ACHIEVING HIGH BROADBAND PERFORMANCE WITH NARROWBAND SONAR ARRAYS

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1. INTRODUCTION

High bandwidth signals have advantages in many active sonar applications. With appropriate pulse compression processing, range resolution is directly proportional to source bandwidth. This improves the signal-to-interference ratio for contacts and provides more detail for contact feature recognition. Large bandwidth also provides frequency diversity. Both transmission loss and contact acoustic cross-section can be highly variable with frequency, sometimes leading to sporadic results with narrowband signals. Use of large bandwidth signals naturally average out frequency dependencies, providing more consistent results. Other applications where broadband signals may be advantageous include underwater communication, covert sonar, spectral classification, and acoustic color [1][2].

Broadband sources of sound are also readily available. Impulsive sources, such as explosives, air-guns, and sparkers can provide both high power and high bandwidth at lower frequencies. Commercial transducers can provide broadband signals if transmitter power is not of the utmost concern.

However, most receiver arrays presently in use are designed for narrowband signals. These have sensors spaced at one-half the acoustic wavelength at the frequency of interest. If such an array is used at a higher frequency, the direction of contacts becomes ambiguous. Using the array at a lower frequency degrades contact detectability because sensors are too closely spaced to be effective in reducing noise.

This paper describes how existing narrowband arrays can be effectively used in broadband sonar systems, and in some cases achieve superior performance over the same arrays when used conventionally.

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2. SPARSE ARRAYS

When uniformly spaced arrays have a sensor spacing less than one-half the acoustic wavelength, the Fourier sampling theorem guarantees that the wavenumber (i.e., spatial frequency) components along the array of any signal can be uniquely determined. This, in turn, determines the direction or directions from which the signal is coming. When the spacing is greater than one-half the wavelength, the apparent wavenumber may be aliased, and one is not sure of the direction of some or all of the signals.

The false directions resulting from spatial aliasing of the array are strongly frequency-dependent. As bandwidth of the signal increases, the response from the false directions is spread over angle, while the response in the true direction remains unchanged. Thus, large signal bandwidth allows the ambiguity of an undersampled array to be resolved.

How much bandwidth is required to effect this can be seen from the expression for the false directions readily obtained from narrow band array theory. The beampattern can be shown to achieve its peak value for angles θ which satisfy

$$\sin\theta - \sin\theta_0 = \frac{M\lambda}{\Delta x}, \qquad M = 0, 1, 2, \ldots$$

where θ_0 is the direction the array is steered, and λ is the acoustic wavelength. When $\Delta x < \lambda/2$, there can only be one solution: $\theta = \theta_0$ for $M = 0$. Otherwise, there may be other solutions for $M \neq 0$ which indicate the false directions.

The width of the peaks, when viewed as a function of $\sin\theta$, is approximately λ/L, where L is the length of the array. The change in frequency Δf required to change the angle of a false direction by one width is

$$\frac{\Delta f}{f} = \frac{1}{M}\frac{\Delta x}{L}$$

where $f = \frac{c}{\lambda}$ is the frequency, and c is the speed of sound.

When a signal has at least this bandwidth the false responses start to become suppressed. Even small fractional bandwidths can reduce false beams since $\Delta x/L$ is always a small number for arrays. Typically, fractional bandwidths much greater than this are used, so one would expect that false directions for sparse arrays are significantly reduced for broadband signals.

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To see what can generally be expected, it is useful to think of both the signals and the array beampattern in the time domain. For a uniform array of N sensors spaced Δx, the temporal response of a delay-and-sum beamformer pointed broadside ($\theta = 0$) is

$$B(t,\theta) = \frac{1}{N}\sum_{n=1}^{N} S(t - n\Delta x \sin\theta/c) \qquad (1)$$

where S(t) is a plane wave signal arriving at angle θ to broadside. We have normalized the beamformer output so that the amplitude of a plane wave signal is not changed by the beamforming process.

