Hochschule Bremen
City University of Applied Sciences

UNDERWATER ACOUSTICS AND SONAR SIGNAL PROCESSING

SS 2018

ASSIGNMENT 7

SONAR ANTENNA DESIGN

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by

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Introduction

For directional reception of wave energy, it is necessary to use equidistantly arranged linear or planar arrays on extended antennas. The sonar transmitting/receiving antenna characteristics can be determined by the geometry and shading of the antenna aperture and also the properties of individual transducers. If simultaneous detection of signals from many directions of incidence is required, beam forming must be carried out in parallel for many direction channels. It is also possible to steer antenna in defined direction and range zones and thus process near-field signals selectively with regard to bearing and range of their source. The term antenna beam pattern (or radiation pattern) most commonly refers to the directional (angular) dependence of radiation from the antenna. It is the geometric pattern of the relative strengths of the field emitted by the antenna.

In this assignment we first develop a MATLAB program that determines the beam pattern for a linear array. Then the graphs are plotted for beam pattern using various parameters. The parameters used in this assignment are beam forming, amplitude shading, beam shaping and electronic sheering.

Theory

0.1 Antenna Beam Pattern

A radiation pattern or the antenna beam pattern defines the variation of the power radiated by an antenna as a function of the direction away from the antenna. Very often, only the relative amplitude is plotted, normalized either to the amplitude on the antenna boresight. As a consequence of the reciprocity theorem, the receiving pattern (sensitivity as a function of direction) is identical to the relative power density of the wave transmitted by the same antenna (power density as a function of direction). The pattern of an antenna may be determined experimentally at an antenna range, or alternatively, deduced by computation. The plots of antenna pattern can be used to benchmark a given radar antenna. They also tell you how much degradation you can expect if the antenna is not aimed properly.

The complex beam pattern for a line array is considered in this assignment. It is defined by

$$\tilde{b}(\beta) = \frac{1}{\hat{Q}} \sum_{n=0}^{N-1} Q_n e^{jy_n' sin\beta}$$

with

$$Q_n = \hat{Q}_n e^{j\alpha_n}$$

and

$$\hat{Q} = \sum_{n=0}^{N-1} \hat{Q}_n$$

For $Q_0 = Q_1 = ... = Q_{N-1}$, i.e., $\hat{Q}_n = 1$, $\alpha_n = 0$ and $y_n{}' = -nd$, the complex beam pattern simplifies to

$$\tilde{b}(\beta) = \frac{1}{N} \sum_{n=0}^{N-1} e^{jkndsin\beta}$$

where $k = 2\pi/\lambda$, d is the element spacing, n is the number of point sources and β is the angle between vector r and axis x.

The squared magnitude of complex beam pattern in dB is called beam pattern and it is expressed as

$$\tilde{B}(\varphi, \theta) = 10 \log_{10} |\tilde{b}(\varphi, \theta)|^2 = 20 \log_{10} |\tilde{b}(\varphi, \theta)|$$

In the following sections, we will discuss in brief the parameters that alter the antenna beam pattern. The parameters discussed in the assignment are beam forming, amplitude shading, parabolic phase shading and linear phase shading.

0.1.1 Beam Forming

Beam forming or spatial filtering is the process by which an array of large number of spatially separated sensors discriminate the signal arriving from a specified direction from a combination of isotropic random noise called ambient noise and other directional signals.

0.1.2 Amplitude Shading

Shading is most commonly used to suppress side lobes (responses away from the main response lobe) or to suppress responses in noisy direction (known as Adaptive Beam forming). Having all coefficients equal, offers the maximum array gain in an isotropic noise field. Shading increases the width of the main lobe, decreases side lobes and reduces array gain. With shading, we are trading off the main lobe width and side lobe level.

0.1.3 Parabolic Phase Shading (Beam Shaping)

According to our requirements, the beam pattern and main lobe can be designed this is known as beam shaping. Time delaying a signal is the time-domain analog to phase shading of the signal in frequency domain. The phase shading provides broadening of the main lobe.

