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Scattering of an FM Signal From an Array of Spheres

Presented at the 127th Meeting of the Acoustical Society of America, 6-10 June 1994, Cambridge, Massachusetts

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PREFACE

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13. ABSTRACT (Maximum 200 words)

This document describes the investigation of the dependence of peak target strength on source bandwidth and scatterer spacing using arrays of rigid scatterers and LFM signals at 200-, 400-, and 800-Hz bandwidths. The results demonstrate that, as the bandwidth increases, the average peak target strength increases and shows less aspect dependence (except near 90 degrees) due to more opportunity for coherent addition of the scattering amplitudes.

As the spacing between the scatterers was increased, there were more fluctuations in aspect angle due to the greater directivity of the scattering pattern. Misaligning scatterers in a regularly spaced array smoothed the overall response and increased the average peak target strength.

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SLIDE 1

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SCATTERING OF AN FM SIGNAL FROM AN ARRAY OF SPHERES

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This study examines the effect of the bandwidth of an incident FM slide on the scattering strength of a simple extended target, which is modeled by a distribution of point scatterers. Spatial averaging of the echo returns is also explored by variation of the scatterer spacing and use of irregular spacings. Although simple, the developed model provides insight into the complicated target-pulse interaction.

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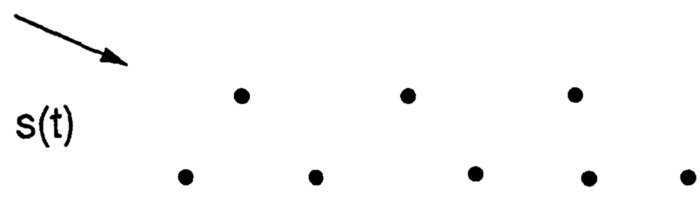
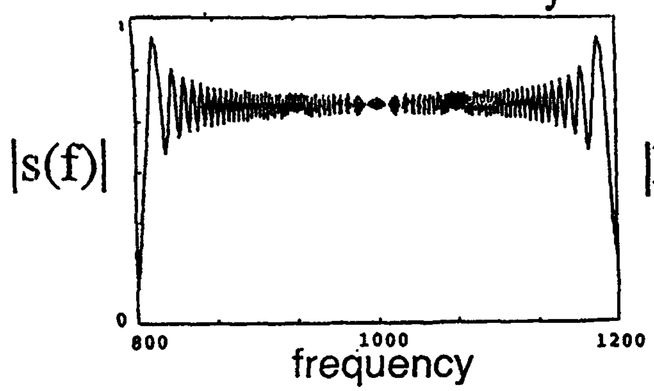
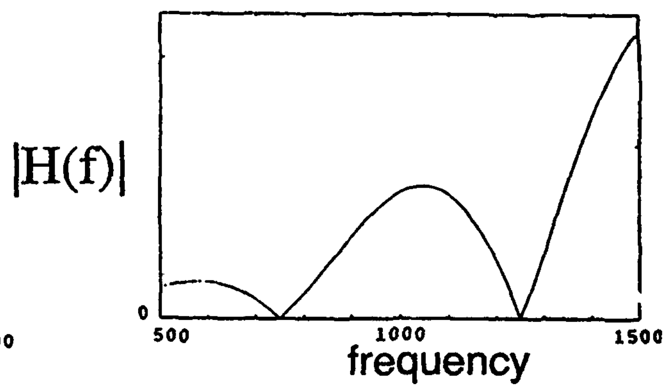
Scattering of FM Slide by Array of Scatterers



$$p(t) = \frac{\pi}{2}\int s(f)H(f)e^{2\pi ift}\,df$$





Peak target strength (PTS) for an LFM signal incident on an array of scatterers was derived in the following way. We assume the echo to be generated by forming the product of the frequency response of the incident LFM signal and the form function of the array. This product yields the frequency representation of the echo. We then use the inverse Fourier transform to obtain the time response and the peak target strength.

The effect of the source bandwidth on the peak target strength was studied by using 100-msec LFMs with bandwidths of 200, 400, and 800 Hz, centered at 1000 Hz.