Several or all of the terms in the sum of (1) can contribute to the response at some angle and time depending on the temporal extent of S(t). As the signal length gets shorter, fewer terms will overlap and the response at any particular time gets smaller. When the temporal extent of the signal is less than $\Delta x/c$, there are angles for which at most one term in the sum contributes at any time, and

$$B_{MAX}^2 = S_{MAX}^2 / N^2.$$

At these angles we may say the sidelobes are N^{-2} below the peak. To achieve N^{-2} sidelobes, the bandwidth must be at least $c/\Delta x$. However, this is not sufficient since the actual extent of the signal may be greater than the inverse bandwidth.

If the bandwidth is at least $c/\Delta x$, but the signal is spread substantially in time, say due to multipath or target spreading effects, then sidelobe characteristics are degraded. If the temporal extent of the signal is greater than L/c, where $L = N\Delta x$ is the array length, then there are times when all of the terms contribute to the sum in (1). If we model the signal as a stationary random process over its duration, the average power response of (1) when the signal is present is

$$\overline{B(t,\theta)^2} = \frac{1}{N^2}\sum_{n=1}^{N}\sum_{m=1}^{N} \overline{S(t - n\Delta x \sin\theta/c) S(t - m\Delta x \sin\theta/c)}.$$

Because of the supposed bandwidth, the signal correlation time is less than $\Delta x/c$, and there are some angles for which the cross-terms are negligible. For these angles the average response is

$$\overline{B^2} = \overline{S^2}/N,$$

and the sidelobes are now N^{-1} below the peak.

Thus, in one extreme where the temporal extent of the signal is less than the time to travel a sensor spacing $\Delta x/c$, the sidelobes are N^{-2} in the sense that the sidelobe

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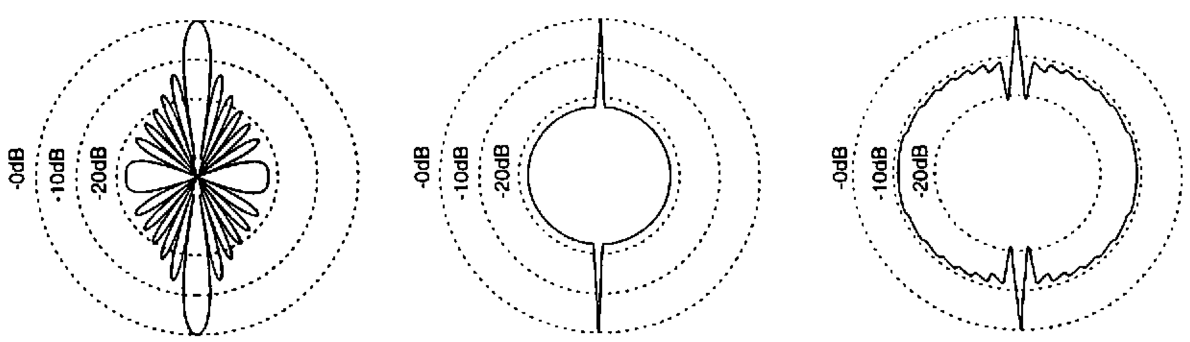
response as a function of time never exceeds this level. In the other extreme where the temporal extent of the signal is greater than the time to travel the length of the array L/c, the sidelobes are N^{-1} in the sense of average power. Typical sidelobe performance may be somewhere in between these two extremes, depending on the degree of signal spread.

Increasing the bandwidth beyond $c/\Delta x$ will reduce the width of the main lobe and hence, resolution, but will not affect the sidelobe level. Further, it will not substantially increase the directivity index of the array. This may seem like a contradiction since the main lobe continues to narrow with increasing bandwidth. The reason directivity index does not increase is because most of the contribution in isotropic noise comes from the sidelobes when $f > c/2\Delta x$, and the sidelobe level is determined solely by the number of sensors N.

