The Feasibility of Monitoring Continuous Wave Sources with Seismic Arrays

John Claassen*, Mark Ladd, and Greg Elbring

Sandia National Laboratories, P. O. Box 5800, Albuquerque, NM 87185-0655

RECEIVED
MAR 19 1999
OSTI

Abstract

This paper identifies and explores the technical requirements and issues associated with remotely monitoring continuous wave (CW) sources with seismic arrays. Potential approaches to this monitoring problem will be suggested and partially evaluated to expose the monitoring challenges which arise when realistic local geologies and cultural noise sources are considered. The selective directionality and the adaptive noise cancellation properties of arrays are required to observe weak signals while suppressing a colored background punctuated with an unknown distribution of point and sometimes distributive sources. The array is also required to characterize the emitters and propagation environment so as to properly focus on the CW sources of interest while suppressing the remaining emitters. The proper application of arrays requires an appreciation of the complexity of propagation in a non-homogeneous earth. The heterogeneity often limits the available spatial coherence and therefore the size of the array. This adversely impacts the array gain and the array's ability to carefully resolve various emitters. Arrays must also contend with multipath induced by the source and the heterogeneous earth. If the array is to focus on an emitter and realize an enhancement in the signal to noise ratio, methods must be sought to coherently add the desired signal components while suppressing interference which may be correlated with the desired signal. The impact of these and other issues on array design and processing are described and discussed.

Keywords: seismic array design, array processing, seismic propagation

1. Introduction

There has been considerable interest in using seismic and acoustic sensors to detect and identify continuous wave (CW) sources [1][2][3][4] within strategic facilities. This paper addresses the challenge of monitoring such sources within a seismic environment having many interfering sources. We review the characteristics of the earth's propagation environment in the light of this application and assess the impact of that environment on array design and processing. Arguments are presented for designing a robust array configuration. We develop an observational model and provide preliminary evaluations of the proposed array design using the observational model and conventional beamforming techniques. Several high resolution methods of mapping the field of coherent emitters are identified and discussed. An adaptive method of continuously monitoring the desired emitters is suggested as a method of identifying the sources. A summary of the work to date and a prognosis on future efforts are also presented.

2. The Challenges in Making CW Observations within a Realistic Earth

The complexities inherent in monitoring continuous wave sources in a noisy environment arise from several factors. In general, the factors can be traced to complex sources, extraneous noise in the environment, and complicated propagation paths. Under these realistic conditions, many of the typical seismic array designs and processing techniques fail, requiring the development and implementation of innovative methods to properly locate and monitor CW sources. To understand the direction these new methods must follow, we first discuss the nature of the earth's propagation environment.

2.1 Source Effects

Continuous wave sources are mechanical or electrical devices that reach a steady state condition and emit a long (minutes to hours) seismic wave train. The emissions can have a broad band nature with poorly defined spectra (Figure 1a) or they may be well constrained to harmonically related frequencies (Figure 1b). Often the primary frequency bands will have side band frequencies separated by only a few Hertz as can be seen in Figure 1b. Sources with varying spectral characteristics require robust and flexible array design and processing techniques when *a priori* detailed source characteristics are not known.

In addition to the spectral differences, the types of seismic waves generated by a particular device and the way this energy is coupled into the media add complexity to the propagating wave field. A CW source may have rotating parts that impart torsional forces which generate shear (S) waves either vertically (SV) or horizontally (SH) polarized; it may be vibrating vertically acting like a vertical point force, producing compressional (P) waves and S waves, simultaneously; or it can be any combination of these force types, as well as others. When both the source wavefield and location are unknown, it is easy to

* Phone: (505) 844-6685, Fax: (505) 844-5321, E-mail: jpcclaas@sandia.gov

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

confuse one wave type, such as SV, with another, such as P, from a different azimuth without careful examination of the polarization and slowness (inverse propagational velocity) characteristics.

To this point, we have been describing the sources as localized point sources, albeit with complex characteristics. This is often not the case. An isolated piece of operating machinery is the exception rather than the rule. A more likely situation is to find several similar or dissimilar pieces of equipment operating in a localized area. The ability to locate and separate sources in such configurations will be dependent upon the spatial resolution of the array. Not only can there be multiple sources in the region of interest, but the sources may be spatially distributed rather than point sources, especially when dealing with large pieces of equipment that may be coupled to the earth at several points or a continuum of points.