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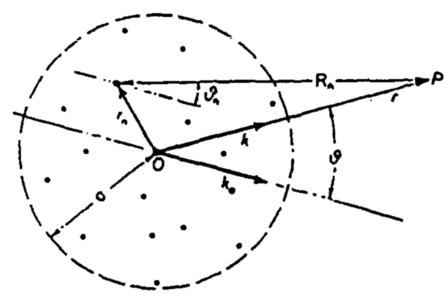
GEOMETRY OF SCATTERING PROBLEM

ANGLES, POSITION AND PROPAGATION VECTORS FOR SCATTERING OF PLANE WAVE BY ENSEMBLE OF SCATTERERS.



THE SCATTERED WAVE AT POINT P IS GIVEN BY:

$$\psi_s = \frac{e^{ikr}}{r} f(k,\theta) \sum_{n=1}^{N} e^{i(k_0 - k)\cdot r_n}$$

WHERE k_o, k, r_n AND R ARE AS SHOWN IN THE FIGURE AND f (k,θ) IS EXPRESSED IN TERMS OF THE BACKSCATTERED PRESSURE FOR A SINGLE SCATTERER. MULTIPLE INTERACTIONS BETWEEN SCATTERERS ARE IGNORED.

The form function for an ensemble of scatterers enclosed in a large sphere is shown here in the equation for Ψ. In our study, we restricted the ensembles to linear arrays of 2 or 11 rigid spheres. The incoming wave has a direction denoted by k_0 while the scattered wave direction to the observation point P is denoted by k. The angle between the incoming and outgoing wave directions is θ. We assume that the range from the origin to the receiver point, P, is great enough so that we may approximate the angle between the individual scatterer vector to point P and vector k_0 as θ; that is, we use the farfield approximation. This simplifies the equation for the ensemble form function Ψ by having a single scatterer form function f(k,θ) that depends only on the frequency and the angle θ. The ensemble form function includes a sum over all the individual scatterers in the ensemble. Multiple interactions between the scatterers are ignored.

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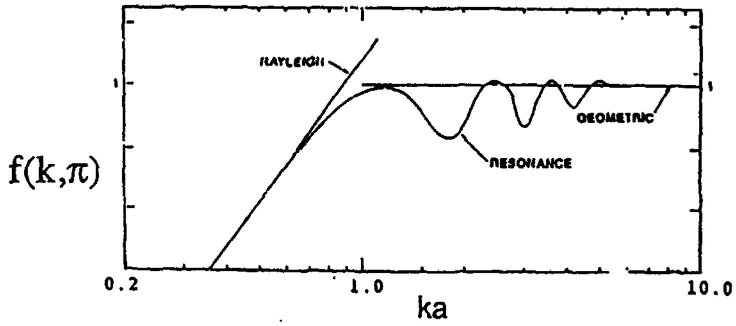
FORM FUNCTION VERSUS FREQUENCY



THREE FREQUENCY REGIONS WERE CONSIDERED:

1. RAYLEIGH REGION: $ka<1,\ f(k,\theta) = \frac{k^2 a^3}{3}\left(\frac{3}{2}\cos\theta - 1\right)$

2. RESONANCE REGION: $ka \approx 1,\ f(k,\theta) = \frac{i}{k}\sum_{n=0}(2n+1)P_n(\cos\theta)\frac{j'_n(ka)}{h'_n(ka)}$

3. GEOMETRIC REGION: $ka>>1,\ f(k,\theta) = 1$

THE PEAK TARGET STRENGTH IS RELATED TO THE FORM FUNCTION BY:

$$PTS=20\log\left(\frac{a}{2}|f(k,\theta)|\right)$$

Three frequency regions were studied where the single scatterer has distinct characteristics: the Rayleigh region (ka < 1), the resonance region (ka ≈ 1), and the geometric region (ka >> 1). The form function for a single rigid sphere in the Rayleigh region is a function of k^2 and cos θ. In the resonance region, f(k,θ) oscillates about 1. In the geometric region, the form function is equal to 1. In the results shown in this document, we will discuss only the Rayleigh and geometric regions, since there is little difference between a function that is approximately 1 and a function that is equal to 1.

The target strength for a single scatterer at a certain frequency is given by 20 log of the product of the form function at that frequency and angle θ and a/2, where a is the radius of the sphere. In the results to be shown, we use an incident LFM signal with an amplitude of 1 having a given bandwidth. By definition, the peak target strength for an ensemble is computed to be 20 log of the maximum absolute value of the complex received echo.