Figure 1 shows actual theoretical response for a modest array of 13 elements designed for operation at frequency f_0. The conventional narrowband beampattern shown in 1(a) has a resolution of 9.5 degrees. The maximum response for an impulsive signal over the band f_0 - 15 f_0 shown in 1(b) has an angular resolution of 1.0 degrees and a sidelobe that is -22 dB almost everywhere. The average beampattern for a temporally spread signal with the same frequency content as that in 2(b) is shown in 2(c). Its beamwidth is comparable to that of 2(b), but its sidelobe level has degraded substantially to -11 dB. Clearly, not only can such an array be used broadband without ambiguous results, but the azimuthal resolution is substantially improved over the conventional design. As expected, the array sidelobe characteristics are critically dependent upon the temporal extent of the signal.



a) Conventional Beampattern at f_0. $\Delta\theta$ = 9.5 deg

b) Impulsive signal over the f_0 - 15 f_0 band. $\Delta\theta$ = 1.0 deg

c) Continuous signal over f_0 - 15 f_0 band. $\Delta\theta$ = 1.4 deg

Figure 1. Theoretical Broadside Beampatterns for a 13-element array designed for frequency f_0. a) Conventional beampattern at f_0 which has 9.5 deg. resolution. b) Maximum temporal response for an impulsive signal bandpassed f_0 - 15 f_0 which has 1.0 deg. resolution. c) Average response for continuous signal with a white spectrum over f_0 - 15 f_0 which has 1.4 deg. resolution.

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3. SIMPLE NESTED ARRAYS

Many times physical arrays are designed to cover a large range of frequencies by incorporating several subarrays designed at different frequencies over the band of interest. Usually these subarrays are physically nested and share some sensors. A typical design with four subarrays and octave spacing in their design frequencies is shown in Figure 2.

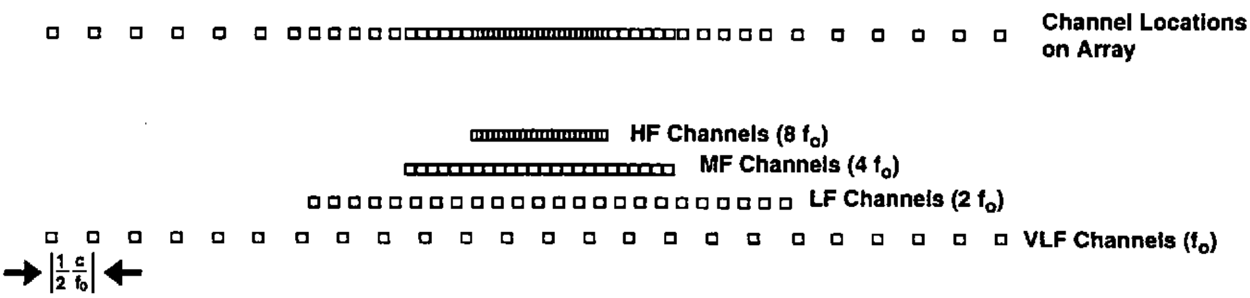

Figure 2. Typical nested array design of four subarrays with octave spacing. Subarrays are designed for operation at frequencies of f_o, 2 f_o, 4 f_o, and 8 f_o.

Conventional processing would treat each subarray independently. In many systems, the broadband data is available on all channels. By using the lower frequency subarrays at the higher frequencies, increases in array gain can be achieved while also achieving the sparse array advantages discussed previously for broadband signals.

To achieve maximum array gain across the band of interest, the sensors must be appropriately filtered to account for unequal spacing. We find that the simple frequency dependent shading to be adequate:

$$a_n = \mathrm{Min}(1, f/f_n), \qquad (2)$$

is adequate, where a_n is the amplitude weight and f_n is the design frequency for the n^{th} subarray. This appropriately attenuates channels which are physically too close together at the lower frequencies and uses all channels equally at the higher frequencies. These weighted channels can then be sent directly to a conventional, time delay beamformer that can accommodate unequally spaced elements. When several subarrays use the same physical sensor, it should of course only be used once in the full array processing.

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4. NESTED ARRAYS WITH HYDROPHONE CLUSTERS

Often the output from a channel of an acoustic array is actually the analog sum of many sensors spaced less than one-half the acoustic wavelength. This cluster design reduces flow noise, but has no other consequence for frequencies at or below the design frequency. A typical cluster configuration for an array like the one used for illustration in Figure 2 is depicted in Figure 3.

