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Estimates of Infrasonic Array Gain Patterns

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ABSTRACT

Infrasonic array gain patterns are discussed and estimated for the infrasonic frequency range and array geometries under consideration by the Conference on Disarmament in the International Monitoring System (IMS). The larger array spacing being considered for the IMS infrasonic arrays is found to be appropriate in maintaining directivity of the steered beam at lower frequencies. A modestly filled array is found to offer great improvement in narrow band side-lobe suppression at higher frequencies, allowing the benefit of greater directivity of the steered beam at these higher frequencies. Narrow band side-lobe suppression is considered of importance in mitigating frequent, naturally occurring "micro-barom" signals in the southern hemisphere.

Keywords: infrasound, array patterns

OBJECTIVES

The United Nations Conference on Disarmament (CD) has recommended an infrasonic network as one of the International Monitoring System's (IMS) technological monitors of compliance of the Comprehensive Test Ban Treaty (CTBT), presently under negotiation. An important step in assessing and optimizing infrasonic arrays for the IMS is to evaluate the directional detection capability of the arrays. Infrasonic array gain patterns are discussed here and then estimated for the infrasonic frequency range and array geometries under consideration by the CD in the IMS.

RESEARCH ACCOMPLISHED

Pattern Calculation

An infrasonic array usually consists of sensor elements arranged in a 2-D configuration, with each sensor providing a single "channel" signal. Signals from the sensors are typically "steered" to a particular direction; ie, the signals are delayed or "lagged", and then summed, so as to reinforce a sensed disturbance propagating with a particular heading and trace speed across the array. The lag is determined by the geometrical range and bearing of the sensor with respect to a reference location, and in relationship to the trace propagation velocity vector:

$$\tau_i = \frac{r_i \cos(\theta_i - \varphi)}{c}, \quad (1)$$

where r_i and θ_i are the range and bearing of the i^{th} sensor, and c and φ are the trace speed and heading of the propagating disturbance. With the channel signals given by $s_i(t)$ or s_i , and the lagged signals given by $s_i(t + \tau_i)$ or $s_i(\tau_i)$, the summed "composite" signal or "beam" can be written as

$$\hat{s} = \frac{1}{N} \sum_{i=1}^N s_i(\tau_i), \quad (2)$$

where N is the number of elements in the array. This composite signal represents the optimized signal for plane wave disturbances and stationary, spectrally-uniform, noise.

The signal-to-noise ratio SNR is defined to be the ratio of mean-squared signal to mean-squared noise, wherein the noise is assumed to be uncorrelated with the signal and stationary. The "gain" of the array is defined as the ratio of the composite SNR to the individual sensor SNR, wherein equal weighting of the sensors is assumed. For noise uncorrelated between sensors and ideal beam steering, the gain of an array is simply N . For the purposes of this paper, a normalized gain for non-ideal beam steering is given by the mean-square of (2); ie, the power of the composite signal. A normalized gain of 1 represents the maximum ideal array gain of N .

The average signal (across channels) is simply the zero-lag composite signal, designated as

$$\hat{s} = \frac{1}{N} \sum_{i=1}^N s_i. \quad (3)$$

In general, the average signal will emphasize the “vertically propagating” disturbances, or common mode signals which arrive simultaneously at all sensors. Indeed, the traditional impulse response of an array embodies this approach [the reader is referred to the work by Wilson, Olson, Spell, and others on the subject of array performance estimates].