2.2 Environmental Effects

The accuracy of the results obtained from array analysis is always dependent upon the quality of the channel data. In an industrial or urban environment, this realization becomes more difficult due to the numerous sources of noise. These sources contribute both colored backgrounds that are continuously distributed in space as well as numerous point or quasi point emitters. The level of background noise will generally dictate the number of array elements required to sufficiently enhance the SNR at the beam output. Lacking specific *a priori* knowledge of the location of the point emitters will require, at least, careful knowledge of the direction of arrival information for the emitters of interest. This information can be obtained by mapping the field of point emitters using array spectral estimation techniques and then identifying the directions of arrival for the sources of interest from this map. Mapping the field of emitters will be made complicated by the partial coherence of some of the emitters at some spectral lines.

Further, the CW emitters will not necessarily be isotropic point sources. More often the sources will be mounted in such a way that their emissions will favor certain azimuths and frequencies. This may explain the lack of signal seen at some stations in Figure 2. Under these circumstances placement and orientation of the array becomes difficult since the unknown radiation patterns of the wave fields produced may have nodes (nulls) at the array azimuth.

2.3 Propagation Effects

The final aspect that needs to be considered when designing arrays for this application is the propagation effects associated with the local media. It is routine practice to model the earth propagation in terms of 1D or 2D models. At the local scale, however, such models are not a reasonable representation of the earth where significant 3D velocity changes can be present. This leads to significant multipath effects with direct, reflected, refracted, and converted waves all present in the wavefield and often not separated significantly in time due to the short travel paths involved. Out-of-plane reflections or refractions may also be present.

The raypath diagram of Figure 3 illustrates the complexity of seismic propagation in its most elementary form. Here the earth is represented as a layered half-space. The upper raypath (D) illustrates the direct path between the source and receiver. This path can support three modes of propagation, each with a distinct polarization (P, SV, and SH). The shear waves propagate with velocity v_s , and the compression waves propagate with velocity v_p . This multi-mode path may be regarded as a subtle form of "multipath." A more conventional source for multipath is attributed to reflections at the interfaces. Raypaths A and C in Figure 3 illustrates two types of reflections. Raypath A emanates and reflects as a P wave; whereas, raypath C impinges on the surface as a P wave but converts to an SV wave on reflection. SV to P conversion (not shown) can also occur at these boundaries. Path B is an interface wave whose propagation is dependent on the velocity contrast between the strata. The surface can support another type of interface wave. Since the collection of arrivals arises from the same source, the potential for them to be coherently related is strong.

These complications are further increased by the nature of the CW source. For transient sources, the difference in velocity between the different wave types leads to separation of arrivals in the wave train. With CW sources, however, the source is continually emitting new energy so that, once steady state is reached, all the varying wave types are overlapping and processing methods relying on the temporal separation of the wave types become much more difficult to implement. A method to isolate these wave types is essential to successfully monitor CW sources.

At local distances higher frequency content will be observed because the waves will have undergone little attenuation. With shorter wavelengths, the waves are much more sensitive to smaller inhomogeneities unrelated to earth layering. Such inhomogeneities act as scatterers and diffractors of the wavefield. The scattering and diffraction along with multipath degrade the spatial coherence available at the array location.

2.4 Impacts on the Array Monitoring

In view of the inhomogeneity of the earth, seismic arrays must be designed for limited spatial coherence. This imposes limitation on the aperture size and consequently on the inherent resolving power of the array. Furthermore, array observations must address multipath, mode conversion, and multi-polarized emissions, all arriving simultaneously. It is, therefore, essential to employ three component (3-c) receivers throughout the array to separate the polarized components before or in conjunction with array processing. The arrays must also contend with partially coherent arrivals. The combined effect of the source characteristics, environmental aspects, and propagation effects results in a wavefield at the array that is significantly different from those encountered in typical array processing applications.

