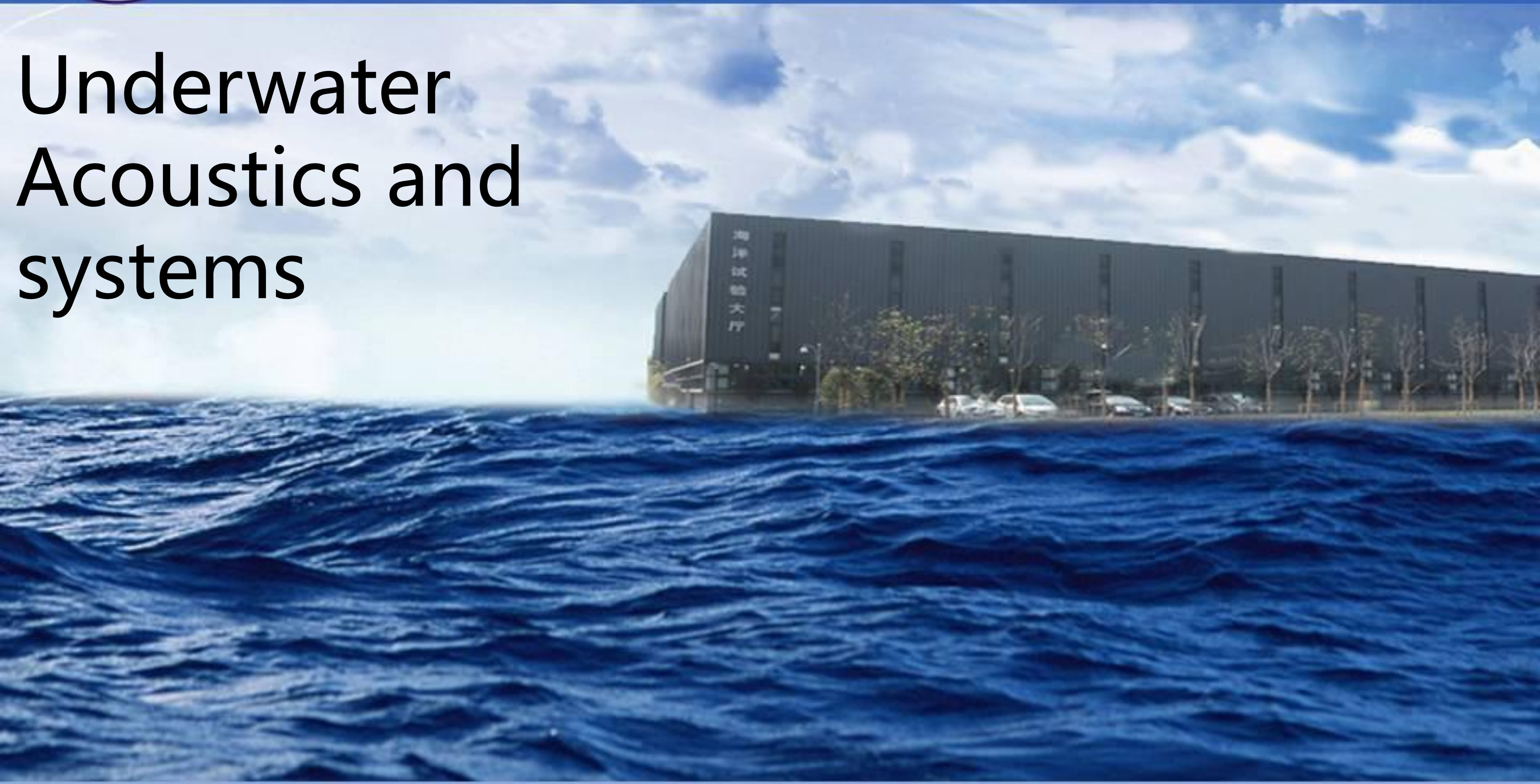
浙江大学 海洋学院
Ocean College,Zhejiang University



Underwater Acoustics and systems

Acoustic Signal Processing -- System Perspectives

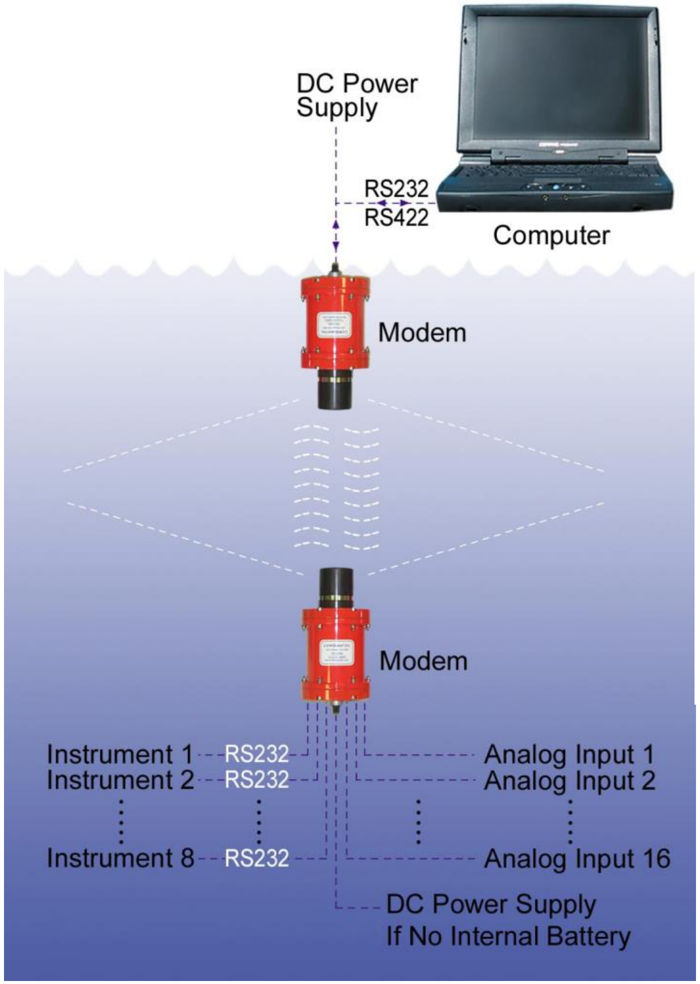
There are many kinds of instruments deployed underwater for communication, localization, detection and imaging.

Most of such applications use acoustics rather than RF signal.

