Sonar Implementation Concepts

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Outline

- **The sonar environment**
- **Typical sonar block diagram**
- **Brief tour of some topics covered in much greater depth in other courses:**
  - **signal representation**
  - **beamforming**
  - **signal detection**
- **Passive processing**
- **Active processing**

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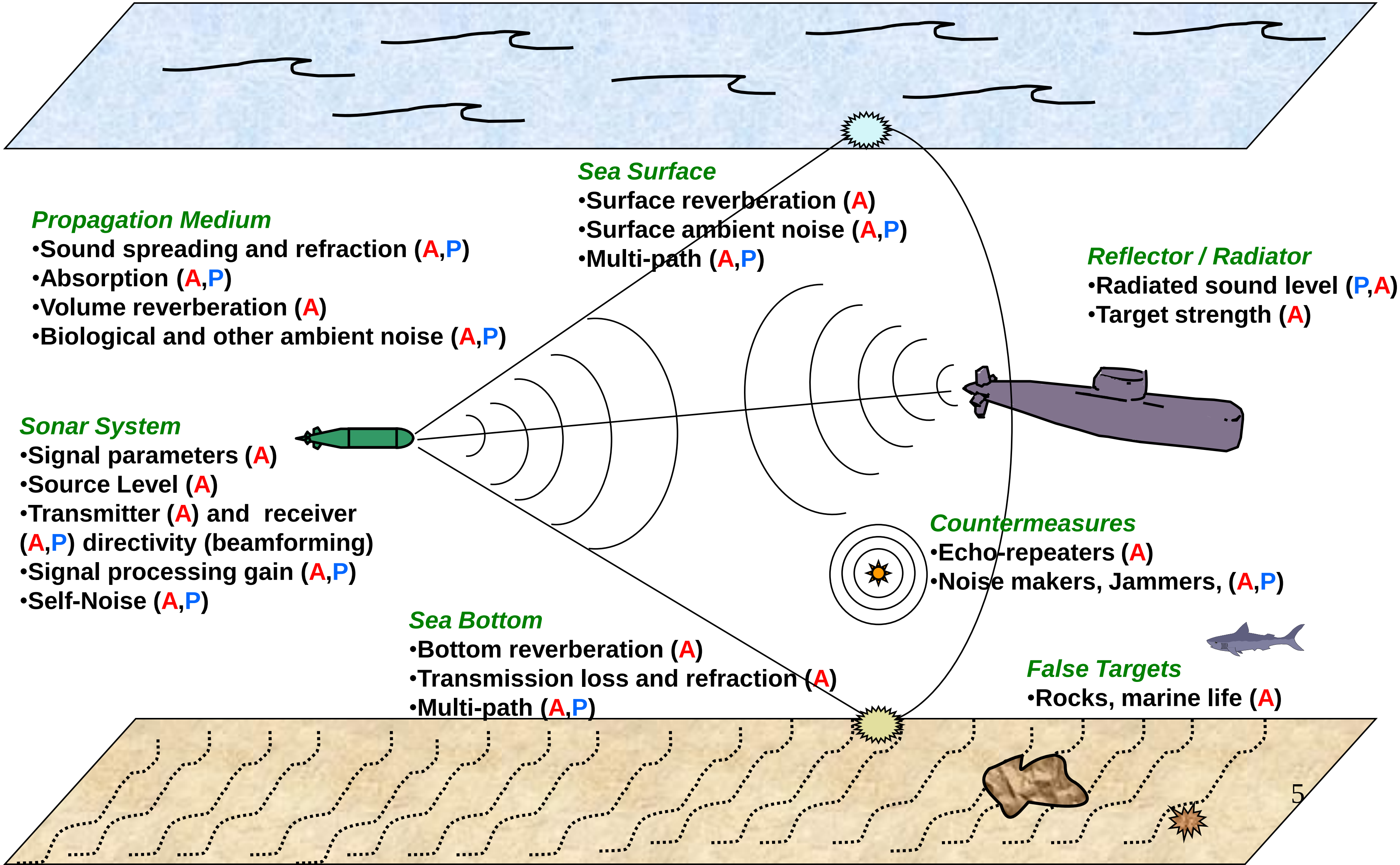
(B) – Basic/Overview/Reference (M) – Mid-level/General/Reference (A) – Advanced/Special Topic

The Sonar Environment and the Sonar Equation

Signals and Noise in Underwater Sonar



Sea Surface

- Surface reverberation (A)
- Surface ambient noise (A,P)
- Multi-path (A,P)

Propagation Medium

- Sound spreading and refraction (A,P)
- Absorption (A,P)
- Volume reverberation (A)
- Biological and other ambient noise (A,P)

Reflector / Radiator

- Radiated sound level (P,A)
- Target strength (A)

Sonar System

- Signal parameters (A)
- Source Level (A)
- Transmitter (A) and receiver (A,P) directivity (beamforming)
- Signal processing gain (A,P)
- Self-Noise (A,P)

Countermeasures

- Echo-repeaters (A)
- Noise makers, Jammers, (A,P)

Sea Bottom

- Bottom reverberation (A)
- Transmission loss and refraction (A)
- Multi-path (A,P)

False Targets

- Rocks, marine life (A)

The Sonar Equation

- **The Sonar Equation represents our confidence about our ability to decide if a signal is present or not.**
- **Details of the equation are derived using our knowledge of physics, signal processing and statistical decision theory.**
- **The Sonar Equation, in its simplest form, is:**

$$\frac{\textbf{Signal Power}}{\textbf{Noise Power}} \quad \begin{matrix} \rangle \\ \langle \end{matrix} \quad \textbf{Decision Threshold}$$

Decibels

- **Sound power per unit area in an acoustic wave is sound intensity.**
- **For progressive plane waves, sound intensity is proportional to the square of sound pressure.**
- **Sound power is often expressed in decibels, and is always given in relation to some reference. So a signal level ("sound pressure level"), in dB, is related to the signal pressure:**

$$S = 20 * \log_{10}(\text{Signal Pressure}/\text{Reference Pressure})$$

- **The reference pressure most often used in underwater acoustics is 1 micro Pascal.**

The Sonar Equation (Cont’d)

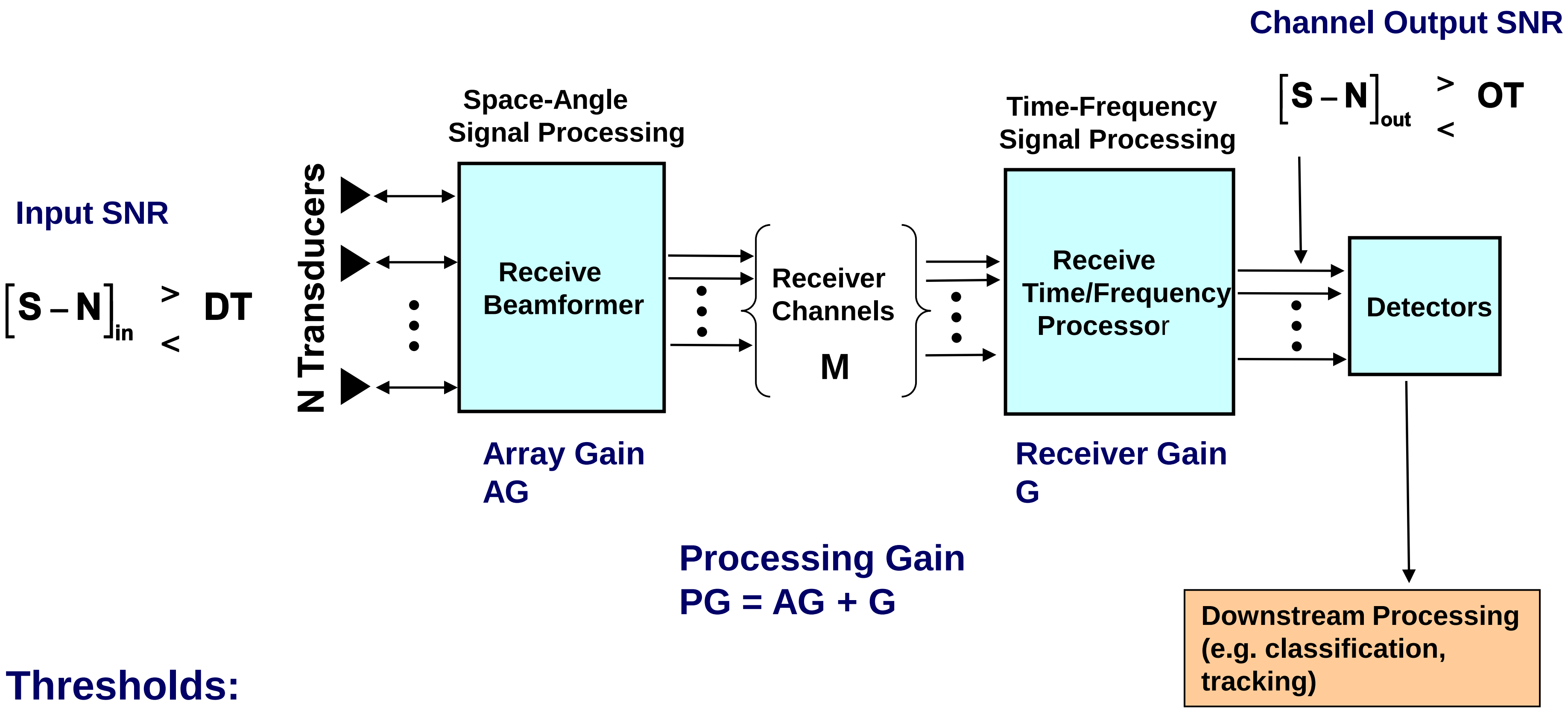
- Signal-to-Noise ratio SNR is sometimes referred to the input to the sonar system (i.e. “in the water”).
- The sonar equation is usually expressed in decibels as a difference:

$$[S - N]_{in} - DT \gtrless 0$$

"Signal Excess"

- In the above,
  - $[S – N]_{in}$ is the signal to noise ratio, expressed in dB, at the input to the sonar system.
  - DT is called the input Detection Threshold.
- The sonar equation can also be written relative to the receiver output at the point where a detection decision is made.

Sonar Signal Processing Gain



Channel Output SNR

$[S-N]_{out} \gtrless OT$

Input SNR

$[S-N]_{in} \gtrless DT$

N Transducers

Space-Angle Signal Processing

Receive Beamformer

Receiver Channels

M

Time-Frequency Signal Processing

Receive Time/Frequency Processor

Detectors

Array Gain
AG

Receiver Gain
G

Downstream Processing (e.g. classification, tracking)

Processing Gain
PG = AG + G

Thresholds:
DT = Input Detection Threshold
OT = Receiver Output Threshold
OT = DT + PG

Sonar System Gains and Losses

- An active sonar transmits sound, or a passive source radiates sound, at a given source level.
- Sonar equation usually expressed in terms of SNR at some point internal to sonar system (beamformer output or receiver input).
- In analyzing the radiated or reflected sound, gains and losses intrinsic to the sonar system must be accounted for:
- Losses may include
  - Transmit and receive beam pointing errors’ effects on signal
  - Signal processing losses (“mismatches” of all kinds)
- Gains may include
  - Beamforming reduction of noise (“array gain”)
  - Receiver signal processing gain

The Sonar Equation (Cont'd)

- With

Receiver Output Threshold (OT) = Input DetectionThreshold (DT) + Sonar Processing Gain (PG)

  - OT depends on desired statistical reliability of receiver and its design characteristics.
  - PG generally depends on the sonar array characteristics, the characteristics of the particular signal being received, and the type of noise that predominates.