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ASPECT, SPACING AND BANDWIDTH DEPENDENCE FOR TWO SPHERES IN THE GEOMETRIC SCATTERING REGION

(1) FOR A CW SIGNAL

$$\psi_s = \frac{e^{ikr}}{r}\left[1 + e^{2ikd\cos\theta}\right]$$

THE ASPECT DEPENDENCE IS GOVERNED BY THE PHASE 2ikdcos θ OF THE EXPONENTIAL.

2) FOR AN FM SLIDE

$$\psi_s \cong \frac{e^{ikr}}{r}\left[e^{i(\Delta k)r} + e^{2ikd\cos\theta}\right]$$

AS THE BANDWIDTH Δk INCREASES, THE PHASE CHANGE OVER THE SLIDE INCREASES, RESULTING IN A GREATER PEAK TARGET STRENGTH.

Looking at the expression for Ψ using two scatterers in the geometric region gives us insight into the behavior of the peak target strength. For a continuous wave (CW) signal, we see that the aspect dependence is governed by the phase term $2ikd\cos\theta$. Since $\cos\theta$ changes slowly near $\theta = 0$ and more rapidly near $\theta = 90$ degrees, we would expect Ψ (and thus the peak target strength) to exhibit the same behavior. As the spacing d is increased, the phase term changes more rapidly. We would expect more variation with aspect (more directivity) as the distance between the scatterers increased. For an FM slide, we see that the unity term now has a bandwidth (Δk) dependence. As the bandwidth Δk increases, the phase change over the slide increases, resulting in a greater peak target strength due to more opportunity for coherent scattering.

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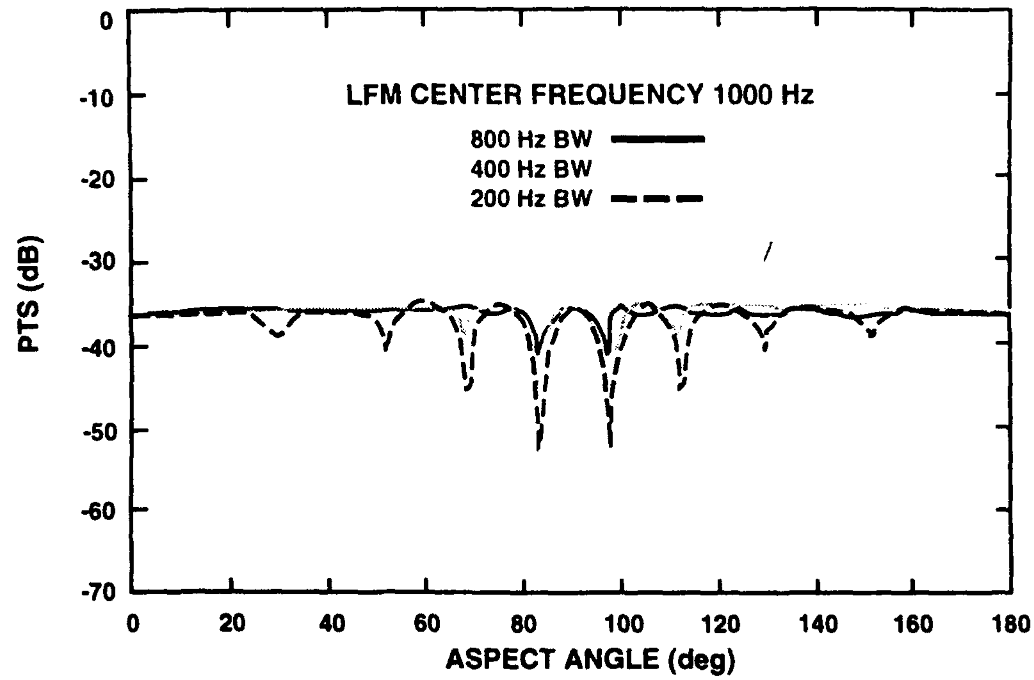
GEOMETRIC REGION PEAK TARGET STRENGTH VERSUS ASPECT ANGLE FOR TWO EQUAL SCATTERERS SEPARATED BY 3 m



Examining an example of two rigid spheres in the geometric region separated by 3 m, we see that, as the bandwidth increases from 200 to 800 Hz, the average peak target strength increases. We also see a smoothing as the bandwidth is increased. As discussed before, the peak target strength shows less variation with aspect near 0 and 180 degrees and varies more rapidly near 90 degrees for all the bandwidths shown.