Including:

1. Underwater communication
2. Underwater Localization
3. SONAR
4. Multi-beam / Single beam SONAR
5. Side-scan SONAR
6. ABS (Acoustic Backscatter System)
7. ADCP (Acoustic Doppler Current Profiler) / DVL (Doppler Velocity Log)

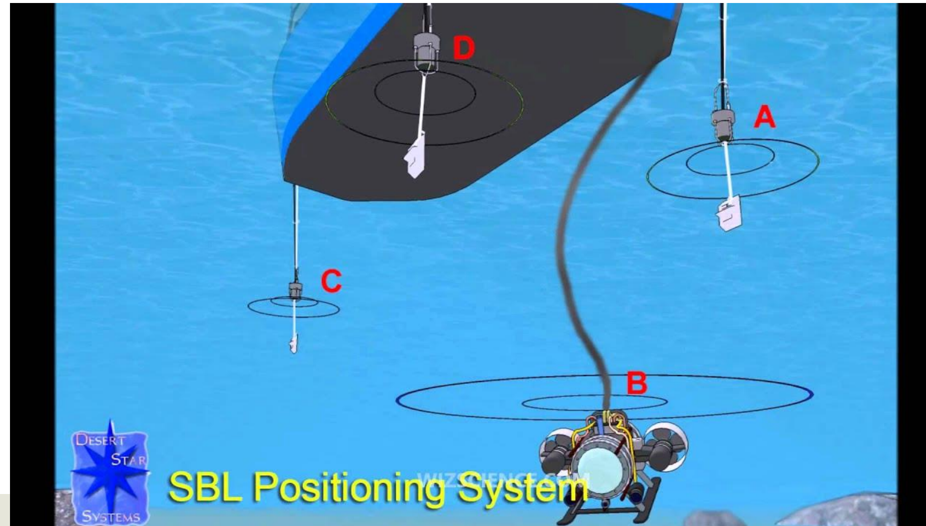