0.1.4 Linear Phase Shading (Electronic Steering)

Electronic steering is about changing the direction of the main lobe of a radiation pattern electronically by changing magnitude and phase of the hydrophone. Since there are no moving parts in Electronic Steering as compared to Mechanical steering, this method of beam steering is more efficient.

For α as an incident angle there would be a delay in receiving the wave by different elements, which corresponds to a phase shift given by

$$\varphi = kndsin(\alpha)$$

$$Q_n = e^{j\varphi} = e^{kndsin(\alpha)}$$

where Q_n denote the amplitude of the n^{th} point source with $n = 1, ..., N$. The complex beam pattern is defined as

$$\tilde{b}(\beta) = \frac{1}{\hat{Q}} \sum_{n=0}^{N-1} Q_n e^{jy'_n sin\beta}$$

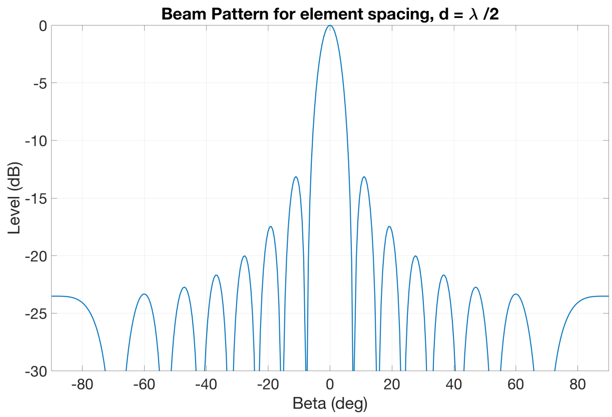
Experimental Research

0.2 Beam Forming

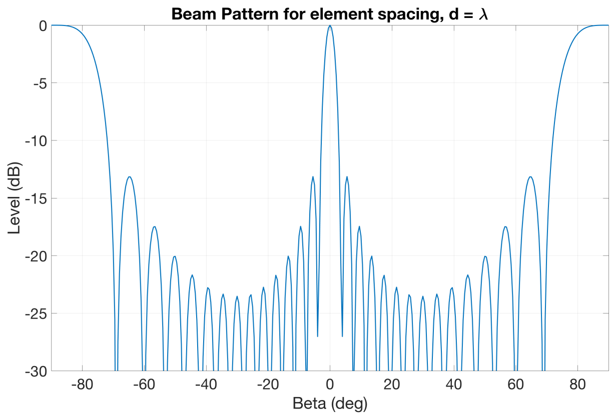
Figure 1 shows the beam pattern with different element spacing. Here, beam patterns with element spacing, d of $\lambda/2$, λ and 2λ is considered and the number of elements, N is taken to be 15. Also, the incident angle, $\alpha = 0°$. For element spacing, $d = \lambda/2$, we see that the main lobe width is large compared to when larger element spacings. Better resolution and precise location of certain sound source can be obtained with a narrower beam width. The wider the beam width, the more noise is received from the surroundings. Thus making it more difficult to identify the signal. It becomes difficult to spot the source with a wider beam width as it is more susceptible to noise received from the surroundings.

We can observe that as we increase the element spacing from $d = \lambda/2$ to $d = 2\lambda$, the main lobe width decreases, but the antenna length increases. If the element spacing is increased so that the element spacing is much greater than half a wavelength, as in the case when $d = \lambda$ and $d = 2\lambda$, the aliasing effect causes the magnitude of the side lobes to increases substantially and approach the level of the main lobe. These lobes are called grating lobes. Because of these grating lobes the antenna is equally sensitive in this direction. This is an unwanted effect. But, there are a some applications where more grating lobes are required.