Given the lags for a steered composite signal of (2), the gain pattern is calculated by assuming propagating disturbances from all other headings, but forming the composite signal with these original steered lags. The “off-beam” signals may be written as $s'_i(t)$ or s'_i , in which the signal at each sensor location is simply the same signal delayed by the lags associated with the off-beam propagation velocity vector; ie,

$$s'_i(t) = s_i(t - \tau'_i) \text{ or } s_i(-\tau'_i). \quad (4)$$

The resulting composite signal for this off-beam signal, formed with the original beam lags, is then given by

$$\hat{s}' = \frac{1}{N} \sum_{i=1}^N s_i(\tau_i - \tau'_i), \quad (5)$$

and the normalized gain is given by

$$g = \hat{s}'^2. \quad (6)$$

For the purpose of simplicity, a sinusoidal waveform is used for the signal. Hence,

$$s_i(\tau_i - \tau'_i) = \exp(i2\pi f(\tau_i - \tau'_i)), \quad (7)$$

where f is the frequency of the wave. Patterns of normalized gain are then given as polar plots for all off-beam signals. The trace propagation speed is taken as a fixed value of 330 m/s.

Gain Pattern Estimates

The first array considered is a “centered-triangle”, depicted in Figure 1. Figures 2, 3 and 4 present the normalized gain patterns for this array with a spacing of $d = 200$ m and for frequencies of 0.1, 0.3 and 1.0 Hz. This array and frequency range are in accordance with the array geometry and approximate frequency band under consideration by the CD for the IMS infrasonic network. The array spacing first examined here of 200 m approximates the spacing of arrays previously used in association with higher frequency infrasonic monitoring at ~ 1 Hz. It is observed in figures 2, 3 and 4 that this array has negligible directivity in its beam steering at low frequencies and has poor side-lobe suppression at high frequencies.

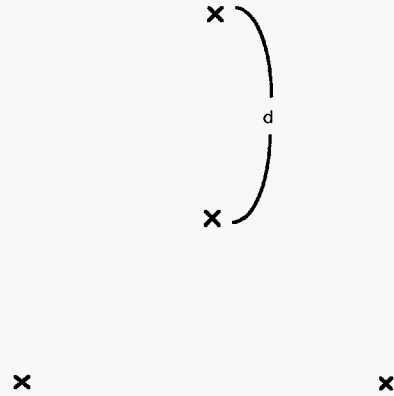
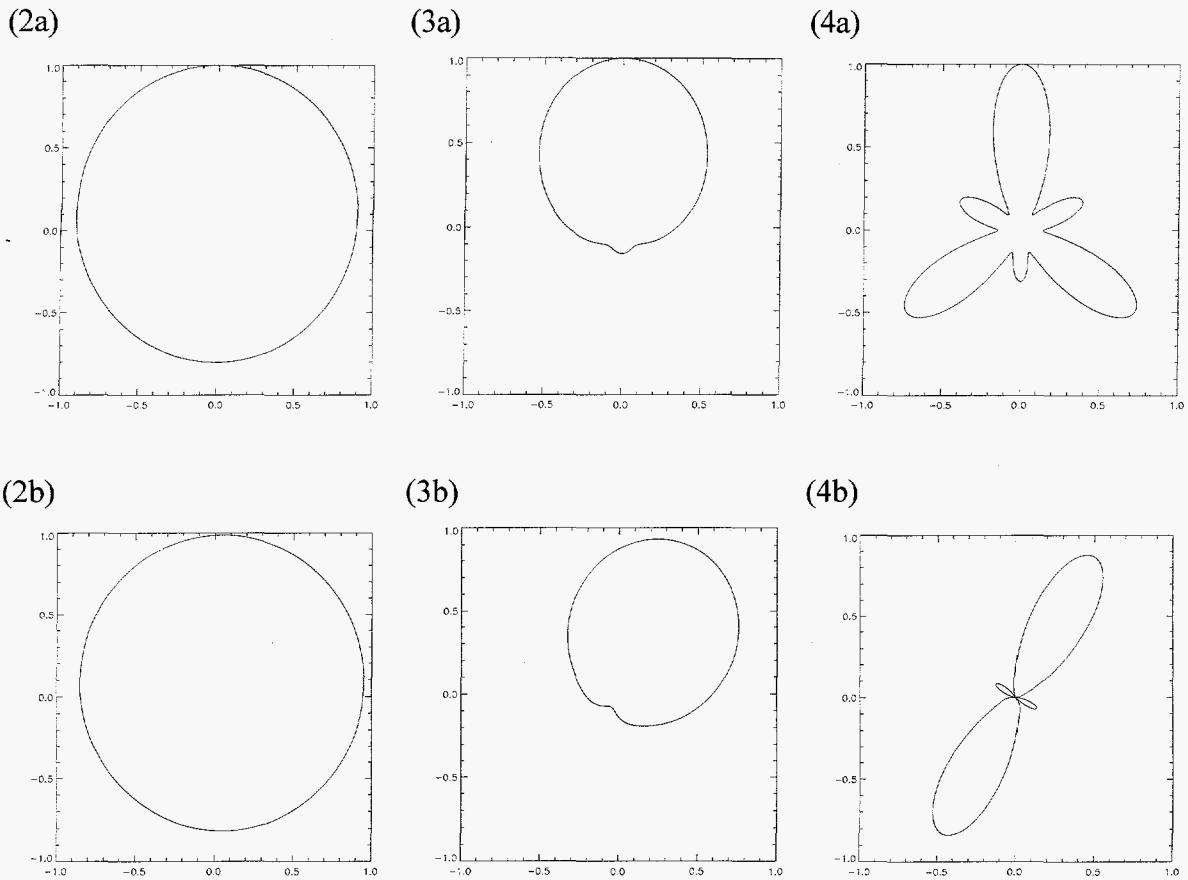