Underwater Communication

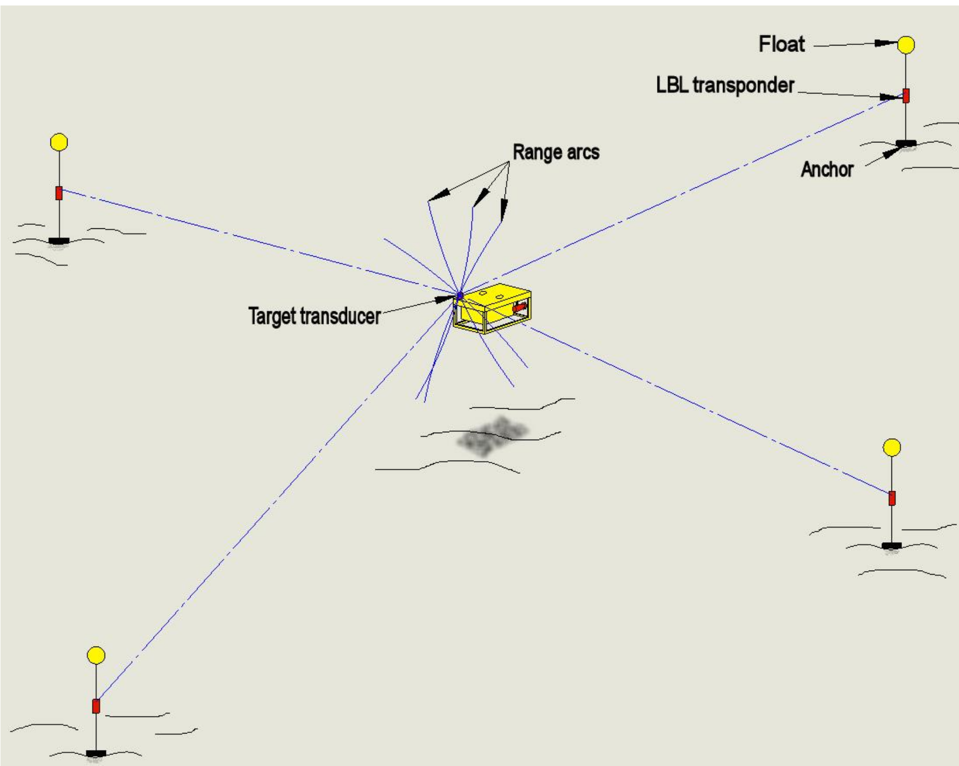


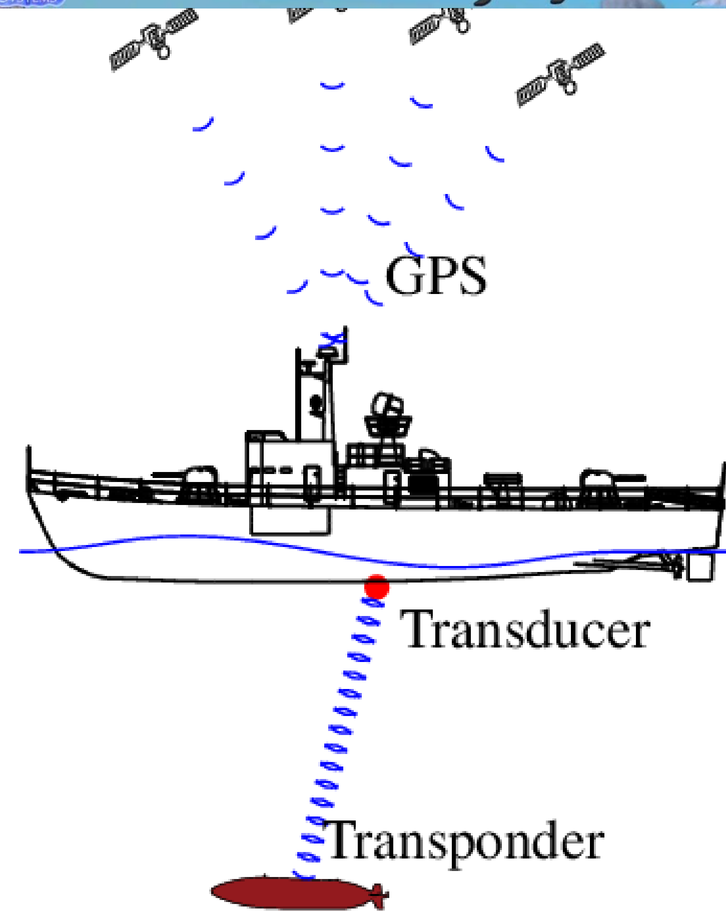
Underwater Communication Modem

Underwater Localization

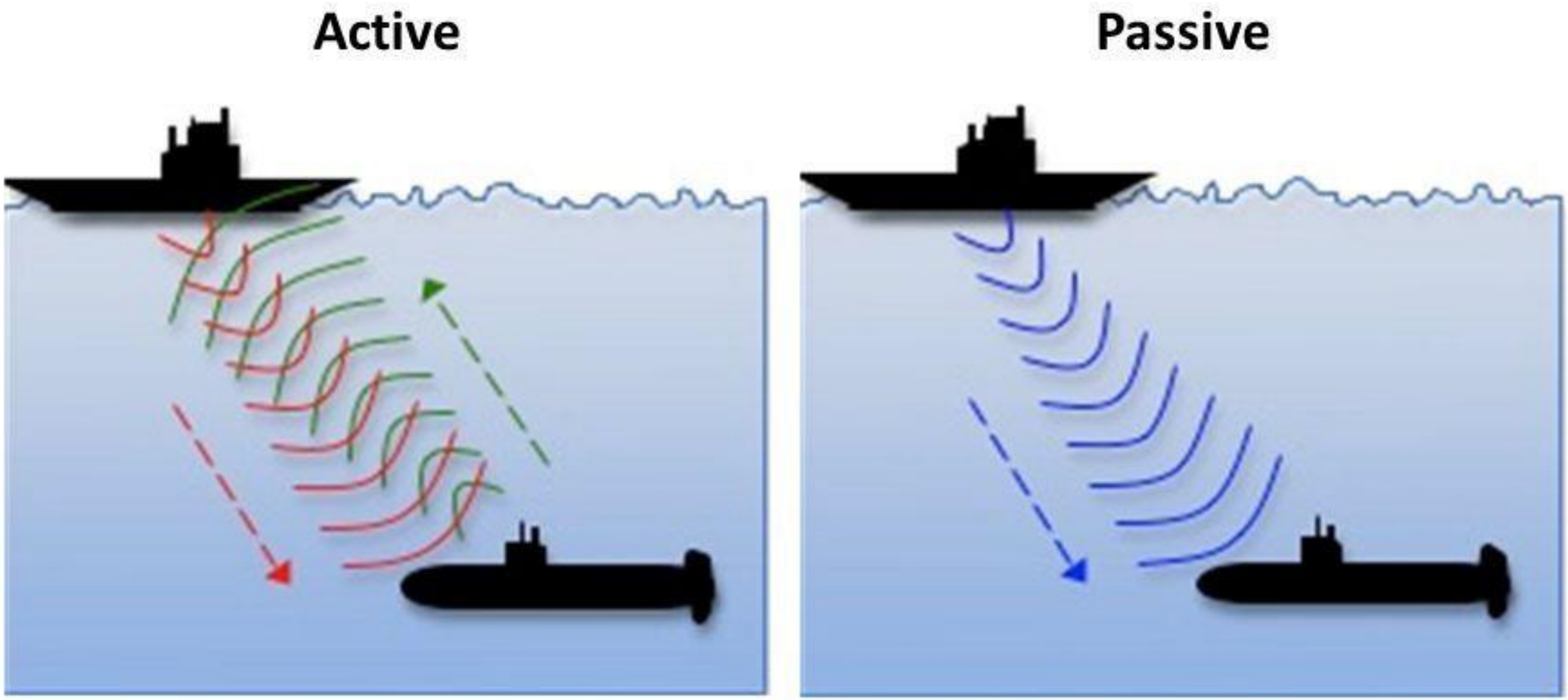
1. LBL (Long Base Line)
2. SBL(Short Base Line)
3. USBL (Ultra-Short Base Line)