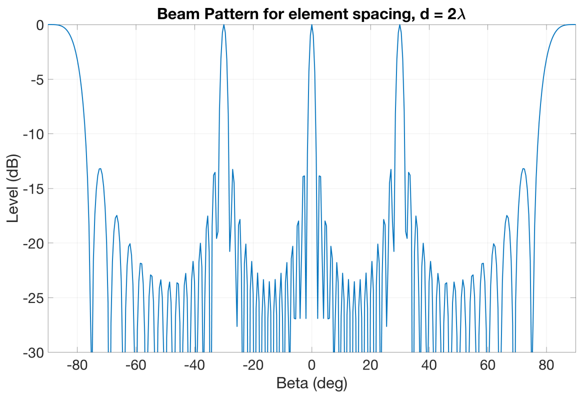
Better resolution can be achieved by having longer antenna lengths. Thus there is a trade-off between the antenna length and beam width, as it is not feasible to have very long antennas. At $d = 2\lambda$, the antenna is four times longer than when $d = \lambda/2$.



(a) Element Spacing, $d = \lambda/2$



(b) Element Spacing, $d = \lambda$

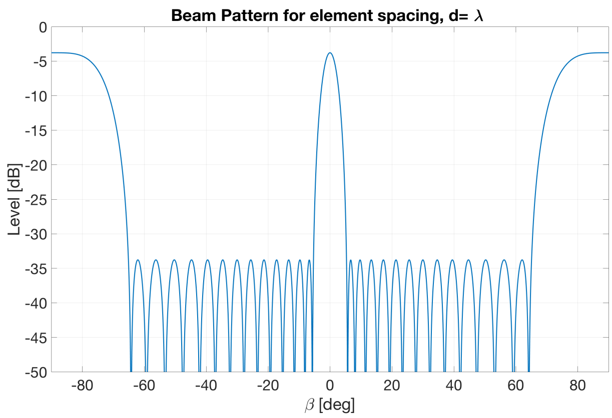


(c) Element Spacing, $d = 2\lambda$

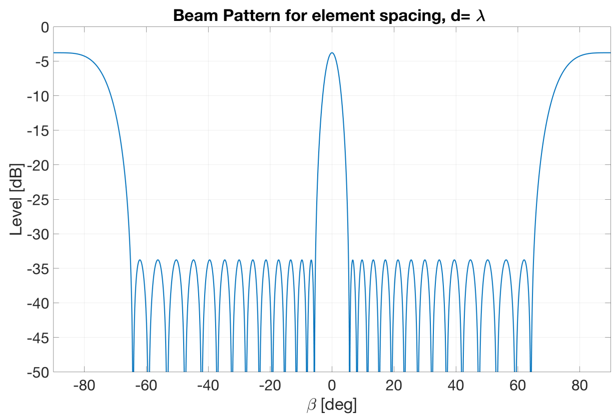
Figure 1: Beam Pattern for different Element Spacing

0.3 Amplitude Shading

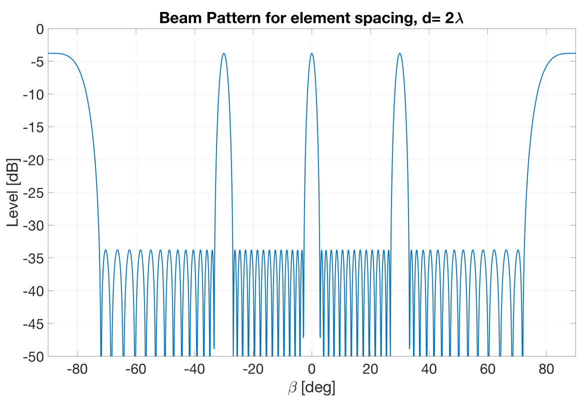
Amplitude shading is an adjustment of array elements with respect to amplitude and phase. It is a convenient way to match the directivity pattern to a desired shape. It is common to employ shading as a mean to reduce the side lobe level of an antenna at the expense of the beam width of the main lobe. In most cases, amplitude shading is used to produce maximum response at the centre of the array and minimum at the ends, i.e. the sensitivity of the elements is said to be tapered from high values inside to low values outside the array. Amplitude shading is a method to suppress side lobes using window functions (example: hamming, triangular or chebychev window). There is tradeoff between beam width of main lobe and resolution.