- The Sonar Equation at the receiver output becomes

$$[S - N]_{out} - OT \gtrless 0$$

where

$$[S - N]_{out} = [S - N]_{in} + PG$$

Sonar Equations (Continued)

- **Active Sonar:**

  $S = TL - (20*\log_{10}(R) + \alpha*R) + TS - (20*\log_{10}(R) + \alpha*R)$

  $= TL - (40*\log_{10}(R) + 2*\alpha*R) + TS$

  where TL = transmitted level;

  TS = target strength;

  α = absorption loss coefficient

  $N = 20*\log_{10}(N_{ambient} + N_{reverb} + N_{self} + N_{target})$

- **Passive Sonar:**

  $S = SL - (20*\log_{10}(R) + \alpha*R)$

  where SL = radiated level of passive source

  $N = 20*\log_{10}(N_{ambient} + N_{self})$

Signal Sources

- **Active:**
  - Received signal is an attenuated and distorted version (echo) of the transmitted signal
  - “False targets” and reverberation are echoes of the transmitted signal off of discrete and distributed environmental reflectors
- **Passive**
  - Sound radiated from a target can be from machinery, flow noise, target sonar, and other sources

Attenuation

- **Sound is attenuated by spreading and absorption**
  - **Sound spreads out geometrically from its source and again upon reflection**
  - **Absorption in salt water is frequency dependent.**
    - **Higher frequencies suffer greater absorption loss.**
    - **Absorption loss is negligible in fresh water**
- **Active sonar suffers a two-way attenuation loss**

Noise Sources: Ambient

- **Ambient noise is the noise that exists in a particular part of the water irrespective of the presence of the sonar or the target**
- **Sources:**
  - **Thermal**
  - **Biological**
  - **Noise from the surface: wind, waves, rain**
  - **Shipping**
- **Ambient noise is location, depth, wind speed, and frequency dependent**
- **Simplest ambient noise model is isotropic; real ambient noise is often direction dependent**

Noise Sources: Reverberation

- Reverberation is the echo of the transmitted signal off of the environment:
  - boundaries – surface and bottom reverberation
  - scatterers in the water – volume reverberation
- Reverberation is directly proportional to signal energy and duration.
- Reverberation varies as $20*\log(r) + 2\alpha r$ (volume); $30*\log(r) + 2\alpha r$ (boundary)
- Due to scatterer motion, spectrum of reverberation is spread in relation to signal spectrum

Noise Sources: Self Noise

- **Self Noise is the noise that the sonar and its vehicle make**
- **Sources:**
  - **Electrical – usually the lowest noise in the system**
  - **Machinery – may be coherent from channel to channel**
  - **Flow through the water – incoherent from channel to channel**
- **Flow noise is usually the dominant source of self noise for a moving sonar system**
- **Flow noise varies as 70*log(v/v_{ref}) (where v is the sonar platform's velocity and v_{ref} is a reference velocity)**

Noise Sources: Target Radiated Noise

- **Target radiated noise can interfere with active reception. Is often the means of detecting a target passively**
- **Noise varies widely in strength with source type**
- **Noise can have a wide variety of spectral shapes**
- **Noise varies as 20*log(r) +** α**r**

Target Echo

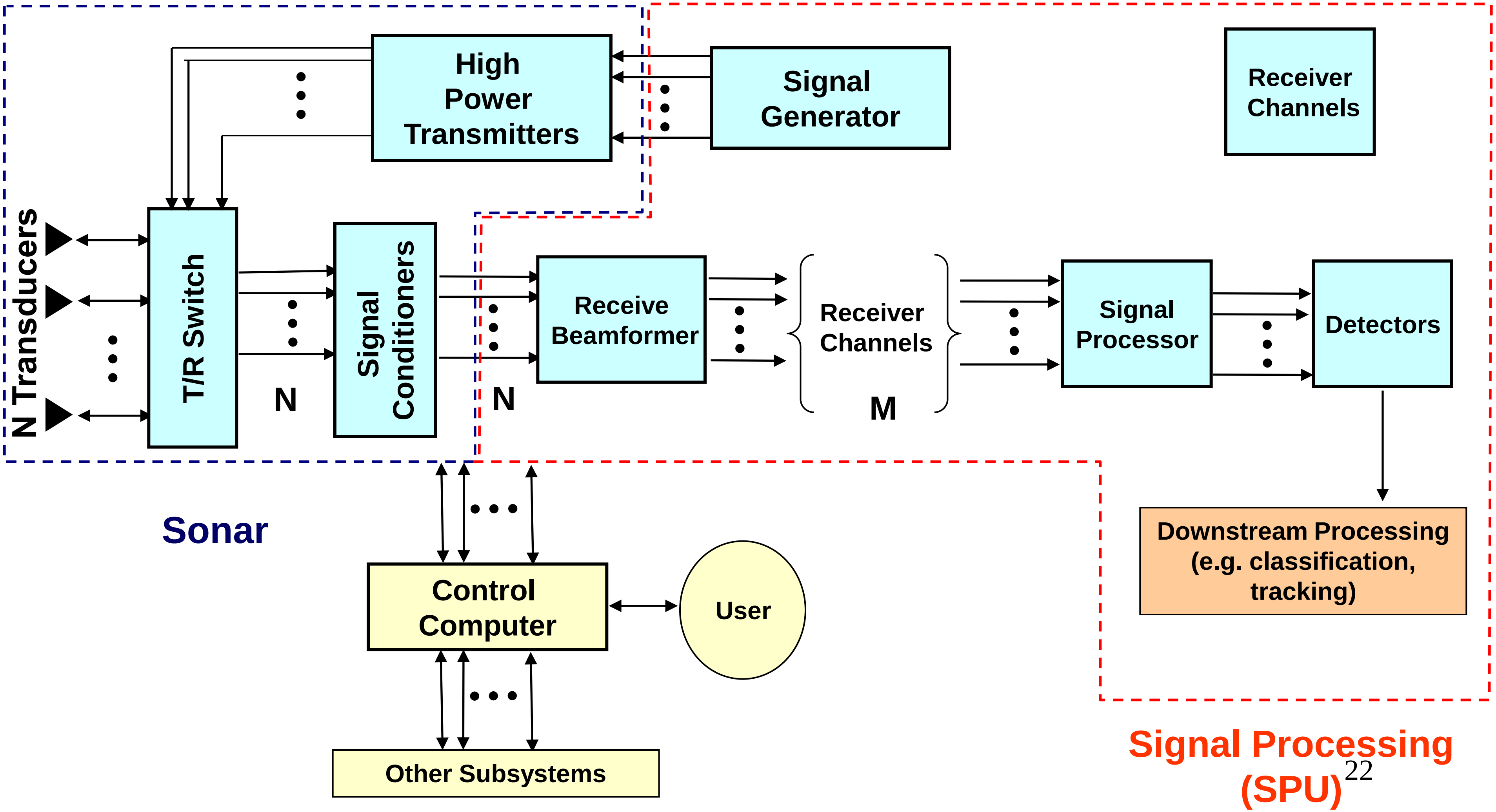
- **The target reflects a replica of the transmitted signal**
- **The echo level is proportional to the transmitted source level.**
- **The proportionality “constant” is target strength (TS), a complex measure of the sound reflecting attributes of the target.**
- **Target echo varies as 40*log(r) + 2αr**
- **Target echo spectrum of a moving target is doppler shifted relative to transmitted signal**

Sonar System Block Diagram

Sonar System

- **A sonar system may be part of a larger system, say an autonomous vehicle, with other subsystems (autopilot, propulsion, etc.)**
- **Sonar systems can contain both a transmitter and receiver, sometimes using the same transducer hardware.**
- **Often broken down into units of the sonar hardware itself, and a signal processing unit (SPU).**

Sonar System Block Diagram



Control Computer

- Maintains control of all sonar subsystems
- Works in concert with other subsystems, e.g. tactical, autopilot, propulsion
- Receives and executes commands from the user. These “commands” may be a suite of programmed behaviors for autonomous vehicles.

Transducers

- Interface between the ocean and the sonar electronics
- Converts sound to electrical impulses and vice-versa
- Can be a linear, planar, or volumetric array
- Transducer functions:
  - Transmit
  - Receive
- Many transducers perform both functions

Transducer Transmit Properties

- **Converts electrical signals to acoustic signals**
  - **Response given as:**

    pressure at a distance for a given voltage or current drive

    dB re 1uPa @ 1m re 1 volt. Generally a function of frequency
- **Requirements/Considerations:**
  - **High power → low impedance**
  - **High efficiency**
  - **Amplitude and phase matched and stable for use in arrays**
  - **Low 'Q' for wideband operation**

Transducer Receive Properties

- **Converts acoustic signals to electrical signals**
  - **Response given as:**

    voltage out for a given pressure at the transducer

    dBv re 1uPa. Generally a function of frequency
- **Requirements/Considerations:**
  - **High sensitivity**
  - **Low noise**
  - **Amplitude and phase matched and stable for use in arrays**
  - **Low 'Q' for wideband operation**

Transmit/Receive (T/R) Switch

- Connects the transmitter to the transducer for active transmissions
- Receiver must be protected from the high transmit power
- T/R switch accomplishes this via switching and isolation circuitry
- Receiver can still be susceptible to transmitter noise coupling through T/R switch

Transmit: Signal Generator

- **Provides drive signals to the high power transmitter**
- **Controls:**
  - **Signal waveform generation**
    - **amplitude**
    - **phase (frequency)**
  - **Multiple transmit sequencing**
  - **Transmit beam shaping**
  - **Transmit beam steering**
  - **Own-Doppler nullification (ODN)**

Transmit: High Power Transmitters

- **Converts low level input signals to high power drive signals**
  - **Input from the signal generator**
  - **Output drives the transducer elements**
- **Considerations:**
  - **High power output**
  - **High efficiency**
  - **Variable load impedance when used in arrays**

Receive: Signal Conditioners

- Peak signal limiting
- Impedance matching
- Pre-amplification
- Band pass filtering

Receive Beamformer

- Combines conditioned transducer signals to form beams
- Each beam acts as a spatial filter
- Uses beam shading and beam steering to form beam sets
- Each receive beam processed in its own channel
- Typical beam types:
  - Multiple narrow detection beams
  - Sum-difference beams
  - Offset phase center beams

Receiver Channels

- Each receive beam has a receiver channel
- Receiver channel functions:
  - Band pass filtering
  - Gain control (historic progression in order of sophistication)
    - Fixed gain
    - Time varying gain
    - Automatic gain control
  - Detection processing within the angular space that defines that channel