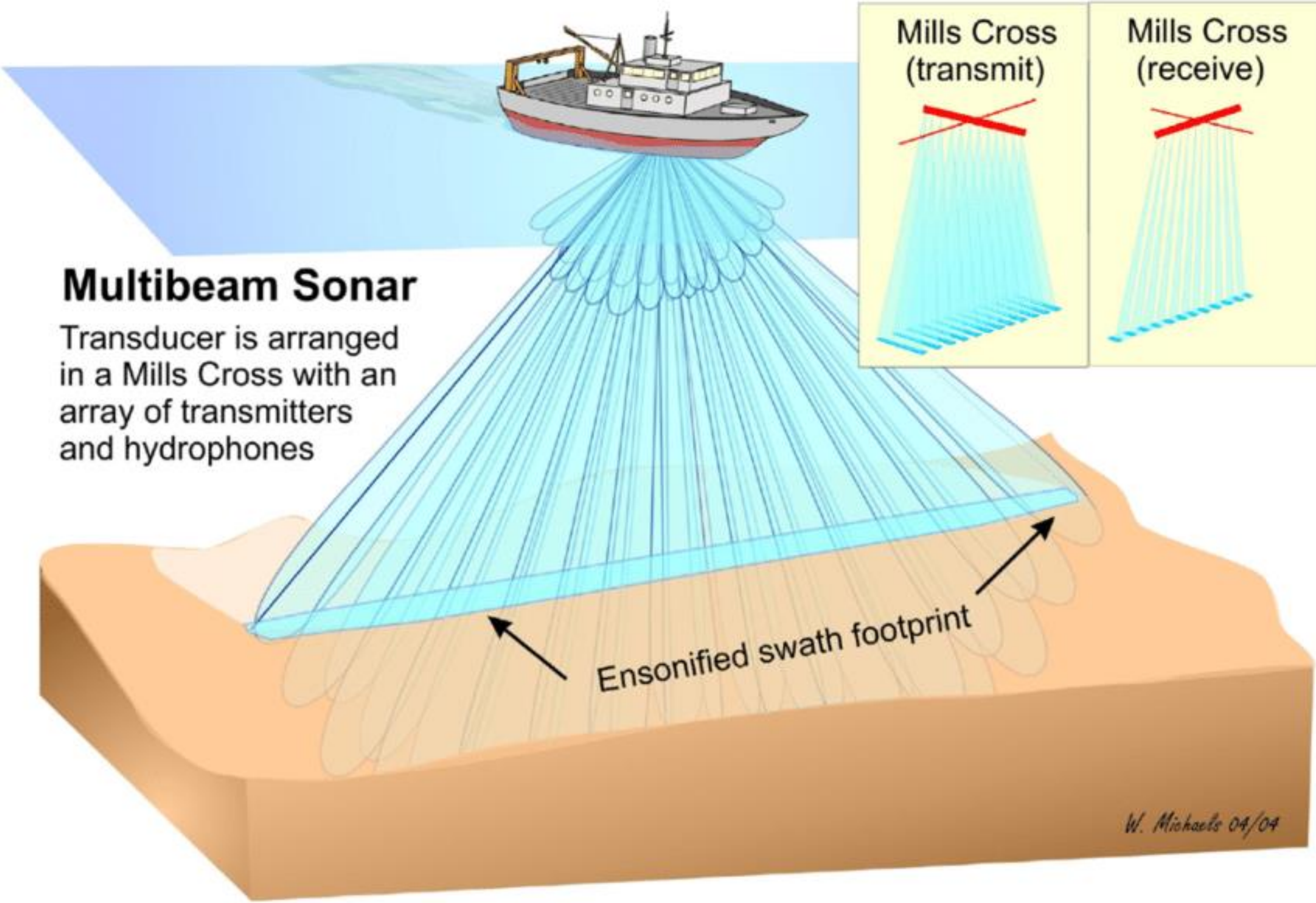




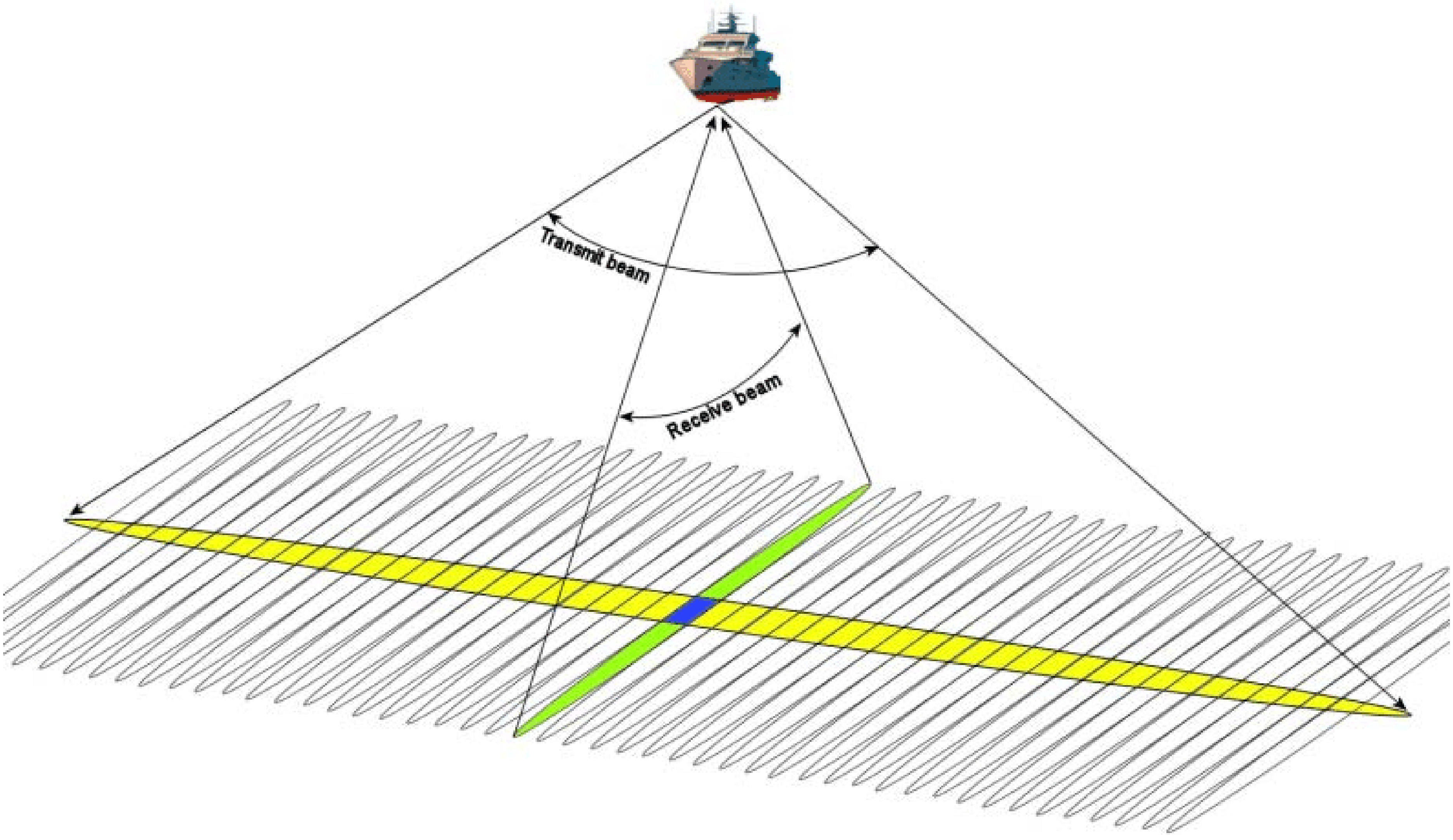
Sonar



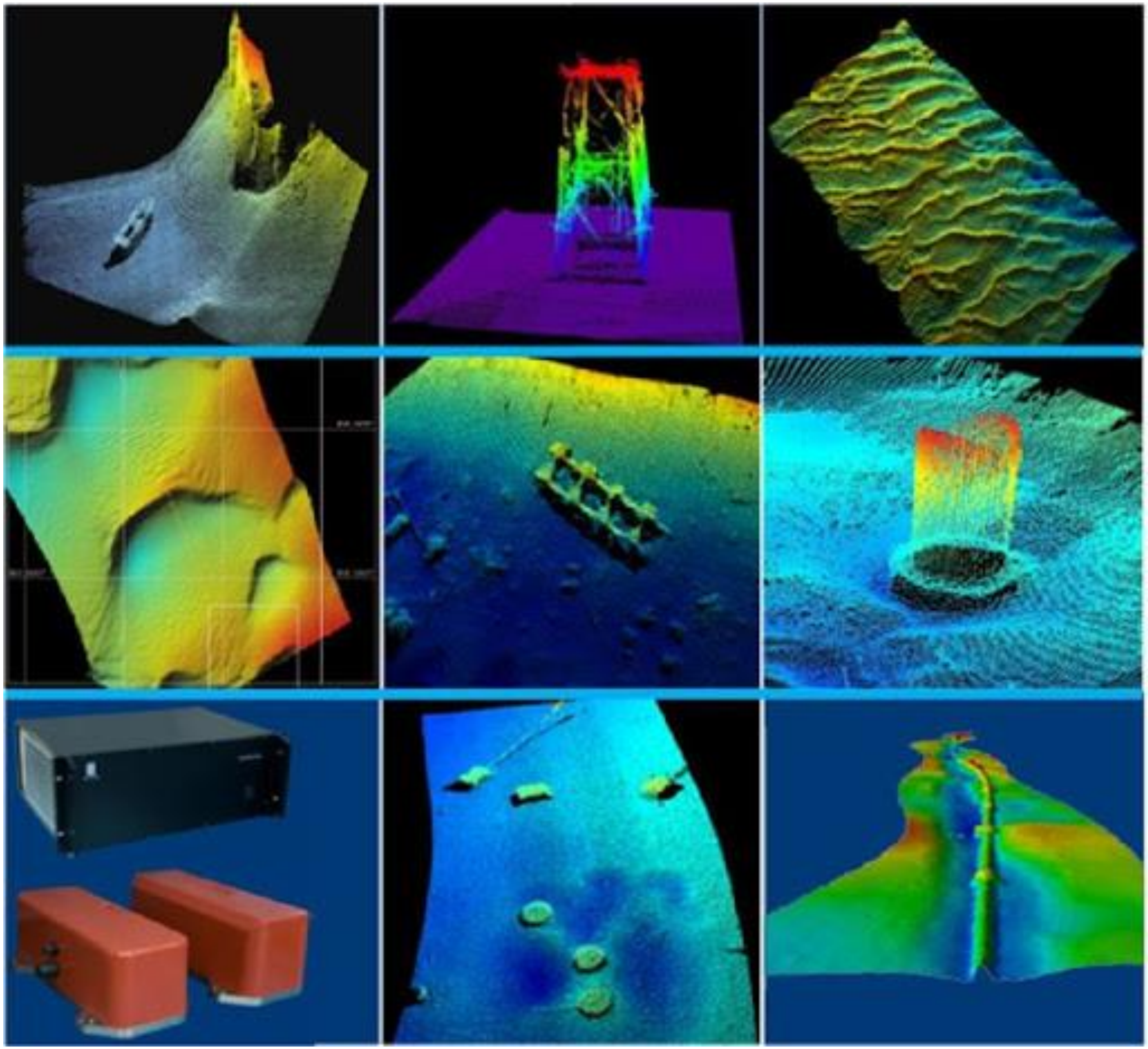