3. Array Design Aspects for this Application

3.1 The Design Approach

In seismic applications it is traditional to deploy planar arrays on the earth's surface. In view of the expense of seismic receivers and the limitations in spatial coherence, the design approach typically emphasizes sparse methods to fill the array to diameters of several wavelengths. When broadband operation is required, the arrays may consist of several concentric rings so that a sub-array within a given ring can be used to monitor frequencies permitted by the spatial coherence associated with that ring diameter. In this application a departure from the traditional approach is required to separate multiple emitters in both the azimuthal and incident angles. Planar arrays certainly provide adequate azimuthal resolution; however, to achieve the required incident angle resolution for shallow arrivals, the array should be extended in the third dimension. Hence, volume arrays are advocated for this application.

Since emitters driven by the same power source can be partially coherent and since multipath will also be partially coherent, it is necessary to depart from sparse design notions and emphasize arrays filled at regular intervals. Uniformly spaced receiver elements are essential to realizing a spatially invariant set of sub-arrays within the entire array in order to decorrelate the coherent arrivals through spatial averaging techniques [5][6]. Furthermore, to assist the array in handling coherent multipath, it is prudent to use 3-c receivers to separate arrivals having different polarization properties but traveling the same path or for that matter different paths. An array having these characteristics is illustrated in Figure 4. The 3-c elements are uniformly spaced within a 3-dimensional grid. A sub-array within the volume array is illustrated by filled circles while the remaining elemental positions are depicted by open circles.

To demonstrate the superiority of a volume array approach in comparison to a planar array approach we first introduce a seismic observational model and then use that model to develop the array response to polarized arrivals. The efficacy of a 3-c volume array in handling polarized and cross-polarized wavefields is then demonstrated.

3.2 The Basic Seismic Observation Model

Suppose M narrowband signals with "directions of arrival" denoted as $\Theta_1, \Theta_2, \dots, \Theta_M$ impinge on an N element array consisting of 3-c receivers. The direction of arrival parameters may include the incident angle θ , the bearing (azimuth) ϕ , the propagational velocities (v_p, v_s), the effective range r , and the polarization state. The total signal impinging on the array elements is given by

$$d(t) = \sum_{m=1}^M a(\Theta_m) s_m(t) \quad (1)$$

where $s_m(t)$, $m = 1, 2, \dots, M$ denote the signal waveforms and $a(\Theta_m)$ denotes the direction of arrival vector for arrival m . Note that bold symbols are reserved for vectors and matrices. $d(t)$ is a $3N$ -dimensional vector whose channel signals are ordered as

$$d(t) = [d_{x1}(t) \ d_{y1}(t) \ d_{z1}(t) \ d_{x2}(t) \ d_{y2}(t) \ d_{z2}(t) \ \dots \ d_{xN}(t) \ d_{yN}(t) \ d_{zN}(t)]^T \quad (2)$$

where $d_{ij}(t)$ is the observed signal on the i th receiver axis of the j th element in the array and d^T denotes the transpose of d . Define a steering matrix as

$$A(\Theta) = [a(\Theta_1) \ a(\Theta_2) \ \dots \ a(\Theta_M)] \quad (3)$$

and a signal vector as

$$s(t) = [s_1(t) \ \dots \ s_M(t)]^T \quad (4)$$

Then in the presence of spatially colored background noise $n(t)$, the complete observational vector becomes

$$g(t) = A(\Theta)s(t) + n(t) \quad (5)$$

Recognize that $A(\Theta)$ is a $3N$ by M matrix.

To develop the array response to a single emitter we will assume that $M = 1$ and that a single polarization state is propagated. If the emitter is in the far field of the array, the search vector associated with an N element array becomes

$$c(\theta, \phi, v, f) = \begin{bmatrix} \exp(j(\mathbf{k} \cdot \mathbf{r}_1)) \\ 0 \\ 0 \\ \vdots \\ \vdots \\ \exp(j(\mathbf{k} \cdot \mathbf{r}_N)) \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ \exp(j(\mathbf{k} \cdot \mathbf{r}_1)) \\ 0 \\ \vdots \\ \vdots \\ 0 \\ \exp(j(\mathbf{k} \cdot \mathbf{r}_N)) \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \exp(j(\mathbf{k} \cdot \mathbf{r}_1)) \\ \vdots \\ \vdots \\ 0 \\ 0 \\ \exp(j(\mathbf{k} \cdot \mathbf{r}_N)) \end{bmatrix} \begin{bmatrix} h_x(\theta, \phi) \\ h_y(\theta, \phi) \\ h_z(\theta, \phi) \end{bmatrix} \quad (6)$$

where $[h_x \ h_y \ h_z]^T$ is a complex-valued polarization search vector, (v, f) are the search velocity and frequency, respectively,