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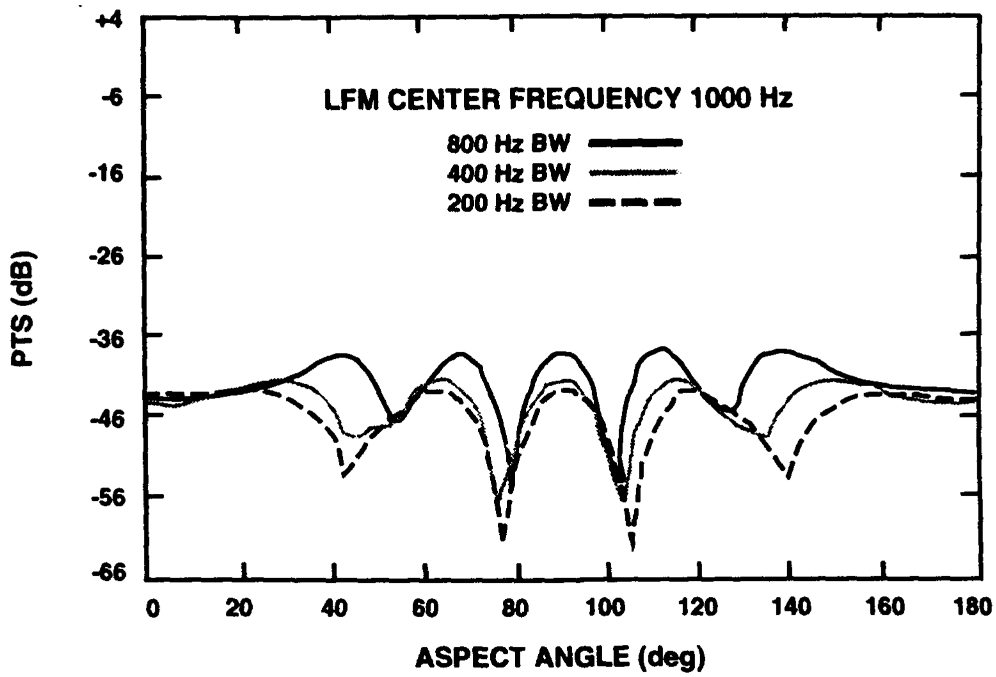
RAYLEIGH SCATTERING REGION PEAK TARGET STRENGTH VERSUS ASPECT ANGLE FOR TWO EQUAL SCATTERERS SEPARATED BY 1.5 m



In the Rayleigh region, where the individual form function has a direct dependence on the frequency, we see that, as the bandwidth increases, the peak target strength increases. This is due to the inclusion of higher frequencies in the larger bandwidth, which produce responses with higher amplitudes because of the form function dependence on frequency. We observe a "squeezing in" of the plots as a function of bandwidth; that is, as the bandwidth is increased, there is less variation near 0 and 180 degrees and the oscillations occur in more narrow regions about 90 degrees. The spacing between the two scatterers is 1.5 m.

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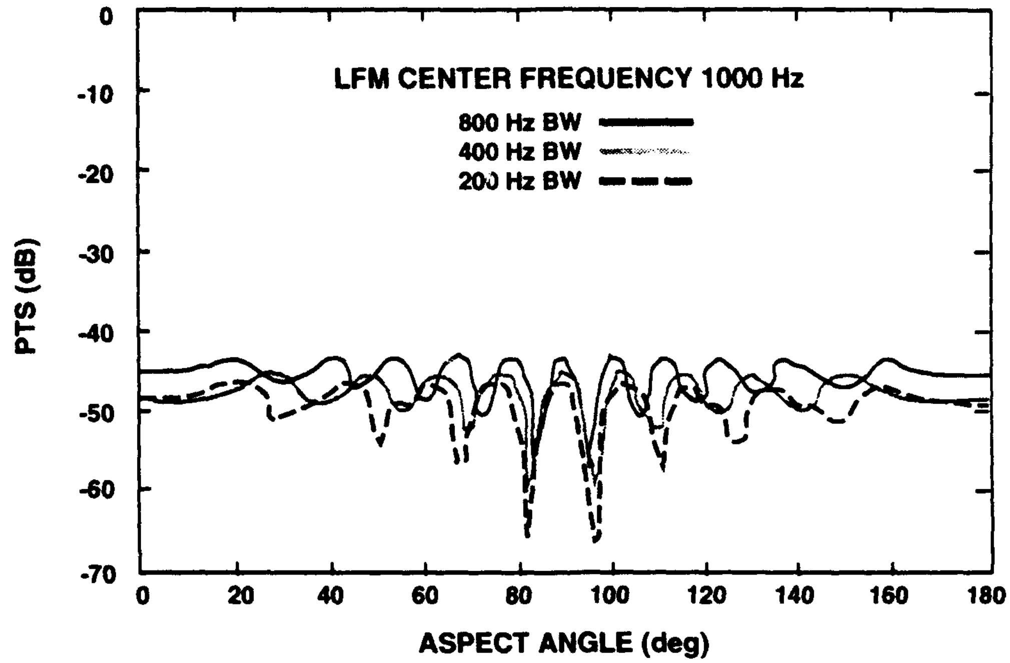
RAYLEIGH SCATTERING REGION PEAK TARGET STRENGTH VERSUS ASPECT ANGLE FOR TWO EQUAL SCATTERERS SEPARATED BY 3 m