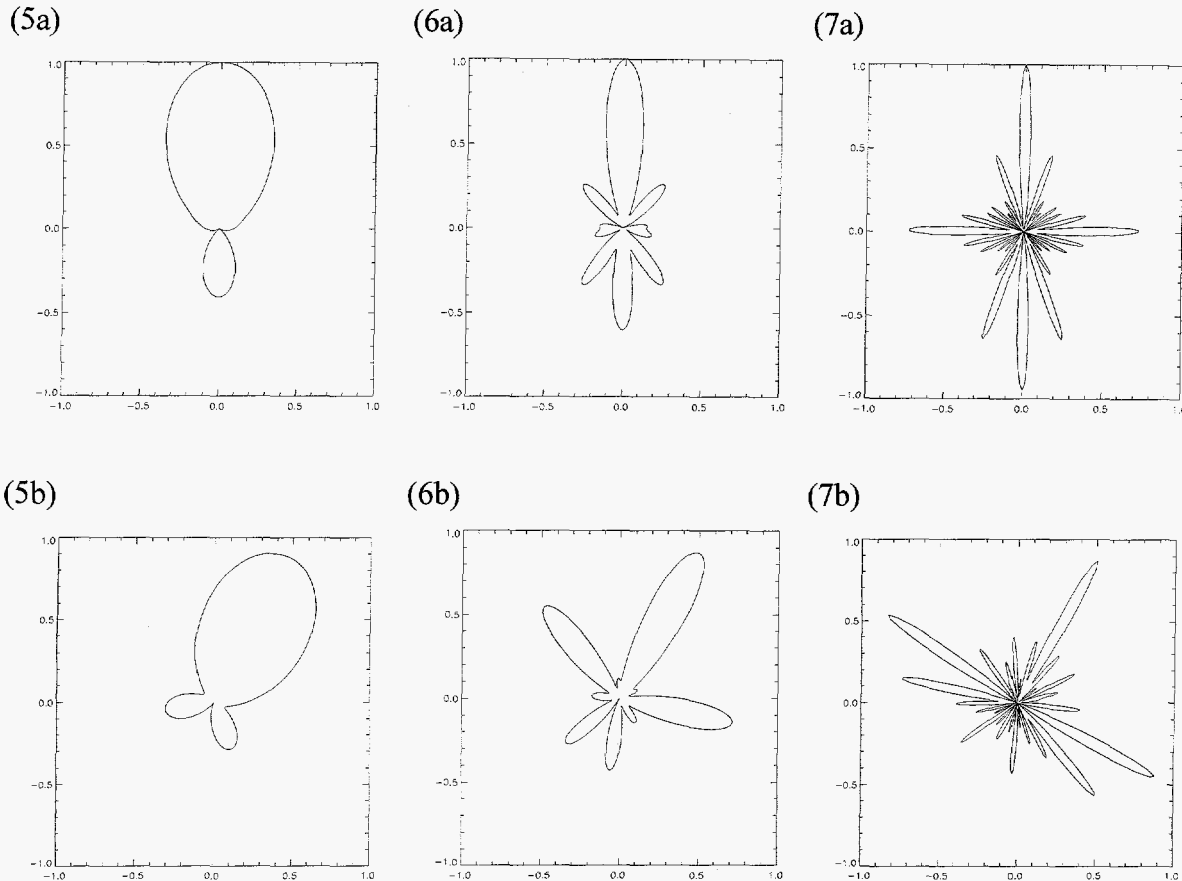
Figure 1. Centered-triangle array geometry.