$\mathbf{k}$ is the wavenumber associated with a polarized arrival, and $\mathbf{r}_j$ is the position vector for the j th element of the array. The wavenumber and polarization vectors are highly coupled through the geometrical parameters. The conventional array power response is given by the quadratic norm

$$\Psi_c(\theta, \phi, v, f) = \|c^H(\theta, \phi, v, f) \cdot G(f)\|^2 \quad (7)$$

where $G(f)$ may be regarded as the Fourier transform of $g(t)$ and H is the hermitian transpose operator. We can bound the beam response by using Schwartz' inequality to yield

$$\Psi_c(\theta, \phi, v, f) \leq \|c(\theta, \phi, v, f)\|^2 \|G(f)\|^2 \leq N^2 \|S(f)\|^2 + N \|N(f)\|^2 \quad (8)$$

The right-hand side is the upper bound of the beam response when the noise is spatially white and non-coherent. This maximum occurs, of course, when the array steering vector $c(\Theta)$ is co-linear with the direction of arrival vector embodied in $D(f)$. In seismic applications one seldom realizes the upper bound response because the spatial coherence is limited.

When it is assumed that the velocities of the stratum in which the array is embedded are constant, the beam response for a given velocity can be plotted as a function of (θ, ϕ) for a given velocity. An alternative method of plotting the beam response is motivated from frequency wavenumber (F-K) analysis in which the beam response is plotted in terms of (χ, ϕ) where

$\chi = \sin(\theta)/v_i$ is the slowness and $v_i = v_s$ or v_p . When F-K analysis is applied to volume arrays, we currently restrict the

response to arrivals from below as opposed to those reflected from the surface. Future work will account for surface reflections when modeling the complete performance of volume arrays.

In this particular application the sources are more likely to be in the "near" range where range r becomes important; as a consequence, the form of the search vector needs to be altered appropriately to model this scenario. However, results from the far field case remain helpful to evaluating array configurations and responses.

3.3 Evaluating the Beam and Polarization Responses of Planar and Volume Arrays

First we demonstrate the benefit of using polarization matched beamforming. Figure 5 shows the conventional beam response of a vertical component planar array to a shallow P arrival from the northeast. The square array consists of 25 uniformly spaced receiver elements separated by a $1/2$ wavelength relative to v_p . When the vertical elements are replaced with 3-c receivers and the receivers are matched to the polarization of the arrival, the beam pattern of Figure 6 results. Note that polarization matching increases the resolution slightly but mainly rejects P polarized arrivals orthogonal to the desired arrival direction and in the backlobe area.

We also show that a volume array of 3-c elements, having a footprint identical to the above planar array, will resolve shallow arrivals better in incident angle than the above 3-c planar array. In addition the volume array will inherently have more array gain as Equation 8 implies, simply because it has 5 times as many elements. The elements in the 3rd dimension are also spaced at a $1/2$ wavelength. The array is focussed on and matched to a shallow P polarized arrival coming from the northeast. The beam response of the volume array appears in Figure 7. There it is noted that the volume array has approximately the same azimuthal resolution as the planar array (see Figure 6), but has a superior incident angle resolution as indicated by the strong gradient in the slowness response across the main beam.

An attractive feature of using 3-component elements is their ability to suppress cross-polarized arrivals and the aliased response of another polarized mode. Assume that the volume array is illuminated by a P polarized wave coming from the northeast at a shallow elevation angle. The ability of the array to reject that arrival when attempting to focus on an SV polarized arrival from an arbitrary direction is illustrated in Figure 8. Strong suppression of the P arrival is observed across the mainbeam and elsewhere. The maximal response is 16 dB down from the P wave response on boresight. This peak response primarily arises as a result of aliasing the P wave arrival when the array is focussed on an SV wave arriving at a smaller incident angle. The aliasing can be entirely prevented by spacing the elements at the Nyquist spacing associated with v_s . The array, however, must be enlarged to achieve the same angular resolution. This result suggests that the Nyquist spacing requirement can be violated to reduce array cost provided polarization matching is used to suppress the aliased response associated with an orthogonal polarization.