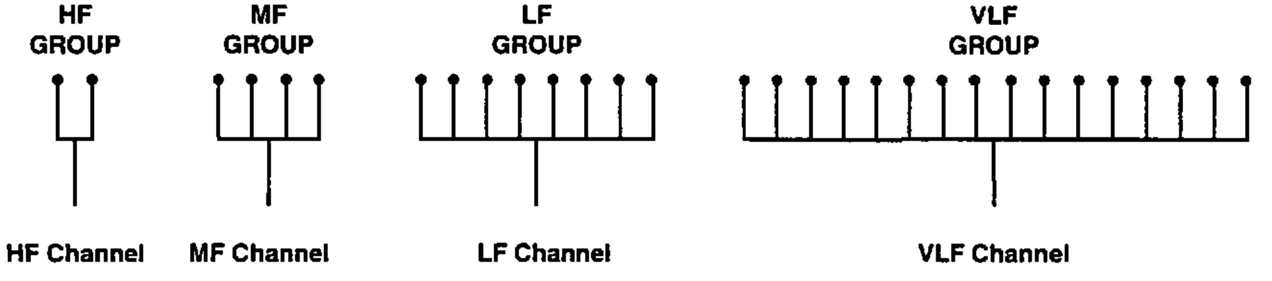

Figure 3. One possible hydrophone cluster configuration for the array shown in Figure 2. Sensors are equally spaced along the array. Spacing is 1/4 wavelength at the HF frequency.

At frequencies above the design frequency, this clustering affects both the signal and the noise on these channels; these clusters act as small subarrays steered broadside. The noise is reduced but signals which are off broadside will also be attenuated. Thus, the greatest advantage is obtained near broadside.

In this situation, not only do the channels have varying spacing, but also have different signal and noise characteristics. This requires additional shading to achieve the maximum performance. For independent channels, the optimal weighting for maximizing directivity index for the n^{th} subarray would be

$$a_n(f,\theta) = s_n^*(f,\theta)/P_n(f) \qquad (3)$$

where a_n is frequency and direction-dependent complex amplitude weights, s_n is the complex amplitude signal out of the hydrophone cluster, and P_n is the power spectral density of the noise out of the cluster.

The combination of (3) with (2) provides a simple shading formula which achieves near maximum directivity index. The signal term in (3) can be readily modeled for any specific cluster configuration. The noise term can either be modeled based on some *a-priori* distribution of the noise, or can actually be measured. The weighted channels can then be passed directly to an appropriate beamformer which treats all channels equally.

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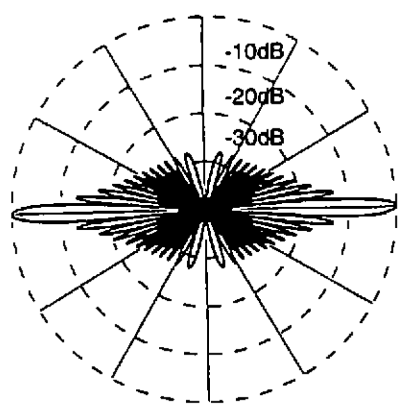
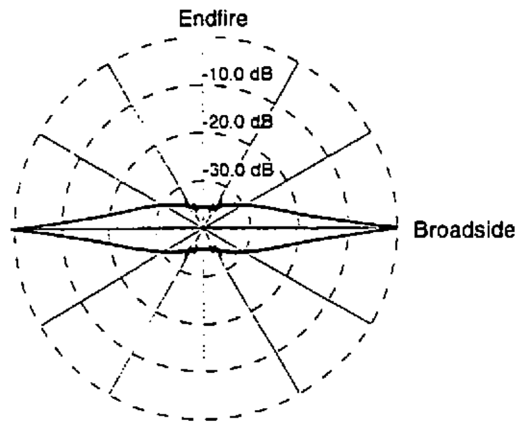
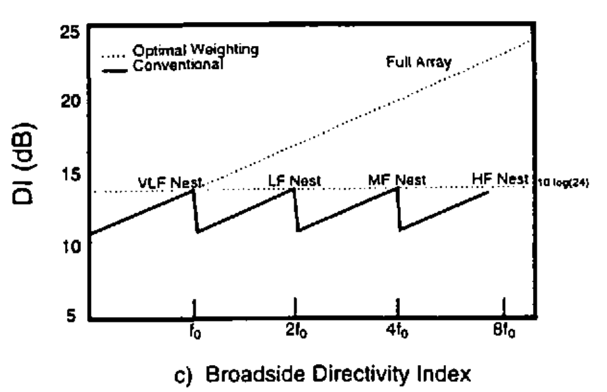
Figure 4 shows the performance enhancement that may be achieved for the array of Figure 2 with the cluster configuration shown in Figure 3. Results are shown for a signal with a band of 1/2 f_0 - 8 f_0. Beampatterns are computed assuming signal spread equal to the inverse bandwidth. At broadside, the broadband full array azimuthal resolution is 1.4 degrees compared to 4.2 degrees for each of the subarrays processed narrow band. The DI enhancement is over 9 dB at the highest frequencies. Improvements will not be as dramatic off broadside, but are still substantial in a sector of about 60 around broadside, and degrade to that of conventional processing near endfire.