Receive: Signal Processor

- Processes beam signals to enhance their signal to noise ratio (SNR)
- Matched filter processing
  - Active
  - Passive
- Performs target angle calculations

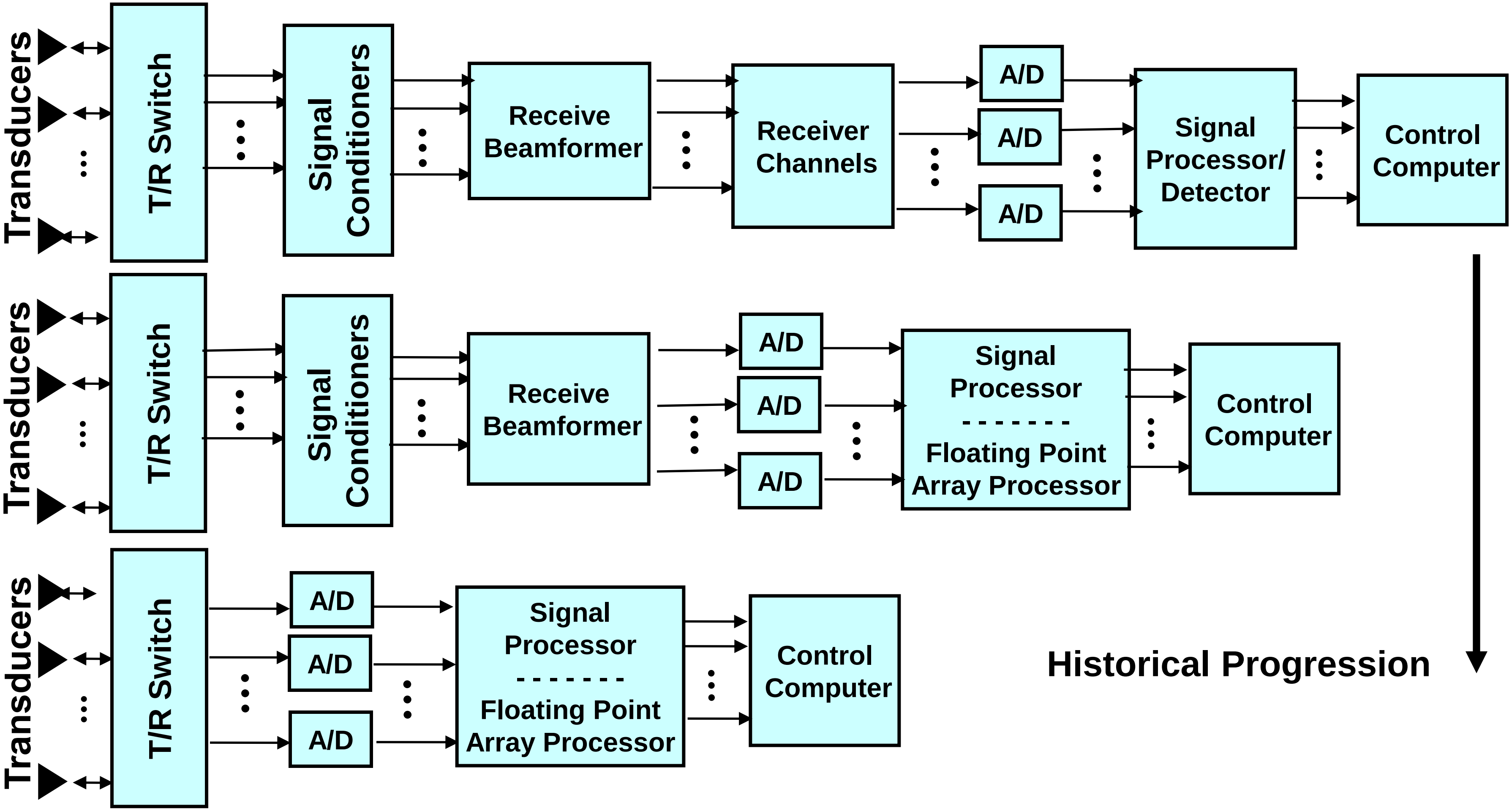
Receive: Detectors

- **Applies a threshold to the signal processor output signals**
- **Fixed threshold:**
  - **Constant probability of detection (CPOD)**
- **Variable threshold:**
  - **Constant false alarm rate (CFAR)**
    - **Requires background estimation**

Digital Receiver Goals

- Stable performance
- Flexible design
- Smaller size
- Lower cost
- Historical progression:
  - Replace analog receiver circuits with digital signal processor

Digital Receiver Configurations



A/D -> A/D Conversion

Digital Receiver Design Considerations

- Operating Frequency
  - Plays into beamwidth, coverage, absorption loss, detection range
- Receiver bandwidth
  - Trend today is wideband signals and receivers
- Dynamic range
  - Instantaneous (Size of A/D)
  - Long term (Gain adjustment over mission).
- Out-of-band signals

Downstream From Detectors

(Beyond Scope of This Course)

- **Clustering – Can the signal that passed the threshold be associated with detections from other channels?**
- **Classification – Does the clustered object have the characteristics of the type of target we are interested in?**
- **Data Fusion – Can the object be associated with a similar object from another sensor?**
- **Tracking – Does the object persist in time? Can we estimate its motion?**

Signal Representation

What Is A Signal?

- **A signal is a change or disturbance in the normal "background" environment that conveys information**
- **The disturbance can be electrical, optical, mechanical, acoustical, etc.**
- **The information is contained in the way the disturbance changes**
  - **with time**
  - **with frequency**
  - **in space**
  - **in direction**
- **Acoustical signals are disturbances in the background pressure level in the medium (air, water, etc.)**

Real and Complex Signals

- A real-valued function of time, f(t), or space, f(x), or both, f(x,t), is often called a “real signal”.
- It is sometimes useful for purposes of analysis to represent a signal as a complex valued function of space, time, or both:

$$s(t) = u(t) + i \cdot v(t)$$

- More often, such a function is written in polar form:

$$s(t) = R(t) \cdot e^{i\phi(t)}$$

$$\text{where}$$

$$R(t) = \sqrt{u^2(t) + v^2(t)} \qquad (\text{magnitude})$$

$$\phi(t) = \arctan\left(\frac{v(t)}{u(t)}\right) \qquad (\text{phase})$$

- The real-world signal f(t) represented by s(t) is just the real part of s(t):

$$f(t) = \Re\mathrm{e}\{s(t)\} = u(t) = R(t)\cos(\phi(t))$$

What Is Signal Processing?

- **Signal processing is altering the properties of a signal to achieve some effect. In sonar, signal processing generally done to enhance the signal-to-noise ratio in order increase the probability of detection of a target, or to continue detecting a target.**
- **Signal processing can be done on the temporally or spatially varying signal, or on its *spectrum* (see the following).**
- **Most modern signal processing is done digitally. A time signal is sampled and converted to a set of numbers using an analog-to-digital (A/D) converter. Signal processing is then done by mathematical operations on the set of numbers.**

Spectral (Fourier) Analysis

- **Any signal, real or complex, that varies with time can be "broken up into its spectrum" in a way similar to that in which light breaks up into its constituent colors by a prism**
- **The mathematical operation by which this is accomplished is the *Fourier transform***
- **The Fourier transform of a time signal yields the "frequency content" of a signal**
- **Much signal processing is done in the "frequency domain" by means of mathematical operations (filters) on the Fourier transforms of the signals of interest**
- **The result of the processing can be converted back to a filtered time signal by means of the *inverse Fourier transform***

Frequency Domain Signal Processing

- Frequency domain signal processing, or “filtering” alters the frequency spectrum of a time signal to achieve a desired result.
- Examples of filters: band pass, band stop, low pass, high pass, “coloring”,
- Analog filters are electrical devices that work directly on the time signal and shape its spectrum electronically.
- Most filtering nowadays is done digitally. The spectrum of a sampled, digitized time signal is calculated using the Fast Fourier Transform (FFT). The FFT is a sampled version of the signal’s spectrum. Mathematical operations are performed on the sampled spectrum.
- Samples of the filtered signal are recovered using the inverse FFT.

Beamforming

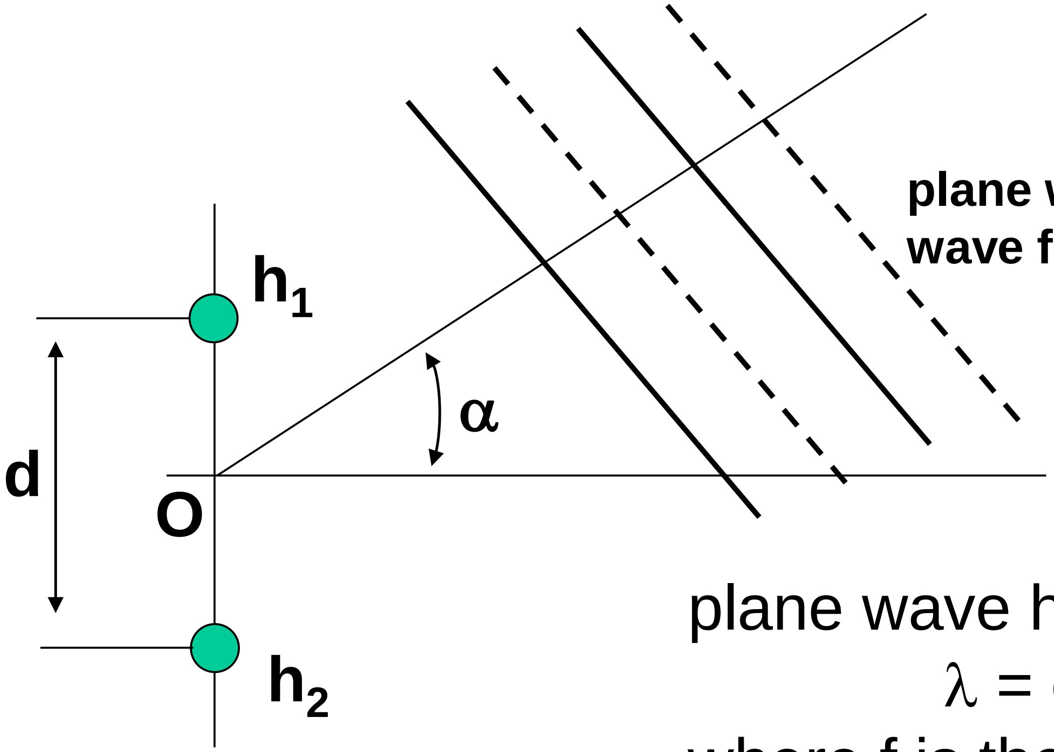
What Is Beamforming?