4. Advanced Approaches to Seismic Array Monitoring

4.1 Defining the Field of Emitters

Having defined the basic seismic observation model and an array design rationale, we now consider the more advanced issues which must be addressed to successfully monitor specific CW sources in a noisy cultural background having other emitters operating in the same frequency bands and where the array must contend with multipath and multi-modal signals, possibly coherently related, while monitoring the arrivals of interest. To successfully observe the emitters of interest while suppressing the background and the interference requires accurate knowledge of emission characteristics of the sources of interest as observed at the array. In practice this means sampling the temporal and spatial properties of the wavefield in conjunction with parametric based estimators to determine the "direction of arrival" vector and signal intensity of each path and mode associated with a source of interest. This information enables the user to focus the array on the more intense arrivals of interest.

Several methods are available to define the wavefield characteristic at the array. Regardless of the method it is necessary to form a sample spatial covariance matrix

$$R = \sum_{k=1}^K \sum_{t=1}^L g_k(t) g_k^H(t) \quad (9)$$

Here each $g_k(t)$, $t = 1, 2, \dots, L$ represents a vector of channel samples associated with the k th sub-array at time t . This matrix contains the desired wavefield information. Averaging across the K sub-arrays is essential to decorrelating the coherent components of the wavefield. Sufficient temporal averaging can also assist in decorrelating some of the coherent components.

An attractive high resolution (HR) approach for estimating the beam steering vectors is based on subspace decompositions [7][8] whose resolution, in theory, is not limited by the size of the aperture provided the observation interval and/or SNR are sufficiently large. Furthermore, these estimators are statistically consistent, meaning that the steering vectors converge to the true value when the number of samples is sufficiently large. When forming the estimates of the directions of arrival, the noise covariance matrix may have to be whitened to realize the subspace decomposition.

Subspace methods can be augmented with maximum likelihood methods to refine and provide additional wavefield information. If the noise field emanates from a large number of independent sources, the emitters can be assumed to be imbedded in a background that is a spatially white gaussian process. The sources of interest may be regarded as point emitters whose waveforms are deterministic to within a set of arbitrary parameters. In the case of narrowband sources the carriers are assumed to be known. If the background is not white, the background may be prewhitened in the standard way. In either case, the resulting vector $g(t)$ may be regarded as a gaussian random process with mean $A(\Theta)s(t)$ and covariance $\sigma^2 I$ where I is the identity matrix. The probability density function of a single observation vector is a complex gaussian M-variate. If non-lapping observations are regarded as independent, the likelihood function for L observations is given by

$$L(\Theta, s(t), \sigma) = \prod_{t=1}^L (\pi\sigma)^L \exp[-\|g(t) - As(t)\|^2 / \sigma^2] \quad (10)$$

As has been shown in [9][10], the emitter properties Θ can be obtained by solving a non-linear minimization problem associated with the above likelihood formulation. The solution of such a minimization problem requires a good initial estimate if the global minimum is to be found. Spectral based solutions, as provided by the subspace methods, can sometimes provide an adequate initial estimate.

4.2 Monitoring the Emitters of Interests

Among the emitters defined by one of the above methods are the emitters of interest. In order to identify the source types we propose to monitor the long term emission properties as induced by load and cycle time variations as well as by their spectral characteristics. In a noisy environment this requires that a particular emitter be observed by adaptive array methods whereby an array is focussed on the measured direction of arrival vector $a(\Theta_d)$ while suppressing the influence of the remaining sources on the beam output. This can be accomplished by using the minimum variance distortionless look beamformer [11]. Spatial averaging for R together with additional beam and polarization constraints may have to be performed to realize a robust adaptive beamformer when focussing on a source whose emissions may be coherently related to other sources and arrivals.

5. Summary and Prognosis

We have outlined a robust and flexible approach to monitoring CW seismic point emitters in a colored background. The approach emphasizes a procedure which first maps the field of emitters to determine the sources that are to be monitored on a long term basis and then focuses an adaptive beamformer on the desired emitters while suppressing the remaining ones. The mapping step is required to carefully define the direction of arrival vector for the desired source. Properly steering the adaptive beamformer assures that the adaptation process does not suppress the desired source signal.