(a) Element Spacing, $d = \lambda/2$



(b) Element Spacing, $d = \lambda$

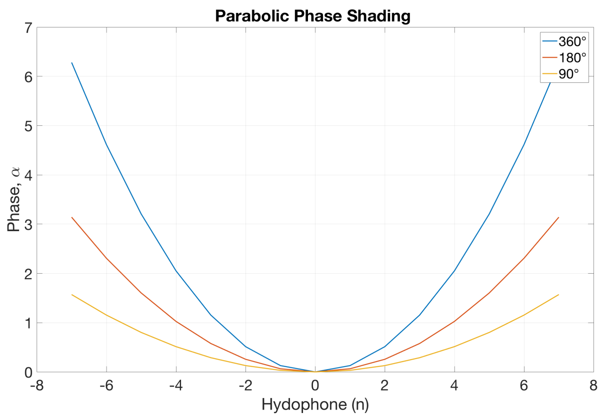


(c) Element Spacing, $d = 2\lambda$

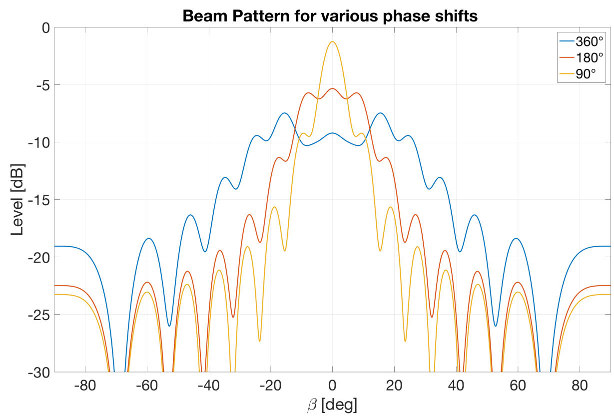
Figure 2: Beam Pattern with Amplitude Shading

In the MATLAB code, the function, chebwin (n,r) is used to suppress the level of side lobs because we can achieve lesser beam width with better side lobe suppression as compared to the other window types. We can vary the fourier transform side lobe magnitude in chebwin function in-order to obtain different side lobe suppressions. The grating lobes are not suppressed by the chebwin window. The grating lobes can be removed by applying rectangular window on the beam pattern, which allow only main lobe to pass.

0.4 Parabolic Phase Shading (Beam Shaping)



(a) Phase Shading



(b) Beam Pattern with Parabolic Phase Shading

Figure 3: Parabolic Phase Shading

Beam shaping is used to design a beam pattern with a certain main lobe according to our requirements. The phase shifts of 90° and 180° and 360° are applied to the signal fed into the transducer elements. This phase shading also provides broadening of main lobe. Many optimisations procedures are used to broaden the main beam and also suppress the side lobes to a desired level.

As seen in Figure 3(a), it is observed that stronger the parabolic curve, stronger is the broadening of the beam. The beam pattern degrades with steeper parabolic phase which can be seen by higher side lobe levels. Also the resolution is decreased, if the beam width is increased. Figure 3(b) shows the beam pattern after parabolic phase shading.

0.5 Linear Phase Shading (Electronic Steering)

Changing the direction of main lobe of the beam pattern is called beam steering. This is done by changing the magnitude and phase of the hydrophones. We considered the incident angle or the steering angle to be $-20°$, $0°$ and $20°$.

The summation of the signals of all the array elements/hydrophones results in the directional pattern with a maximum at the right angle ($0°$) to the linear array or normal to the surface of the plane array. This is called the beam axial direction or broadside direction. It is possible to deflect the maximum towards other directions by mechanical or electronic steering. This procedure is called mechanical or electronic beam steering. Electronic beam steering requires the array of sensors to be composed of individually accessible elements. The device that accomplishes the beam steering is called the beam former.