Multi-beam Echo Sounder



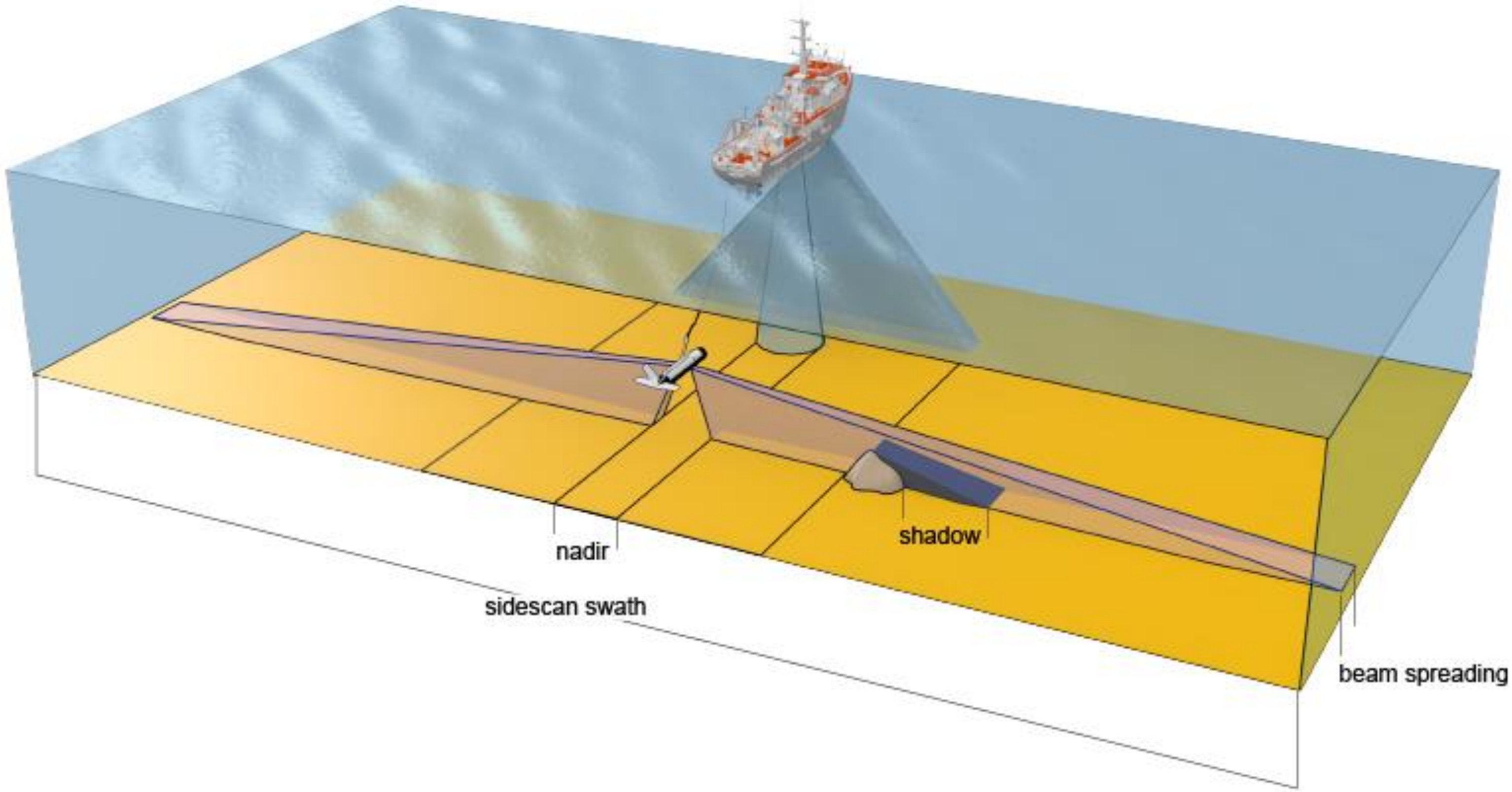
Multi-beam Echo Sounder (II)