To assist in handling coherent multipath, 3-c receivers were introduced into the array to separate orthogonal polarizations propagating along identical paths. It was shown through conventional beamforming techniques that the 3-c receivers also assist in suppressing sidelobes and unwanted polarizations through a pattern multiplication effect. Polarization matched beamforming was also shown to provide relief in observing the Nyquist spatial sampling requirements, thereby reducing the number of elements required by the array.

A volume array with spatially invariant sub-arrays was advocated as a general approach to dealing with coherent multipath through a method which averages the observation matrix over a family of sub-arrays. HR subspace methods of mapping the field of emitters were identified as an effective means of exploiting the spatially averaged observations. It was suggested that the spectral approach may have to be augmented with a maximum likelihood method for withdrawing all the arrival directions. The latter technique does not depend on spatial averaging over sub-arrays and may, as a consequence, provide enhanced resolving power.

The limited spatial coherence associated with the earth is a primary concern. However, we are somewhat optimistic that polarization filtering will induce additional spatial coherence in comparison to that previously observed on vertical component ar-

rays. This improvement is anticipated because P to SV conversions are prevalent in the earth. P waves which are contaminated by coherently related SV waves will suffer an apparent loss in spatial coherence. Therefore, polarized reception should be helpful in suppressing the adverse influence of coherently related mode conversions, thereby increasing the apparent spatial coherence of the received polarization.

To this point in the investigation conventional beamforming products have been used to guide our efforts. Clearly, our goal is to develop more advanced monitoring methods. Whereas in a previous effort adaptive beamforming on vertical component seismic arrays [12] was evaluated, we envision that the use of 3-c elements will present new opportunities. In particular, not only will the array suppress unwanted arrivals in beamspace but also in polarization space. Future efforts will explore this possibility as well as others. Initially, simulated arrivals will be used to evaluate the efficacy of the proposed approach and to explore additional issues not addressed here. The simulations will be based on a variety of modeling tools to include wavenumber integration, ray theory, and finite difference codes. The latter codes, which are under continual development, are capable of handling more realistic features than other approaches. As confidence builds from these simulations, field experiments will be carefully designed and conducted to face the realities of the earth's propagation environment.

Acknowledgments

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL8500.6. The authors wish to thank Gerry Sleefe, Timothy McDonald, and Marianne Walck of Sandia National Laboratories for their helpful comments in reviewing this manuscript.

References

1. Erteza, I. A., G. J. Elbring, T. S. McDonald, J. P. Claassen, D. R. Baumgardt, and J. R. Wolford, "Case Study: Unattended Ground Sensor Phenomenology and Signal Processing", Proceedings of the SPIE, Orlando, Florida, Vol. 3081, pp 88-98, 22-23 April 1997.
2. Der, Z. A. and D. R. Baumgardt, "Applications of Higher-Order Spectral Analyses to Detection and Identification of Seismic and Acoustic Signals Generated by Machinery", Proceedings of the SPIE, Orlando, Florida, Vol. 3081, pp 99-109, 22-23 April 1997.
3. Sleefe, G. E., S. G. Peglow, and R. Hamrick, "Application of Unattended Ground Sensors to Stationary Targets", Proceedings of the SPIE, Orlando, Florida, Vol. 3081, pp 21-29, 22-23 April 1997.
4. Sleefe, G. E., M. D. Ladd, D. E. Gallegos, C. W. Sicking, and I. A. Erteza, "A Novel Algorithm for Real-time Adaptive Signal Detection and Identification", Proceedings of the SPIE, Orlando, Florida, Vol. 3374, pp 495-504, 13-15 April 1998.
5. Evans, J. E., J. R. Johnson, and D. F. Sun, "Application of Advanced Signal Processing Techniques to Angle of Arrival Estimation in ATC Navigation and Surveillance Systems", Technical Report, MIT Lincoln Laboratory, June 1982
6. Shan, T. J. M. Wax, and T. K. Kailath, "On Spatial Smoothing for Direction of Arrival Estimation of Coherent Signals," IEEE Transaction, Vol. ASSP-33, No. 4, pp 806-811, Aug. 1985
8. Bienvenu, G. and L. Kopp, "Adaptivity to Background Noise Spatial Coherence for High Resolution Passive Methods," Proceedings of the ICASSP, pp 307-310, 1980
8. Schmidt, R. O., *A Signal Subspace Approach to Multiple Emitter Location and Spectral Estimation*, Ph.D. Thesis, Stanford University, Nov. 1981
9. Bohme, J. F. "Estimation of Source Parameters by Maximum Likelihood and Non-linear Regression," In Proc. ICASSP, Vol. 85, pp 7.31.-7.3.4, 1984
10. Wax, M. "Detection and Localization of Multiple Sources in Noise with Unknown Covariance," IEEE Transaction, Vol. ASSP-40, No. 1, pp145-249, Jan. 1992
11. Owsley, N. L., "Sonar Array Processing," in *Array Signal Processing*, S. Haykin, Editor, Prentice Hall, 1985
12. Claassen, J. P., "The Application of Multiply Constrained MV Beamformer to Regional Monitoring", BSSA, Vol. 82, No. 5, pp. 2191-2212, Oct. 1992

