detection of signals originating at NTS would be significantly higher than that computed by Evernden (1987) for a single station located some 200 km SE of our proposed site, possibly on the Pinacate quaternary volcanic structure in the northern Altar desert. However, we concur in his opinion that cooperation with Canada for monitoring of NTS and other possible nuclear test sites within the USA would be extremely valuable.

The need for analysis of actual field data, before any definitive measures can be decided upon, cannot be overemphasized. Thus, early implementation, while ongoing nuclear testing can be used for location, yield and pattern calibration (Dahlman and Israelson, 1977), is strongly recommended.

BIBLIOGRAPHY

BACHE, T., W. RODI and D. HARKRIDER, 1978. Crustal structures inferred from Rayleigh-wave signatures of NTS explosions. *Bull. Seism. Soc. Am.*, 68, 1399-1413.

BASHAM, P. and R. HORNER, 1973. Seismic magnitudes of underground nuclear explosions. *Bull. Seism. Soc. Am.*, 63, 105-131.

BLANDFORD, R., 1982. Seismic event discrimination. *Bull. Seism. Soc. Am.*, 72, S69-S87.

BRUNE, J. and C. ALLEN, 1967. A microearthquake survey of the San Andreas fault system in southern California. *Bull. Seism. Soc. Am.*, 57, 277-296.

DAHLMAN, O., 1974. Seismic source and transmission functions from underground nuclear explosions. *Bull. Seism. Soc. Am.*, 64, 1275-1293.

DAHLMAN, O. and H. ISRAELSON, 1977. Monitoring underground nuclear explosions. Elsevier Sci. Pub. Co., Amsterdam, 440 pp.

ELDERS, W., R. REX, T. MEIDAV, P. ROBINSON and S. BIEHLER, 1972. Crustal spreading in southern California. *Science*, 178, 15-24.

EVERNDEN, J., C. ARCHAMBEAU and E. CRANSWICK, 1986. An evaluation of seismic decoupling and underground nuclear test monitoring using high frequency seismic data. *Rev. Geophys.*, 24, 143-215.

EVERNDEN, J., 1987. Further network studies. *Preprint.*

HARJES, H. and M. HENGER, 1973. Array-seismologie. *Zeitsch. Geoph.*, 39, 865-905.

HERRIN, E., 1982. The resolution of seismic instruments used in treaty verification research. *Bull. Seism. Soc. Am.*, 72, S61-S67.

HILL, D., P. MOWINKEL and L. PEAKE, 1975. Earthquakes, active faults, and geothermal areas in the Imperial Valley, California. *Science*, 188, 1306-1308.

JOHANSSON, P. and M. ÅSTROM, 1987. Discrimination of earthquakes and chemical explosions with a regional network. *FOA report* C20668-9.1, Stockholm, 83 pp.

NAVA, F. and J. BRUNE, 1982. An earthquake-explosion reversed refraction line in the Peninsular Ranges of southern California and Baja California Norte. *Bull. Seism. Soc. Am.*, 72, 1195-1206.

NAVA, F. and J. BRUNE, 1983. Source mechanism and surface wave excitation for two earthquakes in northern Baja California, Mexico. *Geophys. J. R. Astr. Soc.*, 73, 739-763.

PEPPIN, W. and T. McEVILLY, 1974. Discrimination among small magnitude events on Nevada Test Site. *Geophys. J. R. Astr. Soc.*, 37, 227-243.

POMEROY, P., W. BEST and T. McEVILLY, 1982. Test ban treaty verification with regional data – A review. *Bull. Seism. Soc. Am.*, 72, S89-S129.

PRIESTLEY, K., 1974. Crustal strain measurements in Nevada. *Bull. Seism. Soc. Am.*, 64, 1319-1328.

Six Nation Initiative, 1988. Monitored nuclear explosions in 1987. *Six Nation Initiative Rept.*, Sweden, 5pp.

STEWART, J., 1971. Basin and Range structure: a system of horsts and grabens produced by deep seated extension. *Bull. Geol. Soc. Am.*, 82, 1019-1044.

THATCHER, W., 1972. Regional variation of seismic source parameters in the Northern Baja California area. *J. Geophys. Res.*, 77, 1549-1565.