- **Beamforming is spatial filtering, a means of transmitting or receiving sound preferentially in some directions over others.**
- **Beamforming is exactly analogous to frequency domain analysis of time signals.**
- **In time/frequency filtering, the frequency content of a time signal is revealed by its Fourier transform.**
- **In beamforming, the angular (directional) spectrum of a signal is revealed by Fourier analysis of the way sound excites different parts of the set of transducers.**
- **Beamforming can be accomplished physically (shaping and moving a transducer), electrically (analog delay circuitry), or mathematically (digital signal processing).**

Beamforming Requirements

- **Directivity – A beamformer is a spatial filter and can be used to increase the signal-to-noise ratio by blocking most of the noise outside the directions of interest.**
- **Side lobe control – No filter is ideal. Must balance main lobe directivity and side lobe levels, which are related.**
- **Beam steering – A beamformer can be electronically steered, with some degradation in performance.**
- **Beamformer pattern function is frequency dependent:**
  - **Main lobe narrows with increasing frequency**
  - **For beamformers made of discrete hydrophones, spatial aliasing (“grating lobes”) can occur when the the hydrophones are spaced a wavelength or greater apart.**

A Simple Beamformer



plane wave signal wave fronts

h_1 h_2 are two omnidirectional hydrophones spaced a distance d apart about the origin O

plane wave has wavelength

λ = c/f,

where f is the frequency

c is the speed of sound

Analysis of Simple Beamformer

- Given a signal incident at the center O of the array:

$$s(t) = R(t) \cdot e^{i\omega(t)}$$

- Then the signals at the two hydrophones are:

$$s_i(t) = R(t) \cdot e^{i\omega(t)} e^{i\phi_i(t)}$$

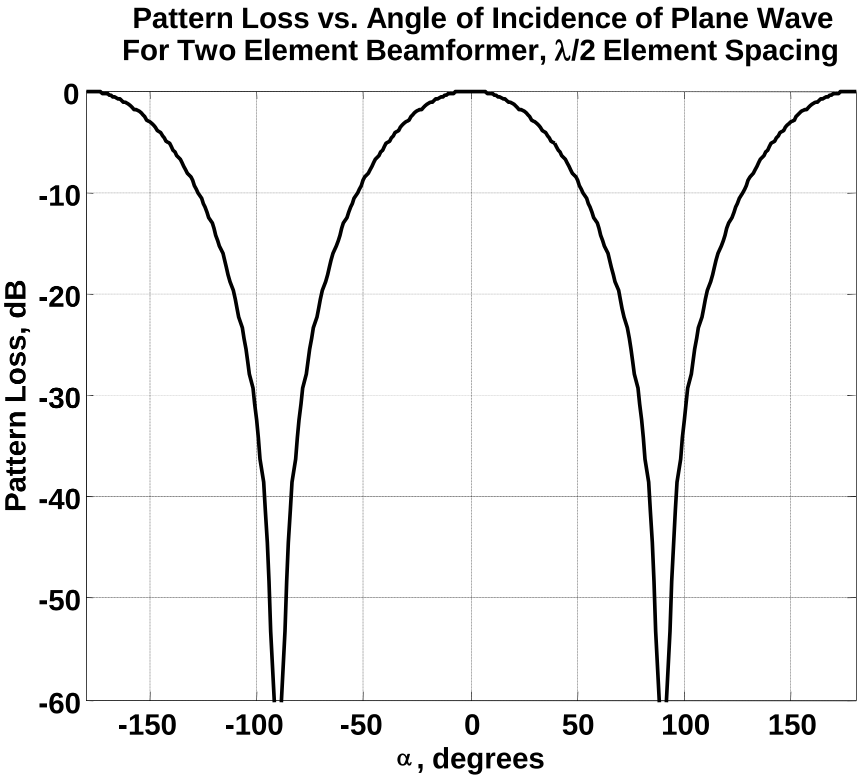
where

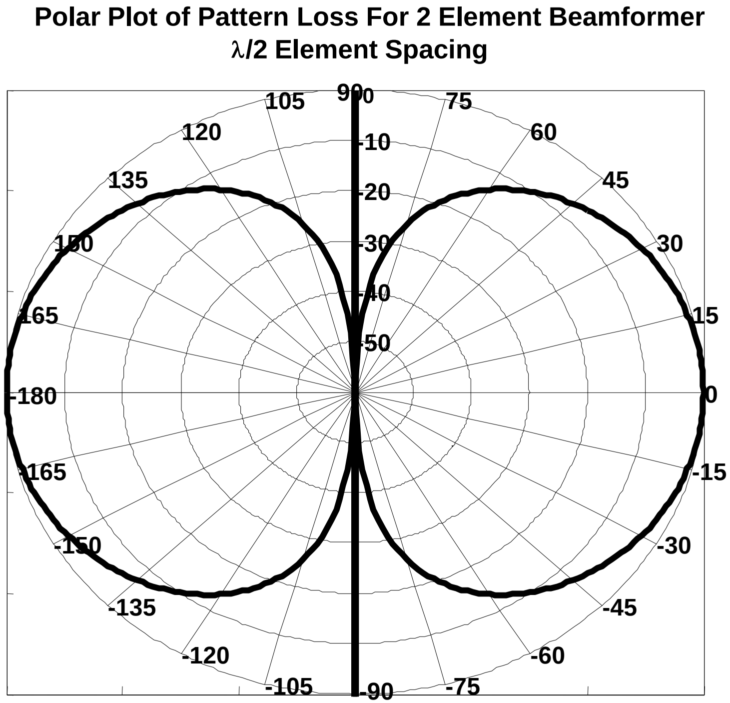
$$\phi_n = (-1)^n \frac{\pi d}{\lambda} \sin \alpha$$

- The pattern function of the dipole is the normalized response of the dipole as a function of angle:

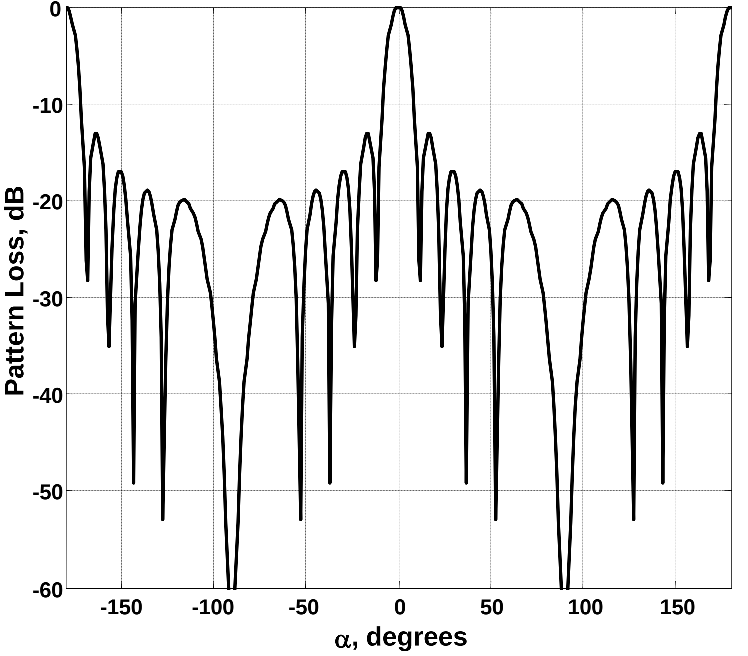
$$b(\alpha) = \frac{s_1 + s_2}{s} = \cos\left(\frac{\pi d}{\lambda} \sin \alpha\right)$$

Beam Pattern of Simple Beamformer

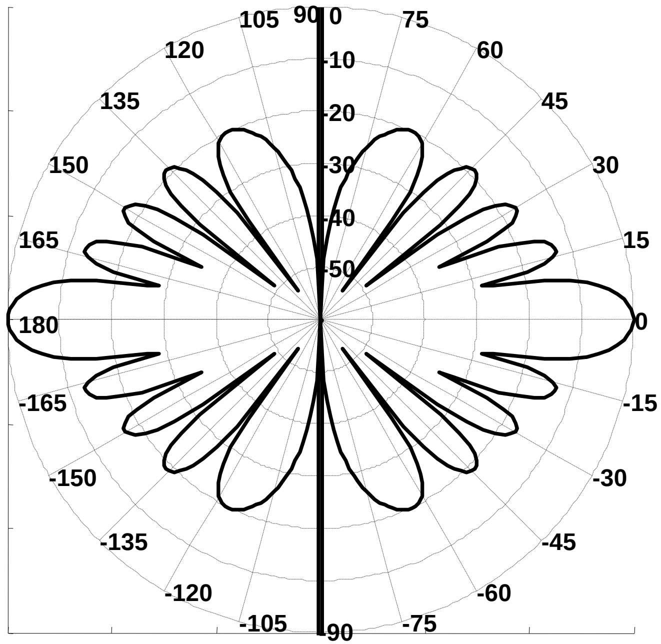




Beam Pattern of a 10 Element Array



Pattern Loss vs. Angle of Incidence of Plane Wave For Ten Element Beamformer, $\lambda/2$ Spacing



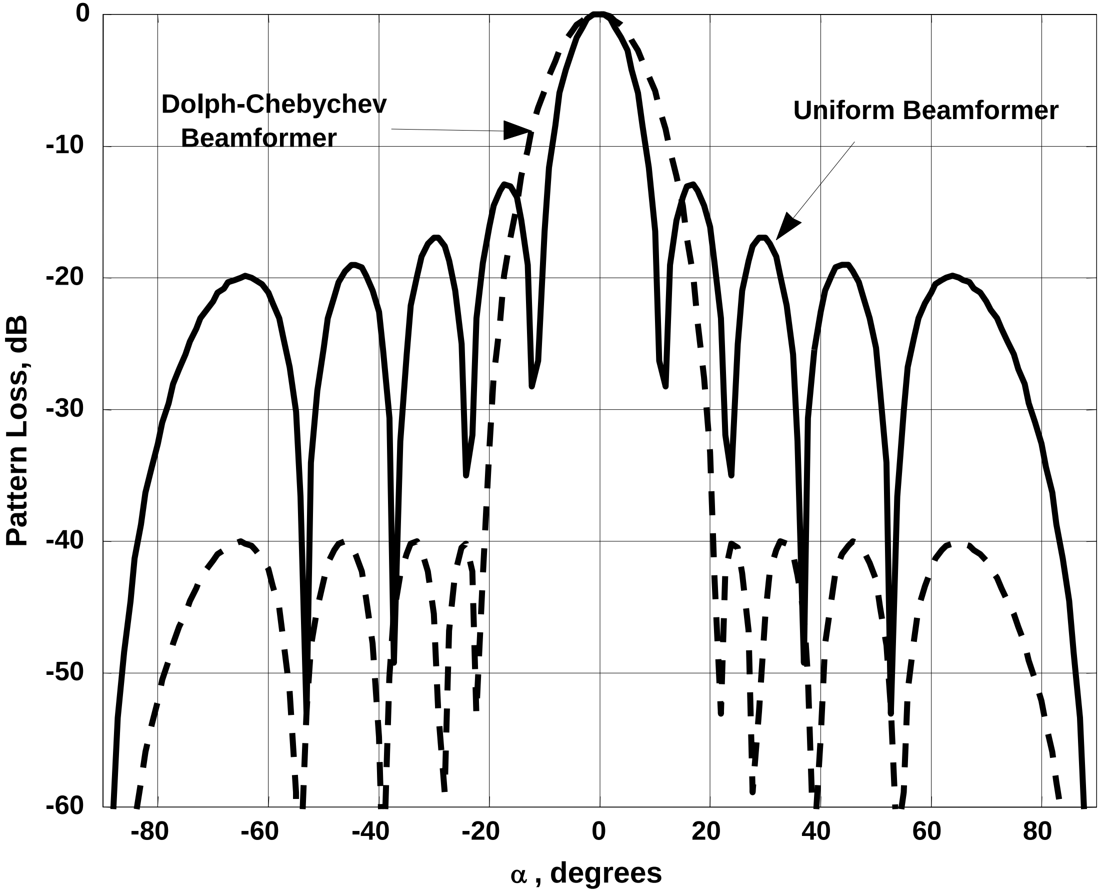
Polar Plot of Pattern Loss For 10 Element Beamformer $\lambda/2$ Spacing