Increasing the spacing from 1.5 to 3 m produces more variation in peak target strength as a function of aspect angle. There are more peaks than in the previous plot with a scatterer spacing of 1.5 m. Again, we see the direct dependence of the peak target strength on frequency as we "open up" the bandwidth and include the higher frequencies, resulting in a higher overall peak target strength for the larger bandwidths. We also see the smoothing out of the plot at the 800-Hz bandwidth and the concentration of the variations with aspect closer to 90 degrees. Note that the difference between the maximum and minimum peak target strength values is less for the 800-Hz bandwidth signal than for the 200-Hz bandwidth signal.

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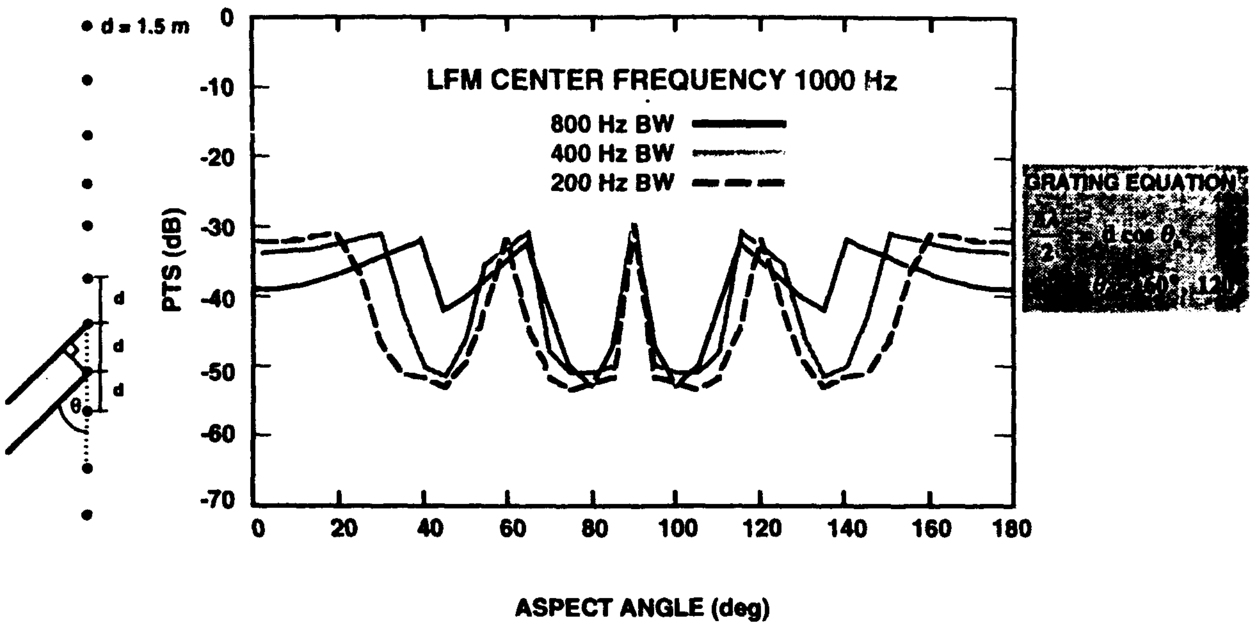
PEAK TARGET STRENGTH VERSUS ASPECT ANGLE FOR ELEVEN EQUAL SCATTERERS SEPARATED BY 1.5 m IN THE RAYLEIGH REGION