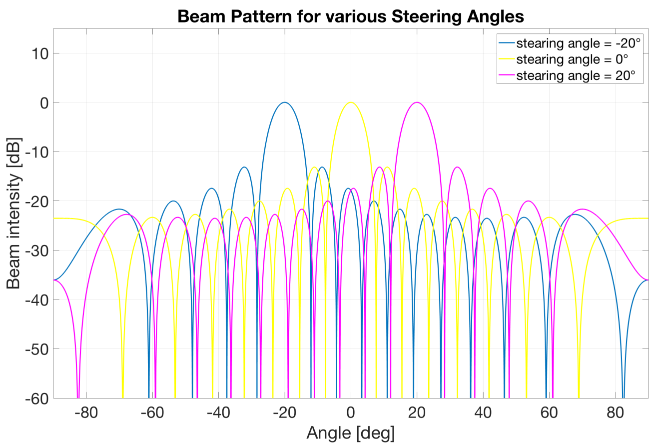


Figure 4: Linear Phase Shading

Conclusion

In summary, the radiation pattern is a plot which allows us to visualize where the antenna transmits or receives power. The beam width of a line array is defined as the angular distance between the ?3dB points of lobes. The beam width increases from a minimum at steering angle, $a = 0°$ (broadside) to a maximum at $a = 90°$ (end fire). To reduce the side lobe level we must weigh the sensor outputs. This procedure of weighing the sensory output is called as Shading. The extra main lobes called the grating lobes are not in the focusing region when the antenna is not steered. But when the antenna is steered, the grating lobes come in to the focusing region which will have a negative influence on the beam pattern of antenna. Sound is slow for propagation in parabolic phase shading. With phase shading the beam is broader for wider transmission from the antenna.

Appendix

0.6 MATLAB code to determine beam pattern for different element spacing

```
N = 15;  % number of elements
k_d = [pi,2*pi,4*pi];  % multiples of k and d
beta = -90:0.5:90;
b = zeros();
q = zeros();
B = zeros();
for i = 1:3
  for bet = 1:361
      b(bet) = 0;
    for j = 0:N-1
        q(bet) = exp(-j*k_d(i)*sind(beta(bet))*1i);
        b(bet) =b(bet)+q(bet);
    end
    b(bet) = b(bet)/N;  % complex beam pattern
    B(bet) = 20*log10(abs((b(bet)))); % beam pattern
  end
  figure
  plot(beta,B,'LineWidth',2);
  if i == 1
      title('Beam Pattern for element spacing, d = \lambda/2');
```

```
  else
      if i == 2
          title('Beam Pattern for element spacing, d = \lambda');
      else
      title('Beam Pattern for element spacing, d = 2\lambda');
      end
  end
  ylim([-30 0])
  xlim([-90 90])
  grid
  xlabel('Beta (deg)');
  ylabel('Level (dB)');
end
```

0.7 MATLAB code to determine beam pattern with amplitude shading

```
deg2rad = pi/180; % conversion to rad
beta_deg = -90:0.1:90; % angle between the vector R and the x-axis [deg]
beta_rad = beta_deg*deg2rad; % angle between the vector R and the x-axis [rad]
N = 15; % number of hydrophones
lambda = 2; % Wavelength [m]
k = 2*pi/lambda; % wave number
d = [lambda/2, lambda, 2*lambda]; % distance between hydrophones (element spacing)
Qn_head = ones(1,N); % Amplitude of the n-th point source or Hydrophone
alpha = ones(1,N); % Phase of the n-th point source or Hydrophone
w = chebwin(15,30);
Q_head = 0; % initialising variable
for n = 1:N
term = Qn_head(n);
Q_head = Q_head + term;
end
for x = 1:3
 bp_sum = 0;
```

```
  for n = 1:N
  sum(n,:) = Qn_head(n)*w(n)*exp(1i*(alpha(n) - k*n*d(x)*sin(beta_rad)));
  bp_sum = bp_sum + sum(n,:);
  end
 bp = 20*log10(abs(1/(Q_head)*bp_sum)); % beam pattern
 figure
 %subplot(3,1,x)
 plot(beta_deg,bp,'linewidth',2)
 grid;
 axis([-90 90 -50 0])
 ylabel('Level [dB]')
 xlabel('\beta [deg]')
 switch num2str(d(x))
case '1'
title(' Beam Pattern for element spacing, d= \lambda/2')
case '2'
title('Beam Pattern for element spacing, d= \lambda ')
case '4'
title('Beam Pattern for element spacing, d= 2\lambda')
end
end
```