Beamforming – Amplitude Shading

- **Amplitude shading is applied as a beamforming function, usually to the received signal.**
- **Each hydrophone signal is multiplied by a "shading weight"**
- **Effect on beam pattern:**
  - **Used to reduce side lobes**
  - **Results in main lobe broadening**

Beam Pattern of a 10 Element Dolph-Chebychev Shaded Array

Comparison Beam Pattern Of A 10 Element Dolph-Chebychev Beamformer With -40 dB Side Lobes And λ/2 Element Spacing With A Uniformly Weighted 10 Element Beamformer



Beamforming – Receive Beam Steering

- To electronically steer a beam to a specific angle, the hydrophone signals must add so that a plane wave received at the desired angle would add in-phase.
- Beam steering implementations:
  - Time delay
  - Phase shift

Beamforming – Transmit

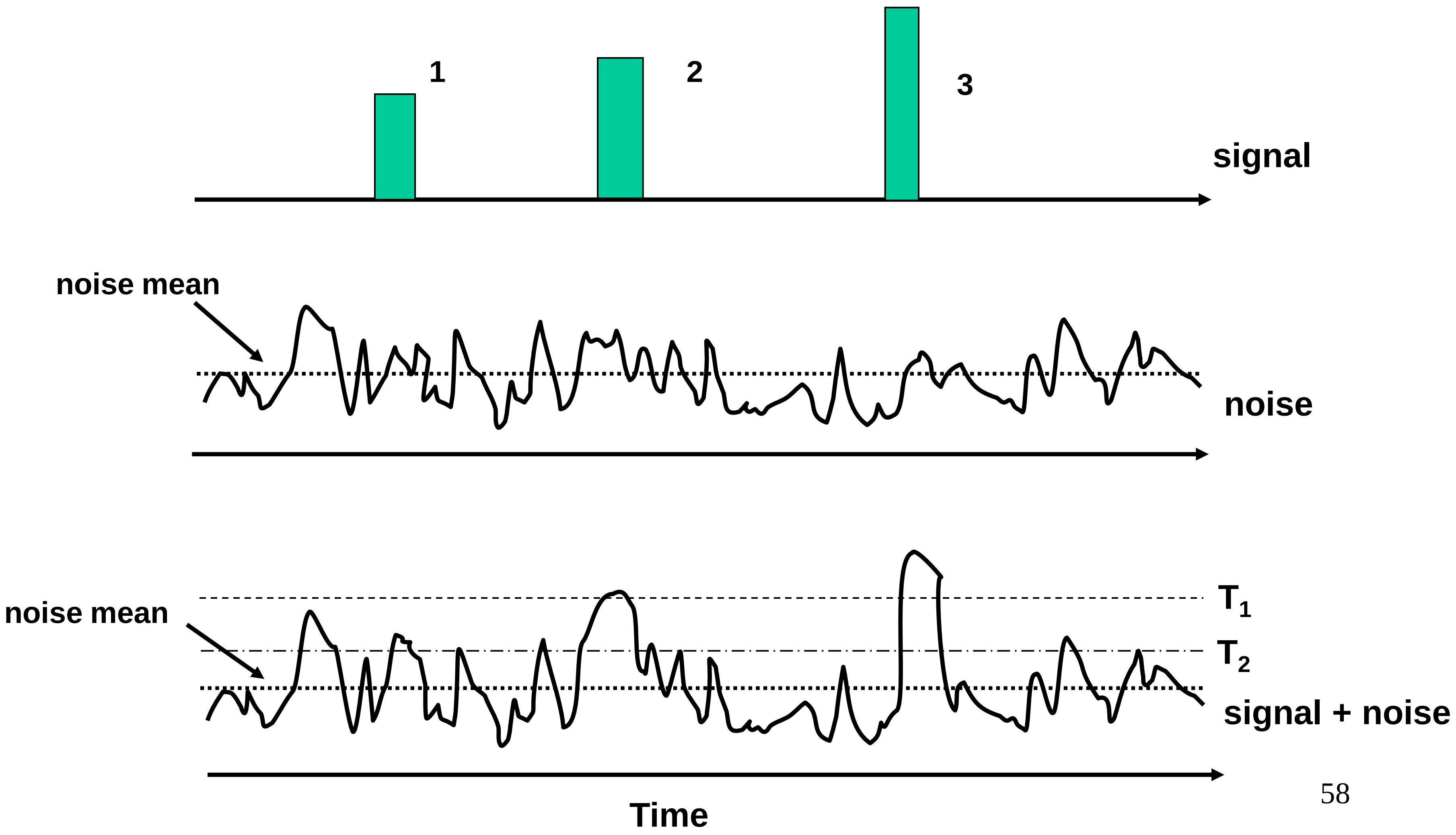
- **High power**
  - **Transmit the maximum power on each hydrophone**
  - **Maximum power limited by cavitation**
- **Desire broad beamwidth for search, narrow beamwidth for homing**
  - **Desire maximum output power for both types of transmits -> Generally do not use amplitude shading on transmit**
  - **Transmit beamforming accomplished by phase shading of transmit hydrophones**

Signal Detection

Signal Detection

- Input to detector is signal plus noise.
- Requirements expressed in terms of
  - probability of detection
  - probability of false alarm
- Threshold for declaring detection is set based on models for signal and noise
- Noise background estimation can be performed on data to improve model.
- Outputs of detector are threshold crossings
- Performance defined by receiver operating characteristic (ROC) curve – probability of detection vs. probability of false alarm for a particular SNR.

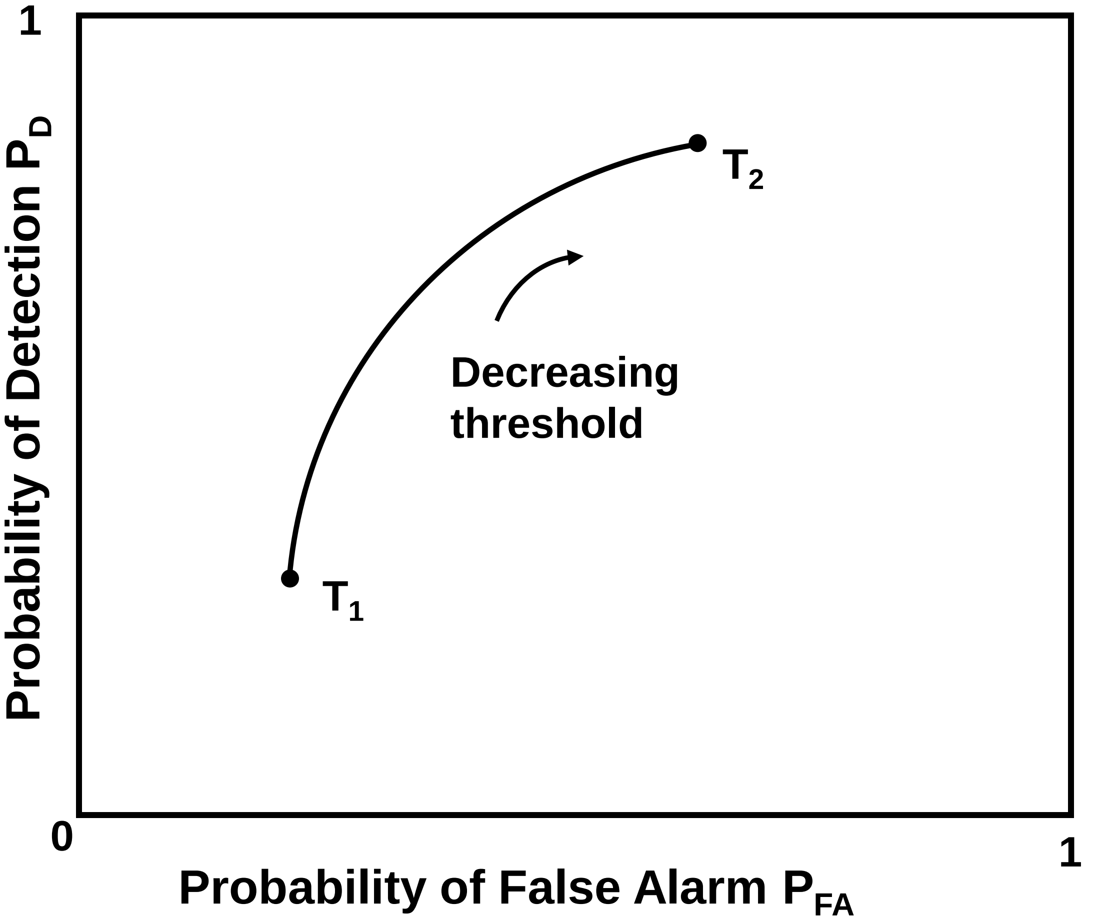
Detection In Noise



Detection Threshold

- Performance Criteria:
  - Probability of detection P_D
  - Probability of false alarm P_{FA}
- These criteria are not independent: a lower threshold increases P_D, but also increases P_{FA}.
- Theoretical ROC is used to set thresholds.
- True test is performance in water.