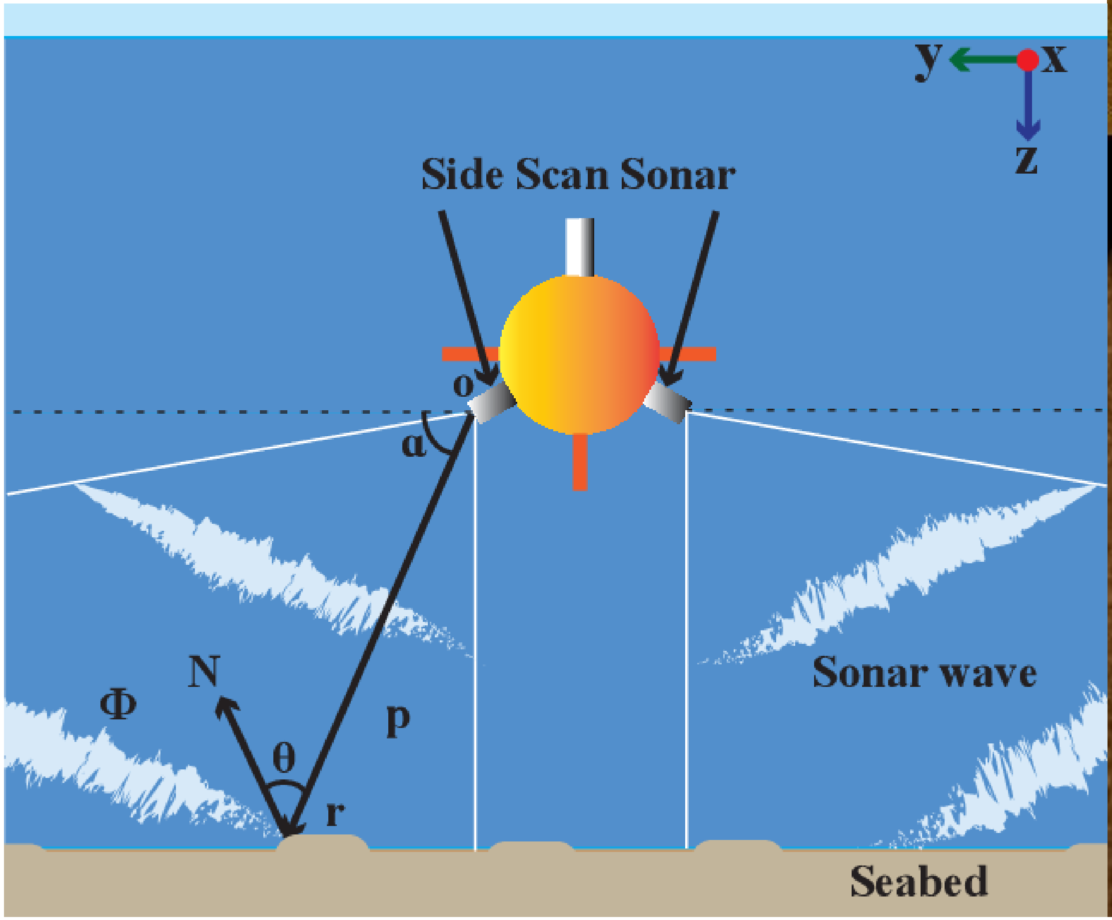
Multi-beam Echo Sounder (III)