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The peak target strength for an array of 11 equal scatterers separated by 1.5 m is shown here. The array produces a grating effect. Maximums in the peak target strength occur where the difference in path lengths to each scatterer, 2dcosθ, is a multiple of the wavelength. The grating equation shows the first grating angle at 60 and 120 degrees. The peak target strength plot shows peaks occurring at the grating angles. Once more we see evidence of the squeezing in of the plots as the bandwidth is increased to 800 Hz.

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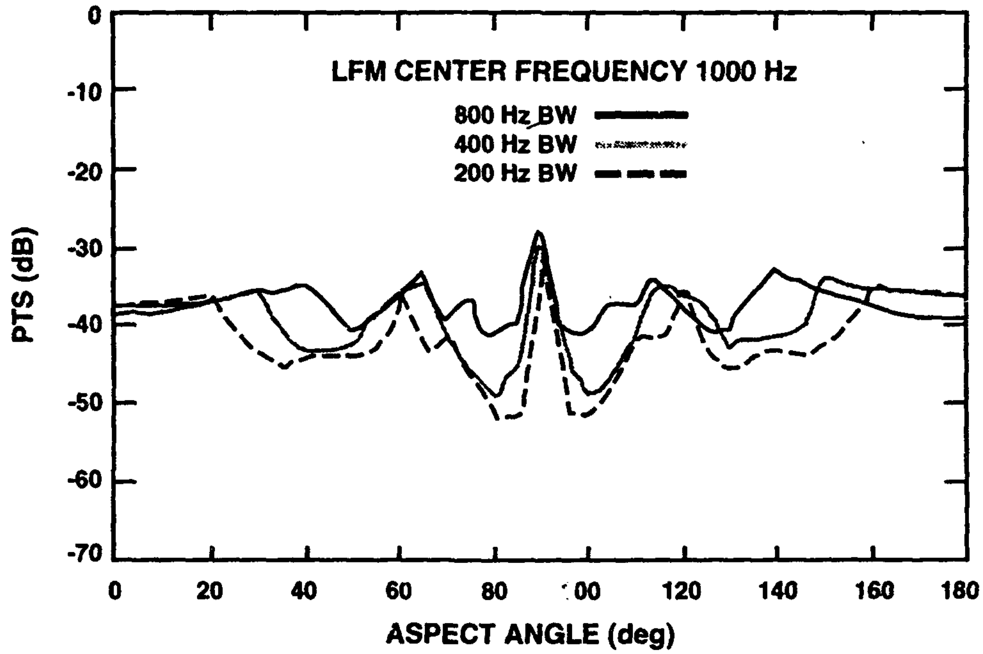
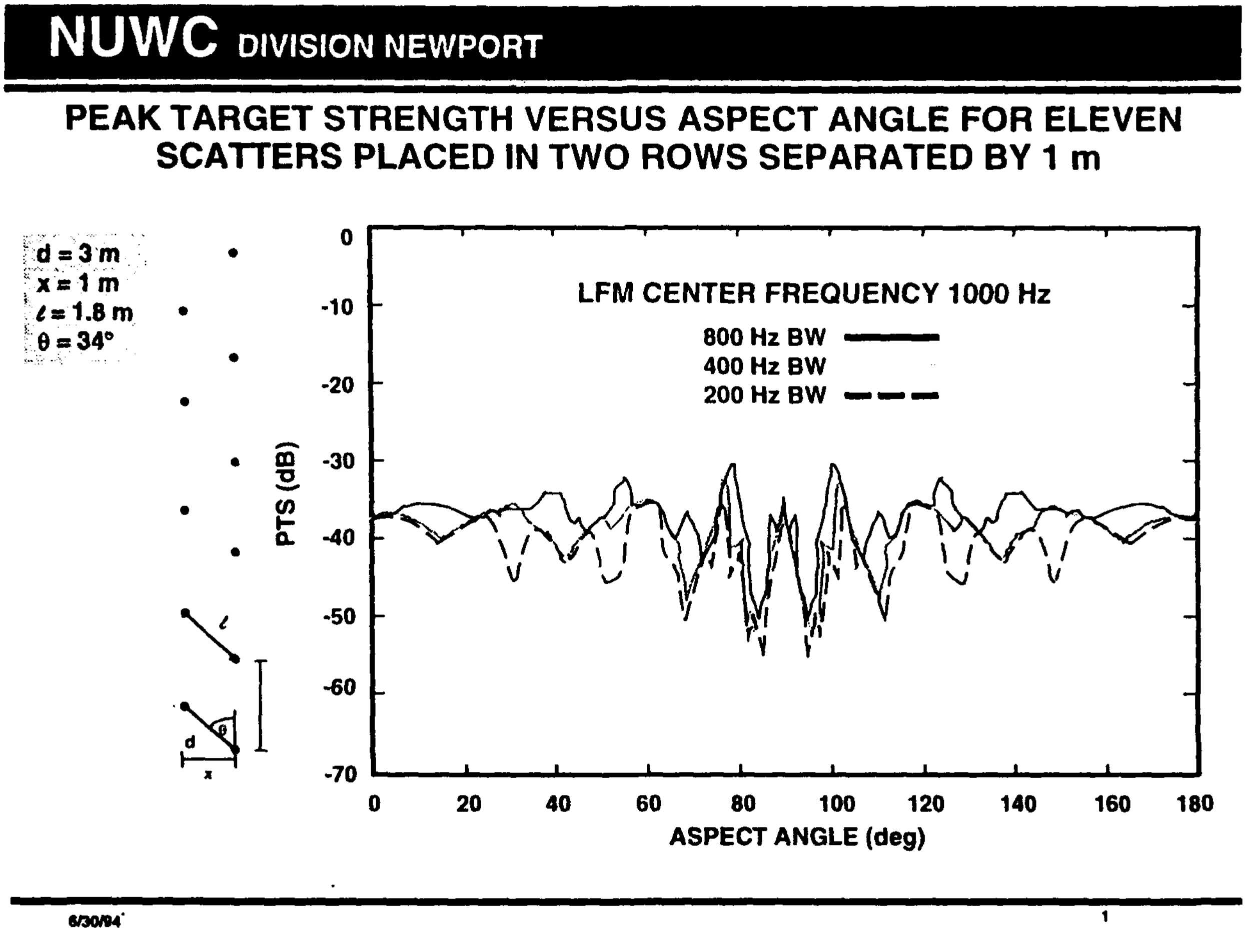
PEAK TARGET STRENGTH VERSUS ASPECT ANGLE FOR ELEVEN SCATTERS SEPARATED BY 1.5 m WITH THIRD AND SEVEN SCATTERERS MISALIGNED