Receiver Operating Curve (ROC)



Noise Background Estimation

- **A moving average of the received signal is calculated. This average is used to estimate the background noise level.**
- **Against noise that changes rapidly with time – e.g. reverberation, noise level must be continually re-estimated for the entire listening interval. -> Use moving average.**
- **Care must be taken not to average over desired echo, but still get a useful average. Window is usually taken to be the length of the transmitted pulse.**
- **Higher order statistics can also be estimated this way.**

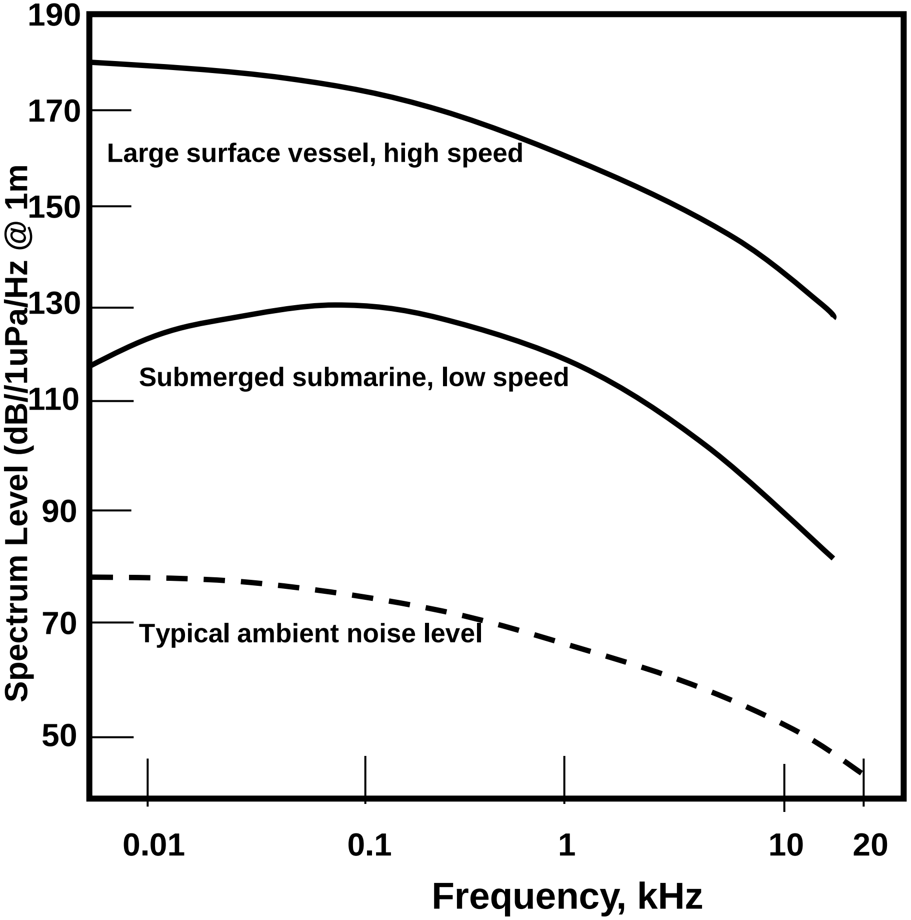
Passive Processing

Passive Processing Requirements

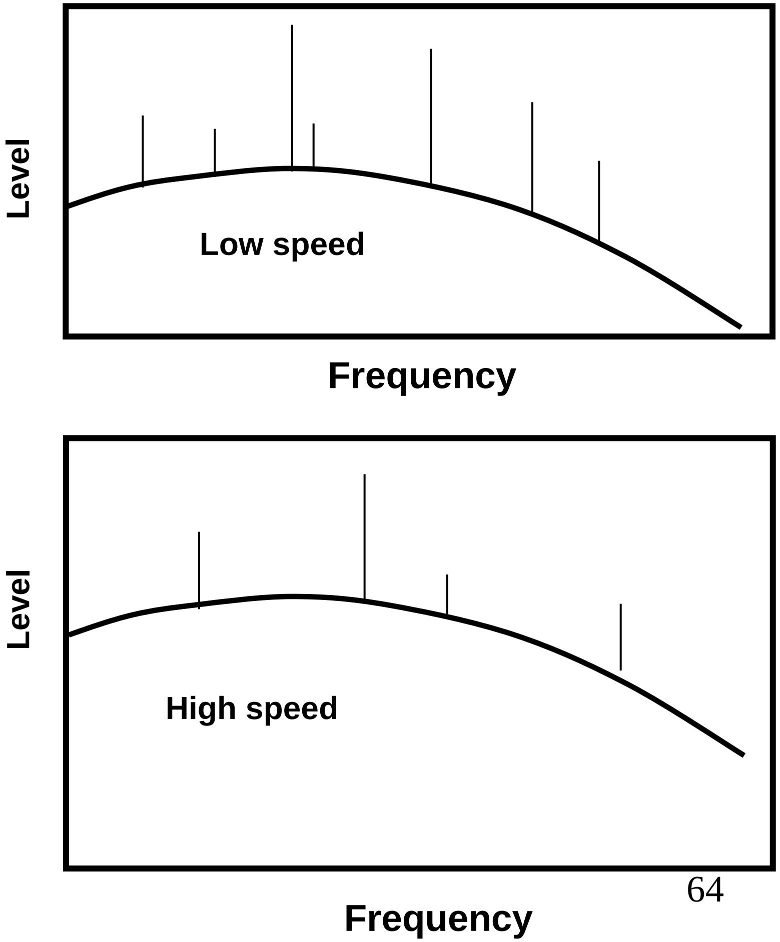
- **Targets:**
  - **Surface ships**
  - **Submarines**
  - **Other sources, e.g. pipeline leaks**
- **Target Characteristics:**
  - **Broad band**
    - **Level and spectrum dependent on target speed**
  - **Narrow band**
    - **Spectral lines**
      - **Propulsion system**
      - **Propeller cavitation**
      - **Auxiliary machinery**
  - **Spatially compact**

Target Emissions

Some Typical Spectrum Levels For Surface Ships and Submarines



Broadband and Narrowband Components Of a Submarine Signature at Low and High Speeds



Passive Sonar Requirements

- **Target Detection**
  - **Passive sonar has an advantage over active for detection range - less spreading and absorption loss.**
- **Target Localization**
  - **Angle to target**
  - **Precise localization, especially in range and velocity, is more difficult with passive sonar**
- **Target Characterization**
  - **Target signatures help identify target**
  - **Passive sonar won’t mistake a rock for a target**
  - **Active is much more useful for discerning size, shape and structural features**

Passive Sonar Capabilities

- Beamforming
  - Spatial filter
  - Increased signal-to-noise – directivity
  - Reduces unwanted (out of beam) signals
- Receiver
  - Bandpass filter – reduces out of band signals and noise
  - Gain adjust – adjust to receiver circuitry, does not increase SNR
- Signal processor
- Detector

Passive Multibeam

- **Increases detection capabilities**
  - **Wide angle coverage**
  - **Directivity of individual beams increase SNR**
  - **Detection processing**
    - **Beam power comparison among beams**
- **Localization**
  - **Provides bearing to target to within beam resolution**
- **Target identification if spectral processing is used.**

Passive Narrowband Signal Processing

- FFT (Spectral Processing)
  - Used to detect tones
  - Improves detection
  - Aids localization by estimating Doppler using frequency changes in the signal
- Can identify target if its signature is known

Passive Short Baseline Localization

- **Useful for small sonar arrays**
- **Technique – offset phase center beams**
  - **Uses the correlation between the inputs of two subarrays of a beamformer to estimate the angle to the target.**
  - **The subarrays are closely spaced – 3/2 λ or 1/2 λ are often used.**
  - **Useful for enhancing passive detection performance by allowing fine estimate of angle to detection.**

Passive Long Baseline Localization

- Useful for arrays of widely spaced hydrophones
- Technique – Correlation processing with variable time shift
  - Time shift with highest correlation gives time delay for reception between each hydrophone.
  - Useful for enhancing passive detection performance.
  - Can be used to estimate angle to target. Multiple hydrophones (3 or more) can be used to triangulate.

Active Processing

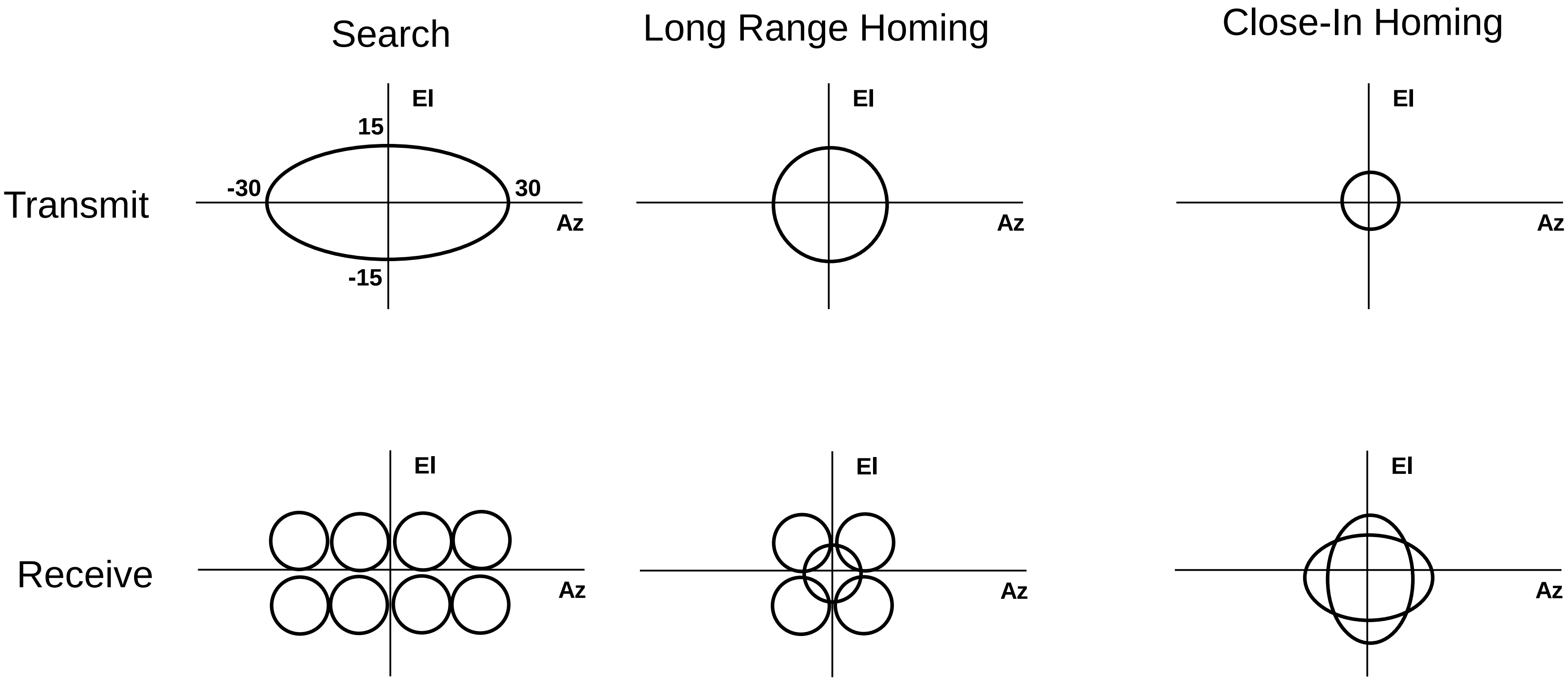
Active Sonar Requirements

- Target Detection
- Target Localization
  - Range
  - Angle
  - Doppler -> line-of-sight velocity
- Target Characterization
  - Size
  - Shape
  - Orientation
  - Finer details

Typical Active Beamformer Configurations

- Transmit
  - Wide angle – search volume coverage
  - Narrow angle – homing
  - Source level increases as beam narrows
- Receive
  - Search – Multiple narrow beams for high directivity
  - Homing – Narrow detection beam with offset phase beams