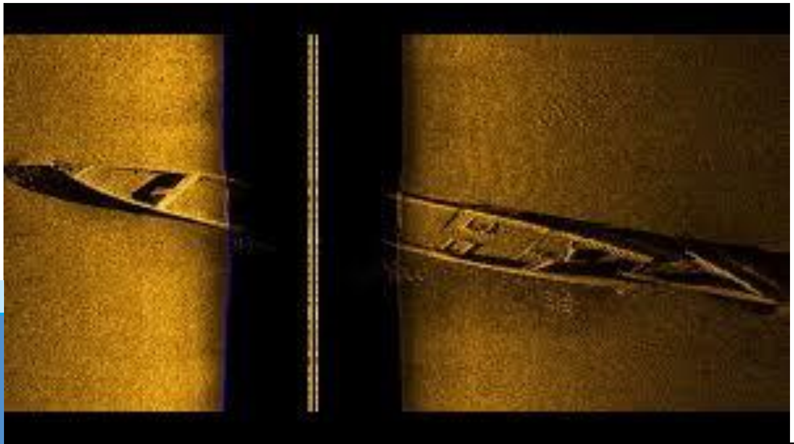


Side Scan SONAR

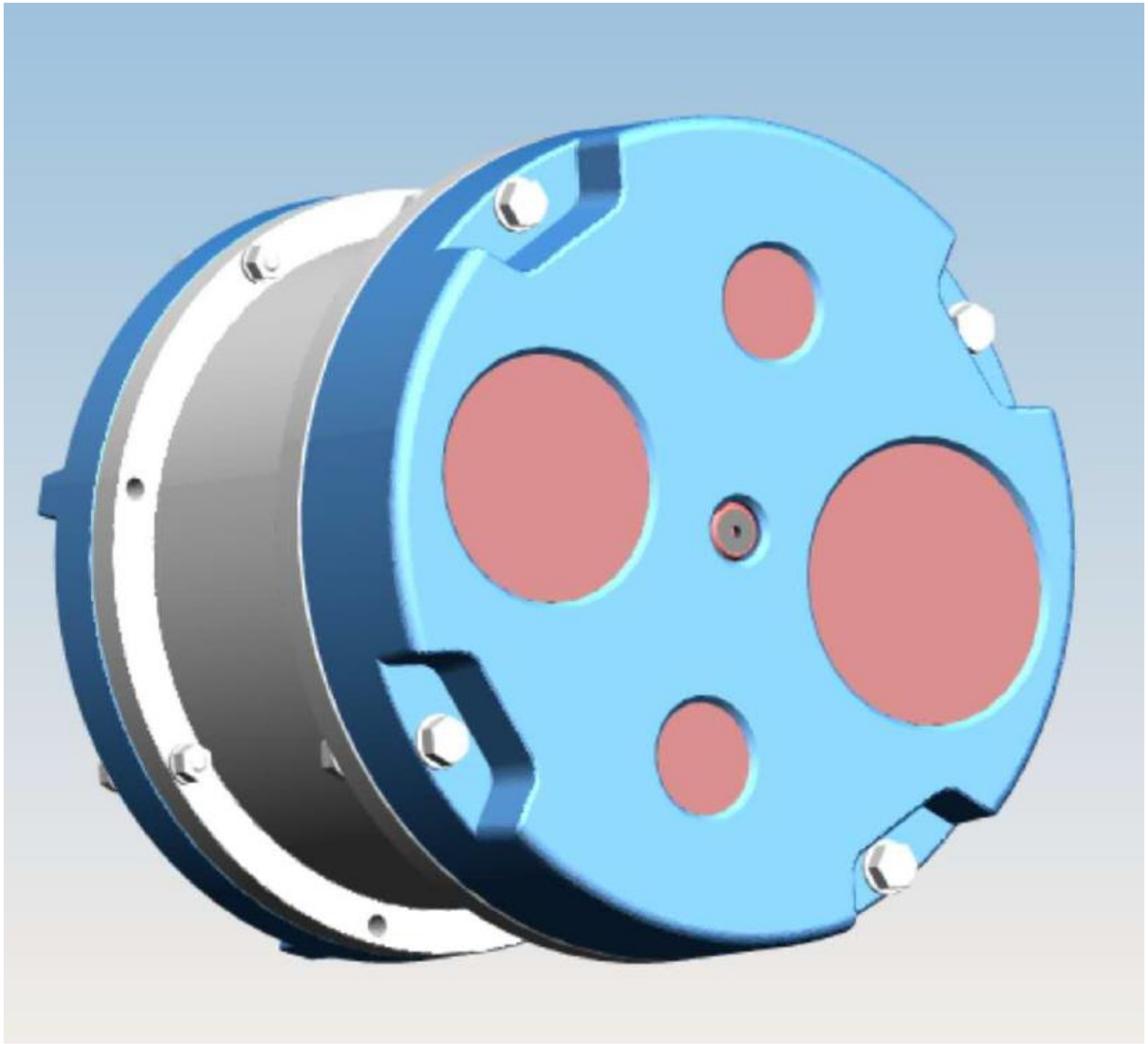


Side Scan SONAR image

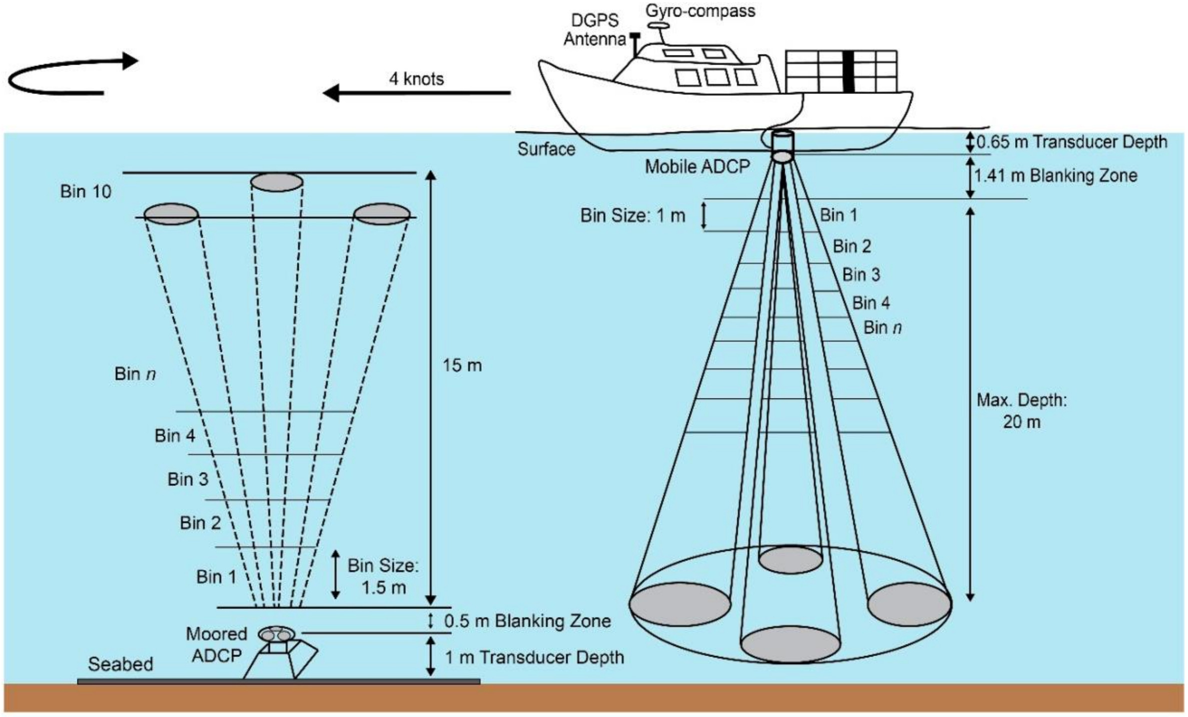




ABS (Acoustic Backscatter System)



ADCP (Acoustic Doppler Current Profiler)