a) Conventional Narrowband beampattern for f_0, $2f_0$, $4f_0$, $8f_0$



b) Impulsive Signal over $\frac{1}{2}f_0$ - $8f_0$ band



c) Broadside Directivity Index

Figure 4. Theoretical performance for the array in Figure 2 with hydrophone clusters shown in Figure 3. a) Conventional CW pattern at the design frequency of each subarray which has 4.2 deg. resolution. b) Maximum temporal response for an impulsive signal bandpassed 1/2 f_0 - 8 f_0 which has 1.4 deg. resolution. c) Directivity index vs. frequency for a broadside beam.

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5. SPECIAL PROCESSING REQUIREMENTS

When arrays are used at higher frequencies than that for which they were originally designed, the resolution is improved, but so are sensitivities to wavefront curvature and sensor position errors.

The maximum range for which near field curvature must be compensated is given by the parameter L^2/λ, where L is the array length and λ is the acoustic wavelength. The range at which near field effects become important increases linearly with the highest frequency processed. If the signals are well within the nearfield of the array, dynamic focusing in which the proper time delays are computed continuously over range and angle may be required.

Similarly, sensitivity to relative sensor position errors will be greater at the higher frequencies. Care must be taken so that array gain is not seriously degraded because of this. For bottomed arrays, this can be minimized by carefully surveying in the sensor positions. For towed arrays, beamforming performance will be more sensitive to array motion. If precision heading sensors are available, these can be used to estimate array shape and correct sensor positions. If not, some auto-registration scheme may be required which determines array position by maximizing contrast or some other parameter related to array focus for certain high signal-to-noise contacts that happen to be available.

In the case were hydrophone clusters are used to reduce flow noise, the optimal sensor weights are look-angle as well as frequency dependent. Thus, one set of filtered channels will only be optimum for a particular look direction. In practice, one may use conventional processing to obtain a preliminary view on all beams simultaneously and then use the full array with weights chosen to improve performance in a particular direction of interest. Alternately, if sufficient computational power is available, weighted channels can be re-computed as beam direction varies so that near optimal results are obtained on all beams.

6. EXAMPLE WITH OPEN OCEAN DATA

This technique has been used on data collected with a 123-element uniformly spaced array designed for 300 Hz. The array has hydrophone groups to reduce flow noise. Broadband data was recorded on all channels with an upper frequency cutoff of 1500 Hz. At the highest frequency, this array is undersampled spatially by a factor of five. The array is uniformly spaced so that no special array shading is required for broadband processing. Checks on array gain from high signal-to-noise point-like scatterers indicated that array distortion was not significant for this measurement. The nearfield of this array extends to 90 km at 1500 Hz.

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For the data presented here, the array was towed at a depth of 270 meters in deep water. Broadband reverberation from near sea-surface scattering at about 1800 meters range was generated using the MK-59 Mod1 A SUS, which is equivalent to 1.8 kg of TNT, detonated at 565 meters depth and 980 meters forward of the array. The waveform from the source was measured on a direct path with a monitor phone, and this was used to effectively remove the bubble pulse oscillations through deconvolution processing. The result is equivalent to that of transmitting an impulsive signal of duration less than 1 msec.