Figures 2, 3, 4. Gain patterns are shown for the centered-triangle 4-element array of figure 1 with 200 m spacing. Figures 2, 3, and 4 show patterns for 0.1, 0.3, and 1.0 Hz, respectively. Subframes a and b show pattern variations for 0° steering and 30° steering, respectively.

Gain patterns for the same array is again considered in figures 5, 6 and 7, but with spacing of the elements of $d = 1000$ m. The prior frequencies of 0.1, 0.3 and 1.0 Hz are retained. This spacing

approximates the array size proposed for the IMS infrasonic network. With this larger spacing, it is observed that reasonable directivity of the steered beam is now obtained at low frequencies. However, side-lobe suppression is still poor at higher frequencies.



Figures 5, 6, 7. Gain patterns are shown for the centered-triangle 4-element array of figure 5 with 1000 m spacing. Figures 5, 6, and 7 show patterns for 0.1, 0.3, and 1.0 Hz, respectively. Subframes a and b show pattern variations for 0° steering and 30° steering, respectively.

A final array considered here is shown in figure 8. This filled centered-triangle array geometry is simply a combination of the previous small and large centered-triangle arrays. The combination of an inner and outer triangular array combination is again similar to a 7-element array previously proposed for the IMS infrasonic network. This array differs slightly from the proposed IMS array in having the inner triangle rotated 60° so as to be aligned with the outer triangle. The differences in the gain patterns for the two arrays are insignificant, while in-line elements are preferable for ease of installation. The resulting gain patterns for the "filled" array of figure 8 are shown in figures 9, 10 and 11. These patterns exhibit moderate directivity in the low frequency steered beam, as well as good side-lobe suppression at higher frequencies. Also expected and seen in earlier patterns, the width of the beam narrows sharply with increased frequency.

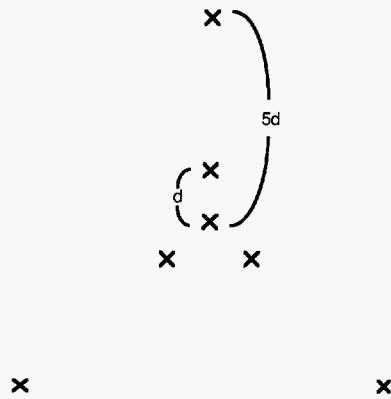
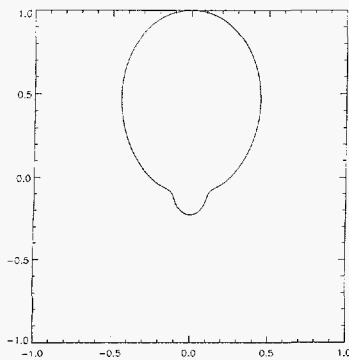
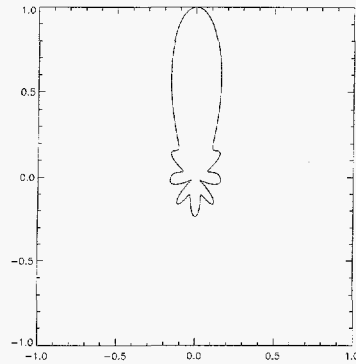


Figure 8. Filled centered-triangle array geometry.