Active Sonar Beamsets



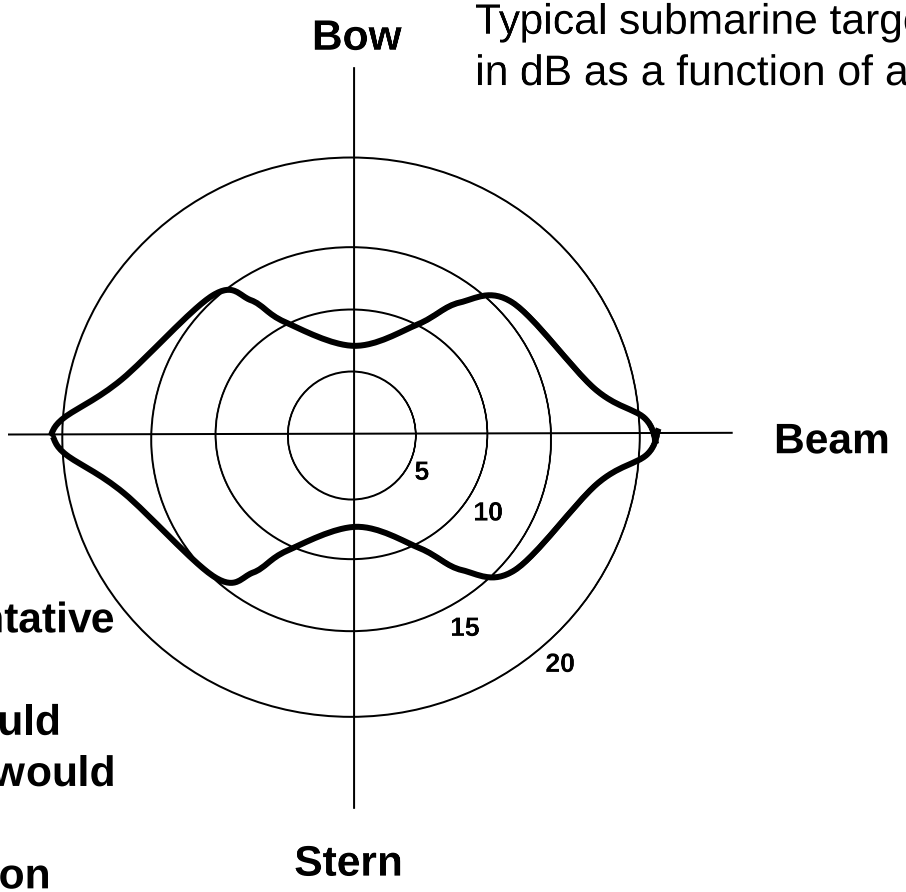
3 dB Beamformer Contours

Target Properties

- **After accounting for propagation losses, the target echo level is proportional to the transmitted source level**
- **The proportionality "constant" is the *target strength***
  - **Depends on sound reflecting properties of the target**
  - **Function of frequency, signal resolution, and aspect angle**
  - **Target highlights (echoes from reflecting surfaces) add with random phase.**

Variation of Target Strength

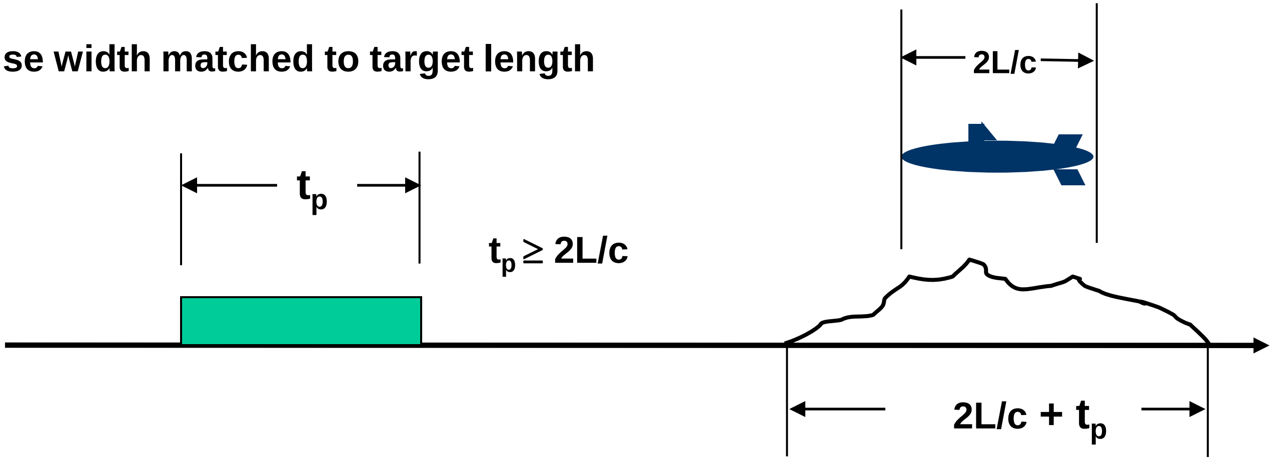
Typical submarine target strength in dB as a function of aspect angle



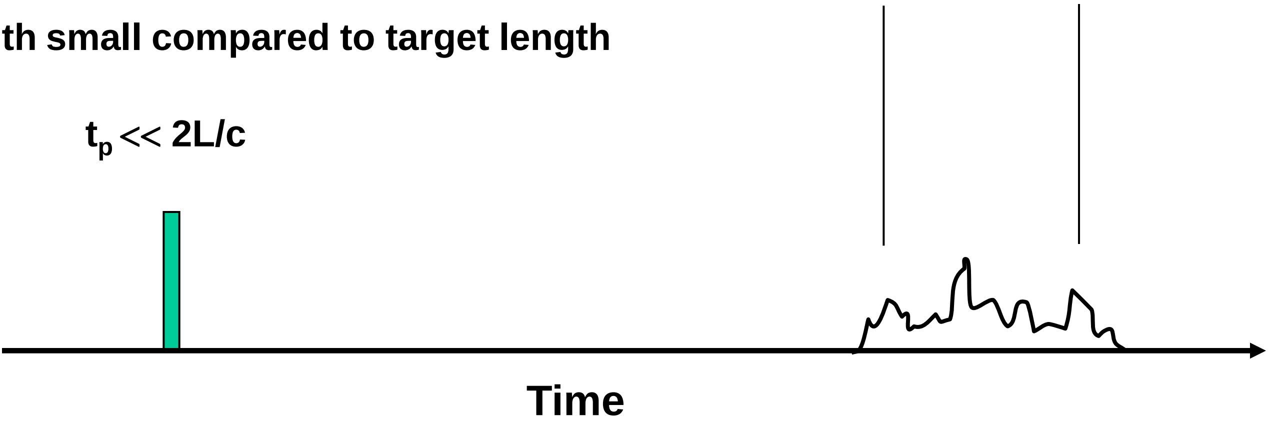
Notes:
- **TS is a function of frequency**
- **Graph at right is more representative of a low frequency**
- **High frequency graph of TS would have similar rough shape, but would have significantly more detail**
- **“Spikier” due to higher resolution of target features**

Target Echo and Signal Resolution

Pulse width matched to target length



Pulse width small compared to target length



Effect of Motion on Echo

- For stationary sonar and target:
  - Echo spectrum ≈ Signal spectrum
- For moving sonar or target, spectrum of echo is shifted and spread.
- Shift is “Doppler shift”. Doppler shift is due to:
  - Target motion
  - Sonar motion
- Doppler shift due to sonar motion can be somewhat negated by shifting the transmit or receive frequency to account for sonar motion – own-Doppler nullification (ODN).
- Spectral spreading is due to numerous factors, in particular the fact that different parts of the target move with different speeds relative to line-of-sight vector.

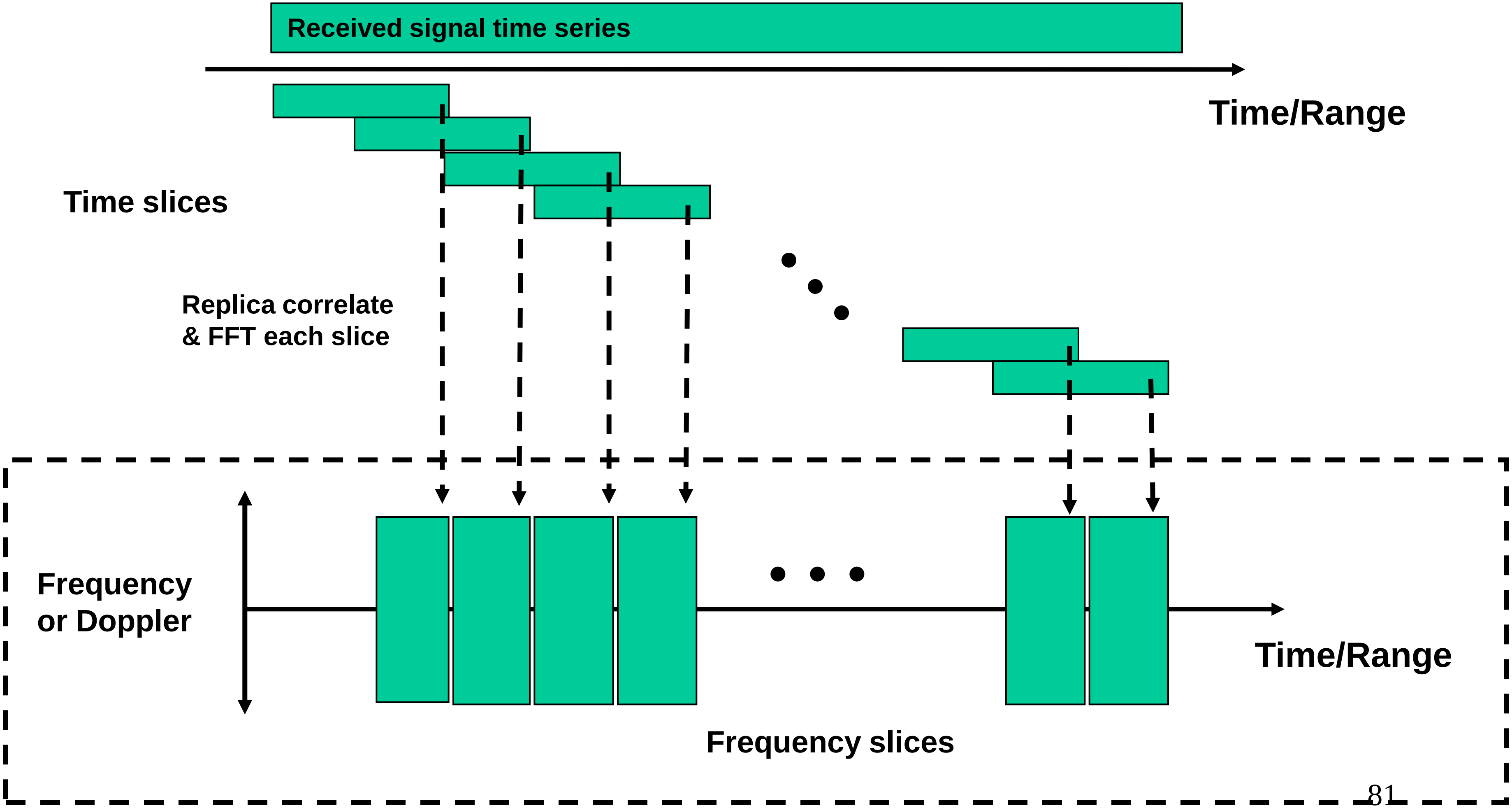
Effect of Reverberation

- For stationary conditions ("quiet sea"):
  - Reverberation spectrum ≈ Signal spectrum
- Spectrum of reverberation is more generally shifted and spread.
- Spectral shift and spreading is due to:
  - Scatterer motion
    - Surface reverb scatterer motion dependent on sea state
    - Volume reverb scatter motion depends, e.g., on presence of fish, suspended bubbles or solid material, currents, etc.
  - Sonar motion
    - Off-axis scattering

Active Detection Processing

- One of the most common active detectors is the matched filter.
  - Peak output SNR is optimized against additive white Gaussian noise with a matched filter.
- Can be implemented by correlating received signal with replica of transmitted signal at varying time shifts.
  - Time shift with peak output above threshold yields target range,
- To account for frequency (Doppler) shift in received signal due to target motion, the detector is usually implemented in the frequency domain – frequency shifted detections can be located on “Range-Doppler map.