Taking the 11-scatterer array and misaligning 2 of the scatterers, as shown here, smoothes the peak target strength plots. The average peak target strength is greater than it is for the equally spaced array.

SLIDE 11



The last example is a two-dimensional array formed by taking the evenly spaced 11-scatterer array and displacing every other scatterer 1 m.. The peak target strength plots look very different than they do for the one-dimensional array. The 3-m spacing between scatterers increases the number of peaks. Additional grating angles due to the diagonally aligned scatterers are evident in the target strength plots. The average peak target strength is higher than the peak target strengths in the one-dimensional case.

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CONCLUSIONS

- Bandwidth Dependence: As the bandwidth increases, the peak target strength increases and shows less aspect dependence, except near 90°, due to the increased opportunities for coherent addition of the scattering amplitudes.
- Spacing Dependence: As the spacing between scatterers increases, the aspect angular fluctuations increases due to the increased directivity of the scattering pattern.
- Irregularity: Misalignment of regularly spaced scatterers smoothed the overall response as a function as aspect angle.

To conclude, we have examined the effect of source bandwidth and scatterer spacing on the peak target strength of an array of rigid scatterers in the Rayleigh and geometric regions. We have found that, as the bandwidth increases, the peak target strength increases and shows less aspect dependence (except near 90 degrees) due to more opportunity for coherent addition of the scattering amplitudes. In the Rayleigh region, we saw a direct dependence on the bandwidth of the incident signal. As the bandwidth increased, the peak target strength increased due to the dependence of the form function on frequency.

As the spacing between the scatterers was increased, there were more fluctuations in aspect angles due to the greater directivity of the scattering pattern. Misaligning scatterers in the regularly spaced array smoothed the overall response and increased the average peak target strength.

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