Figure 5 shows images of an isolated (unknown) broadband scatterer from data collected under high winds [3]. Images were generated by computing oversampled range-beam data near broadside and mapping to a rectangular grid. The image in Figure 5a is generated for a band of 100-300 Hz, which would be consistent with the design frequency of the array. Figure 5b shows the same data using the full bandwidth available, 100-1500 Hz. Full dynamic nearfield focusing was done for both cases. The same feature is seen in each image, but the broadband result is much better resolved in azimuth as well as range. Measured 3 dB beamwidths are .90 degrees narrowband and .25 degrees broadband, both in exact agreement with theoretical performance.

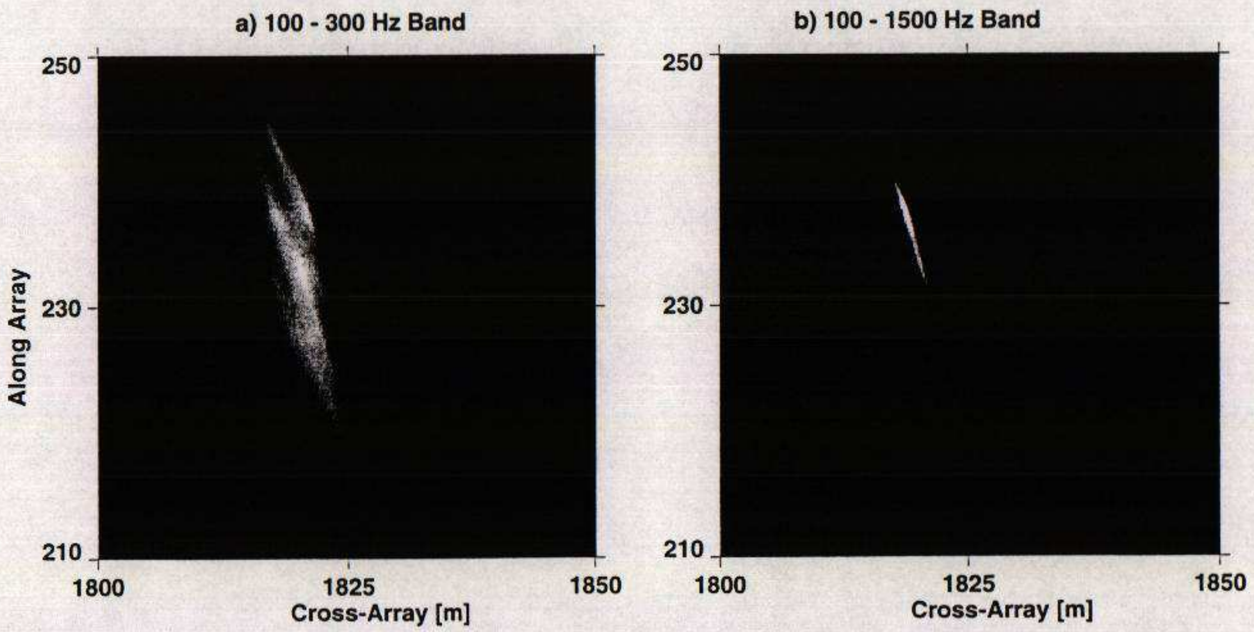

Figure 5. Resolution of an unknown broadband scatterer during high winds using a towed array designed for 300 Hz. Dynamic range of 3 dB is shown. The direction in which there is higher apparent resolution is the range coordinate. The array is located at (0, 0). a) 100 - 300 Hz band consistent with array design, b) 100 - 1500 Hz band showing improved azimuthal and range resolution.

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7. CONCLUSIONS

Narrow band arrays can be used as effective broadband active sonar receivers without ambiguity in contact direction if only modest bandwidth requirements are met. In addition, azimuthal resolution and, in some cases, directivity index can be substantially improved over that of the original design. Temporal spread of the received signal determines sidelobe characteristics. To achieve these capabilities, special channel weighting, near field focusing, and array auto-registration may be required. For arrays with hydrophone groups, usefulness may be limited to a sector around broadside.

8. REFERENCES

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9. ACKNOWLEDGMENTS

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