Matched Filter Implementation



Received signal time series

Time/Range

Time slices

Replica correlate
& FFT each slice

Frequency
or Doppler

Time/Range

Frequency slices

Range-Doppler Map

Range-Doppler Maps

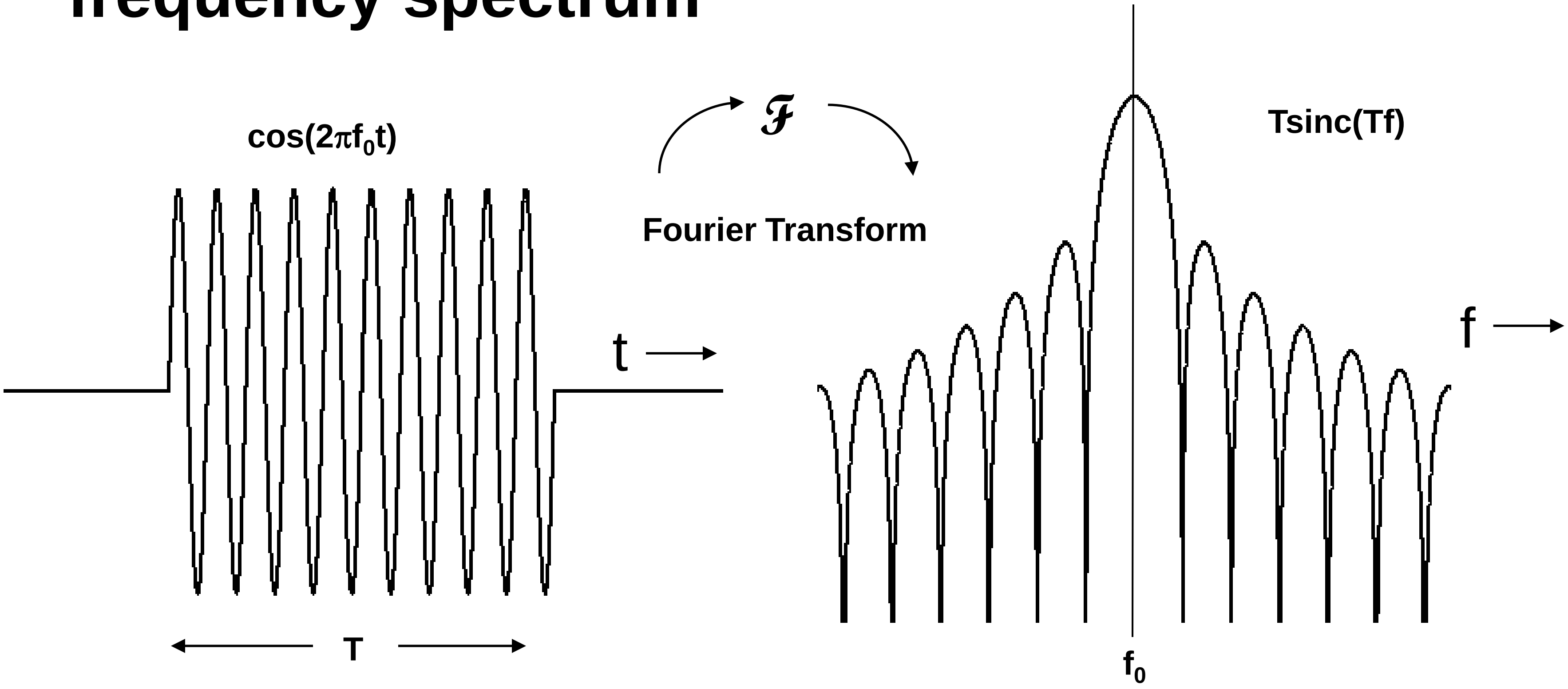
- **A Range-Doppler map is a representation of the power spectral level of an acoustic echo as a function of time.**
- **The time axis is usually converted to range, while the frequency axis is converted to equivalent Doppler shift.**
- **The resulting surface is reduced to a two dimensional plot for presentation using colors to represent level.**
- **The levels in each Range-Doppler cell can be processed to find detections.**

Effect of Reverberation (Continued)

- Reverberation is an echo of the transmitted signal.
- When ODN is used, the reverberation spectrum is centered at about the transmit frequency (zero frequency when basebanded).
- The spectrum continues as long as the reverberation can be detected. (“Reverb ridge”)
- Even though target echo level falls off faster than reverberation with range, targets off of the reverb ridge (high Doppler targets) can be detected at long range.
- Signal design for low Doppler targets attempts to mitigate effects of reverb ridge.

Example of Range Doppler Map

- **Unwindowed tone pulse has sinc-function frequency spectrum**

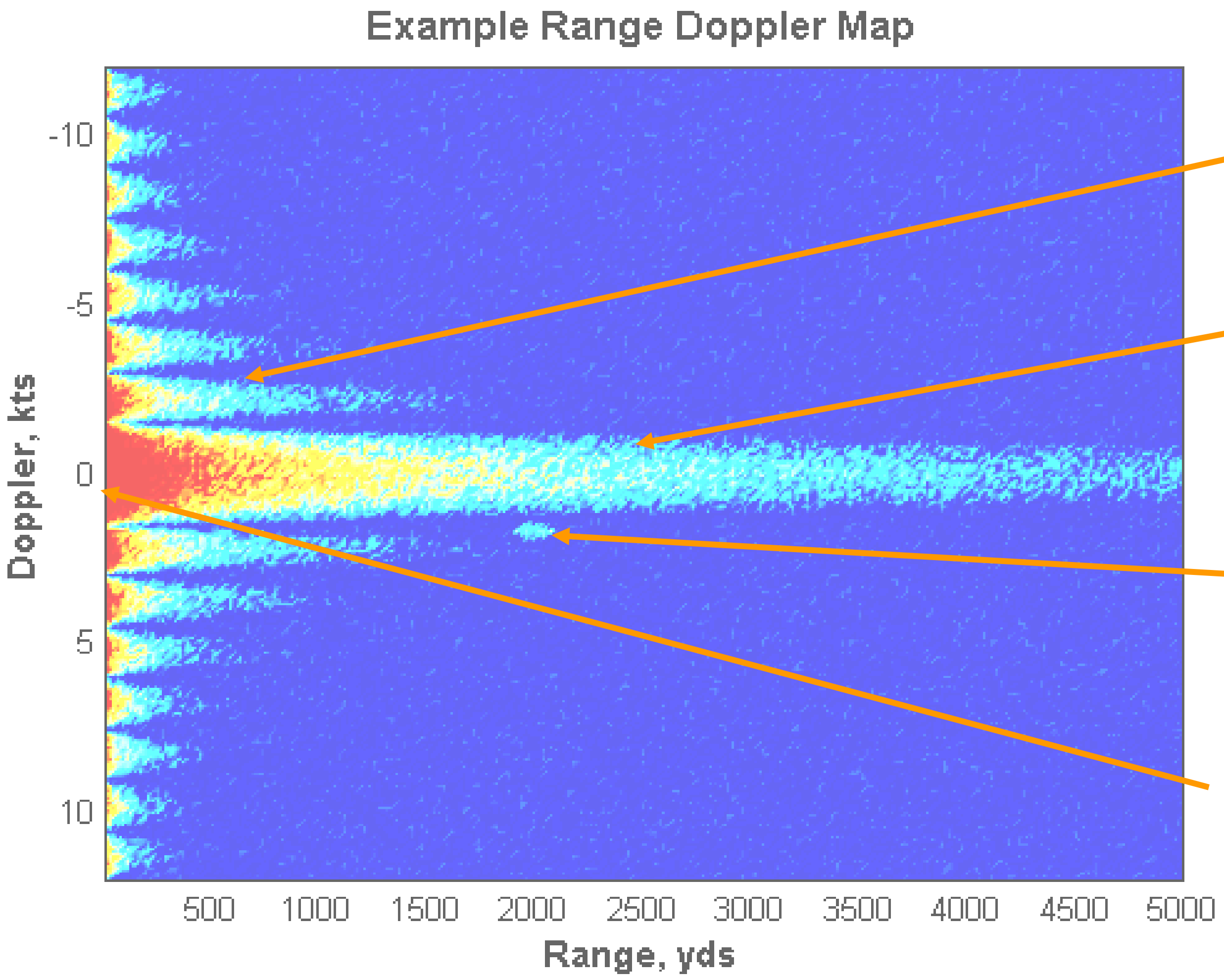


Tone pulse in time domain

Spectrum of tone pulse in frequency domain

Example Of A Range-Doppler Map

(Volume Reverberation, Stationary Sonar)



High sidelobes of unwindowed tone pulse

Reverberation ridge

Target detection: Would not have been detected if it had been moving slower.

Basebanding and ODN shifts spectrum to 0 Hz and eliminates sonar's motion

Signal Selection

- **Range resolution is inversely proportional to signal bandwidth.**
  - **For tone pulses, this translates to range resolution is proportional to pulse length:**
    - **Pulse bandwidth is inversely proportional to tone pulse duration, so**
    - **Short pulses => Short (“high”) range resolution**
  - **For linear FM sweeps, range resolution is inversely proportional to width of sweep.**
    - **Wide frequency sweep => Short (“high”) range resolution**
- **Doppler resolution is inversely proportional to pulse length.**
    - **Short pulse duration => Wide (“low”) Doppler resolution**

High Doppler Targets

- **Tone pulses can be good choices for high Doppler targets:**
  - **Target is out of the reverberation ridge**
  - **Longer pulses used for detection have excellent Doppler resolution**
  - **Short pulses used for close-in homing have excellent range resolution.**
- **Drawbacks:**
  - **Targets that are changing aspect can be lost in reverberation ridge**
  - **As sonar closes in on target, short pulses are used. Reverberation spectrum is very wide for short pulses. Can loose even high Doppler targets**

Low Doppler Targets

- Processing gains can be attained against low Doppler targets by using linear sweep FM pulses.
- Advantages: spreads (and hence lowers) reverberation power over bandwidth of frequency sweep, but coherently processes echo => Processing gain ~ 10·log(TW), where T is pulse length and W is signal bandwidth
- Drawbacks:
  - Increasing T to increase PG is not viable when target is very close or target position is changing rapidly. But short T means less Doppler resolution.