0.8 MATLAB code to determine parabolic phase shaping

```
beta_deg = -90:0.1:90; % angle between the vector R and the x-axis [deg]
beta_rad = beta_deg*pi/180; % angle between the vector R and the x-axis [rad]
N = 15; % number of hydrophones
lambda = 2; % wavelength
k = 2*pi/lambda; % wave number
d= [lambda/2, lambda, 2*lambda]; % distance between hydrophones (element spacing)
Qn_head = ones(1,N); % Amplitude of the n-th point source or Hydrophone
alpha = ones(1,N); % Phase of the n-th point source or Hydrophone
scaling = [pi*2, pi, pi/2, pi/10]; % scaling factor for the parabolic shading
alpha_parabolic = zeros();
for x=1:3
```

```
 for n= -7:1:(N-1)/2
  alpha_parabolic(n+8,x) = scaling(x)*n^2/(((N-1)/2)^2);
 end
end
figure
plot(-7:7,alpha_parabolic(:,1),-7:7,alpha_parabolic(:,2) ,...
     -7:7,alpha_parabolic(:,3),'linewidth',2);
title('Parabolic Phase Shading ')
grid
legend('360^{\circ}','180^{\circ}','90^{\circ}');
xlabel('Hydophone (n)')
ylabel('Phase, \alpha')
Q_head = 0; % initialising variable
for n = 1:N
 term = Qn_head(n);
 Q_head = Q_head + term;
end
for x = 1:3
 bp_sum = 0;
 for n = 1:N
  sum(n,:) = Qn_head(n)*exp(1i*(alpha_parabolic(n,x) ...
       - k*n*d(1)*sin(beta_rad)));
  bp_sum = bp_sum + sum(n,:);
 end
 bp(x,:) = 20*log10(abs(1/(Q_head)*bp_sum)); % beam pattern
end
figure
plot(beta_deg,bp(1,:),beta_deg,bp(2,:),beta_deg,bp(3,:),'linewidth',2)
title('Beam Pattern for various phase shifts ')
grid;
hold on;
legend('360^{\circ}','180^{\circ}','90^{\circ}');
axis([-90 90 -30 0])
ylabel('Level [dB]')
xlabel('\beta [deg]')
```

0.9 MATLAB code to determine linear phase shading

```
stear_1 = -20; % steering angle in degrees
stear_2 = 0;
stear_3 = 20;
deg2rad = pi/180;
stear1 = stear_1*deg2rad;
stear2 = stear_2*deg2rad;
stear3 = stear_3*deg2rad;
R = 30;
f = 100000;
c = 1480;
lamda = c/f;
d = lamda/2;
N = 15;
n = 0:N-1;
rho_deg = -90:0.01:90;
rho_rad = rho_deg*deg2rad;
sinerho = sin(rho_rad');
part2 = 2*pi*d*n/lamda;
Q = exp(1i*sinerho*part2);
y1 = exp(1i*sin(stear1)*part2); %-40
B1 = (Q*y1')/N;
y2 = exp(1i*sin(stear2)*part2); %0
B2 = (Q*y2')/N;
y3 = exp(1i*sin(stear3)*part2); %20
B3 = (Q*y3')/N;
gn1 = 20*log10(abs(B1));
gn2 = 20*log10(abs(B2));
gn3 = 20*log10(abs(B3));
figure(1);
plot(rho_deg,gn1,'linewidth',2');
hold on;
plot(rho_deg,gn2,'y','linewidth',2');
hold on;
plot(rho_deg,gn3,'m','linewidth',2');
```

```
hold on;
ax = gca;
ax.FontSize = 30;
grid;
axis([-90 90 -60 15])
title('Beam Pattern for various Steering Angles');
xlabel('Angle [deg]');
ylabel('Beam intensity [dB]');
hL = legend('stearing angle = -20^{\circ}','stearing angle = 0^{\circ}','stearing angle = 20^{\circ}');
hL.FontSize = 25;
```