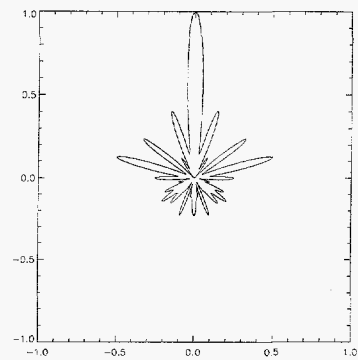
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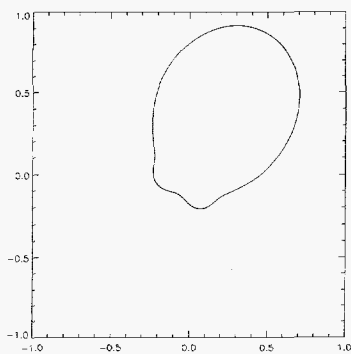
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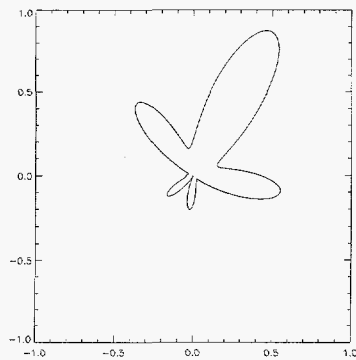
(11a)



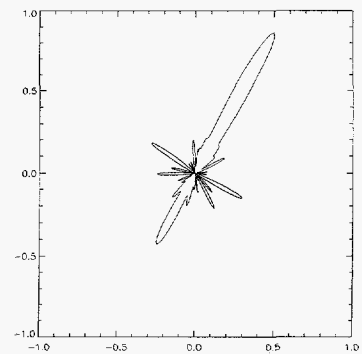
(9b)



(10b)



(11b)



Figures 9, 10, 11. Gain patterns are shown for the filled centered-triangle 7-element array of figure 8 with 200 m inner spacing and 1000 m outer spacing. Figures 13, 14, and 15 show patterns for 0.1, 0.3, and 1.0 Hz, respectively. Subframes a and b show pattern variations for 0° steering and 30° steering, respectively.

CONCLUSIONS AND RECOMMENDATIONS

Though the gain pattern estimates presented here are expected to be representative of actual array performance, some variations of these results can be anticipated. First, the signal processing assumed here is a simple composite signal. Actual signal processing will likely consist of some form of correlation of signals, in which a finite window period will be applied to the signal. Hence, additional signal structure will be utilized in identifying the signal from the noise. In particular, modulation of the signal is anticipated to assist in suppression of side-lobes. In effect, processing of finite bandwidth signals will promote improved directivity of the array. Although sensitivity to narrow band side-lobes will still exist as indicated here, overall sensitivity in the direction of beam steering will be improved with increasing bandwidth.

Another difference in actual signal processing will be the steering of the beam not only in azimuth, but also in trace speed. Changes in the gain patterns are expected which would be achieved with complimentary change in frequency.

After considering these approximations made in the present gain pattern estimates, several conclusions are made. The use of a steered beam is important in estimating off-beam gain. The steered beam helps greatly in evaluating side-lobes of the gain pattern at low and intermediate frequencies. The larger array spacing being considered for the IMS infrasonic arrays is appropriate in maintaining directivity of the steered beam at lower frequencies. A modestly filled array offers great improvement in the side-lobe suppression at higher frequencies, allowing the benefit of the greater directivity of the steered beam at these higher frequencies. Narrow band side-lobe suppression is considered of importance in mitigating frequent, naturally occurring "micro-barom" signals in the southern hemisphere.

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