Figure 1. Several examples of CW spectra are shown here. Spectrum (a) is a broadband source operating in the time interval spanning 0:30 to 0:50 seconds. Spectrum (b) is a harmonically related source operating in the time interval 5:00 to 7:30. Note the sidebands associated with some of the spectral lines

Figure 2. The variations in frequency spectra as a function of azimuth for three sensors equidistant (100 m) from a seismic/acoustic source are illustrated here. The thick lines indicate signal plus background spectra; whereas, the thin lines are background noise only.

Figure 3. Various forms of multipath in the earth are illustrated. A subtle form of "multipath" occurs in the direct path (D). Multiple modes propagate along this path with different velocities and with different polarizations as illustrated by the 3-components of particle motions. Other forms of multipath also arises, such as reflections (raypath A) and refractions (raypath B). In seismic media reflections are complicated by mode conversion as shown by raypath C where P waves (solid lines) convert to S waves (dashed lines). S to P conversions (not shown) can also occur at the interface.

Figure 4. This diagram illustrates the configuration of a volume array having spatially invariant sub-arrays within it. All elements in the array are uniformly spaced 3-component receivers

Figure 5. This F-K diagram illustrates the beam pattern of a 5 by 5 surface array when focussed on a P arrival coming from the northeast. The square array consists of vertical receiver elements spaced at $\lambda/2$ wavelengths relative to the v_p . The P arrival has an incident angle of 75 degrees

Figure 6. This F-K diagram illustrates the beam pattern of a 5 by 5 surface array when focussed on a P arrival coming from the northeast. The array elements consists of 3 component receivers matched to the polarization. The elements are spaced at $\lambda/2$ wavelengths relative to v_p . The arrival has an incident angle of 75 degrees. Note that introducing polarization primarily suppresses the reception of P arrivals in directions orthogonal to the look direction and in the backlobe area. The beam plot was truncated to slownesses associated with 90 degrees since polarization matching is included in the response.

Figure 7. This F-K diagram illustrate that lower beam pattern of a 5 by 5 by 5 volume array when focussed on a P arrival arriving from the northeast. Note that the beam has superior resolution in the incident angle direction than the planar array having the same footprint (See Figure 6). The arrival has an incident angle of 75 degrees. The array element were spaced at $\lambda/2$ wavelengths relative to the v_p

Figure 8. This F-K diagram illustrates the ability of a 5 by 5 by 5 volume array to reject a P arrival arriving from the northeast at a 75 degree incident angle when really searching for an SV arrival. Note the suppression on boresight as well as elsewhere. The maximal response is 16 dB down from the P wave response on boresight (see Figure 7). This peak response primarily arises as a result of aliasing the P wave arrival at a smaller incident angle associated with v_s . The aliasing can be entirely prevented by spacing the elements at the Nyquist separation associated with v_s . The array, however, must be enlarged to achieve the same angular resolution. This result suggests that the Nyquist spacing requirement can be violated to reduce array cost provided polarization matching is used to suppress aliased responses associated with an orthogonal polarization.