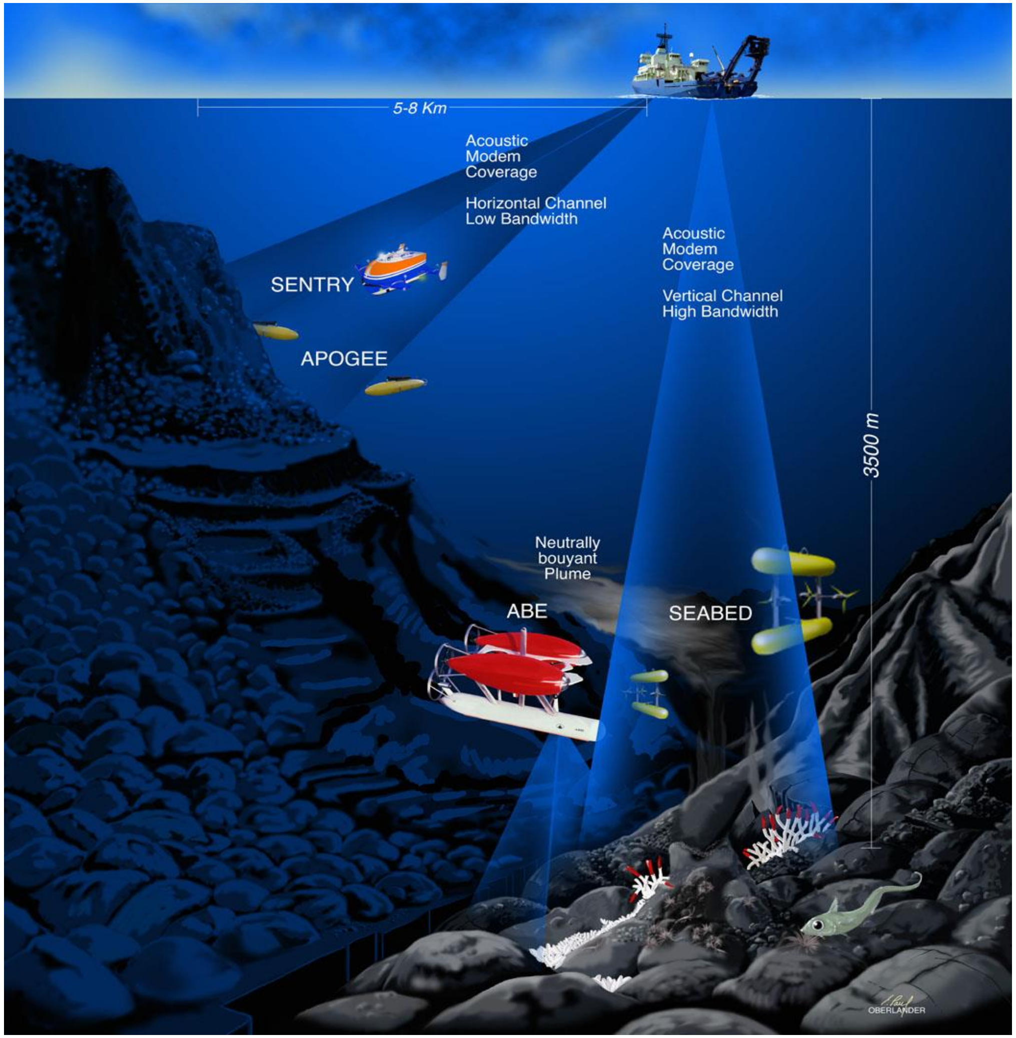


(a) (b)

Why use Acoustics

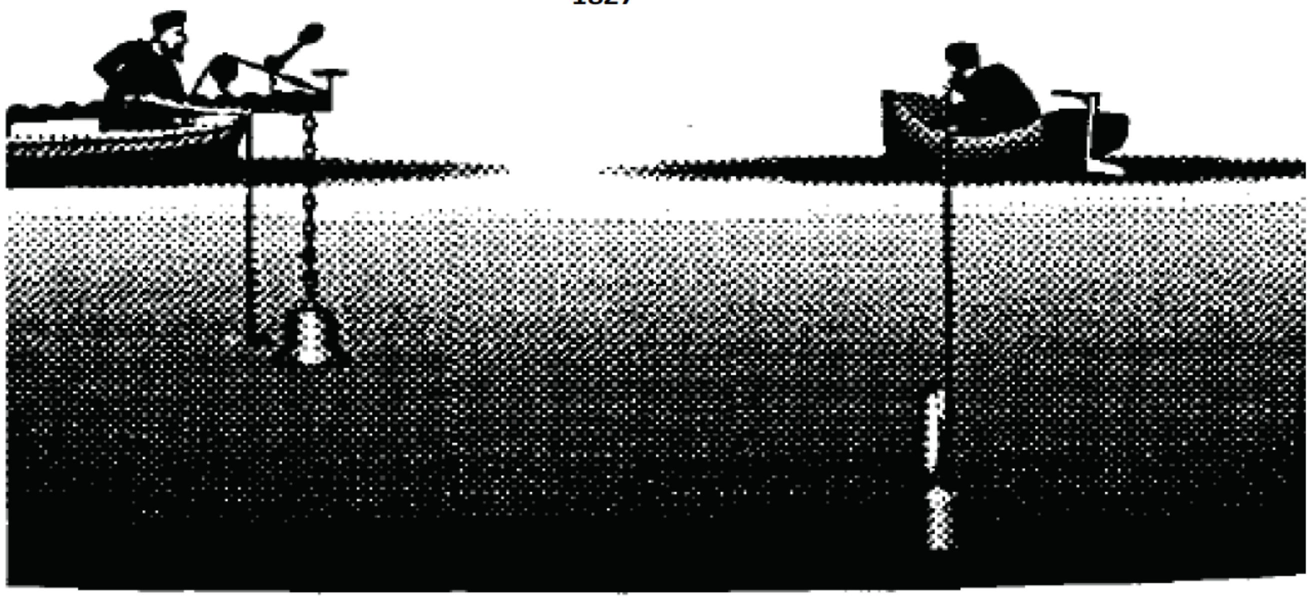
- ElectroMagnetic wave attenuates rapidly in water
- Acoustic can propagate long distance
- Acoustic wave is equivalent to the EM wave above water
- We will mainly focus on acoustics in this course

Future UWC systems



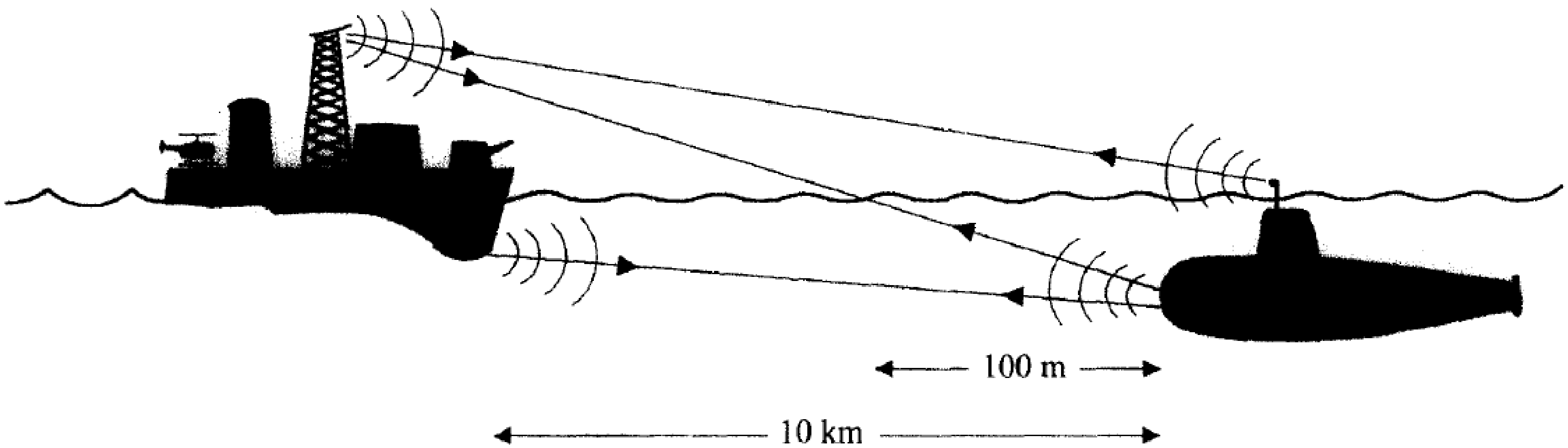
- Today: point-to-point acoustic links
- Future: Autonomous networks for ocean observation
- Example of future networks:
  1. Ad hoc deployable sensor networks
  2. Autonomous fleets of cooperating AUVs/Gliders

Sound propagation in Water



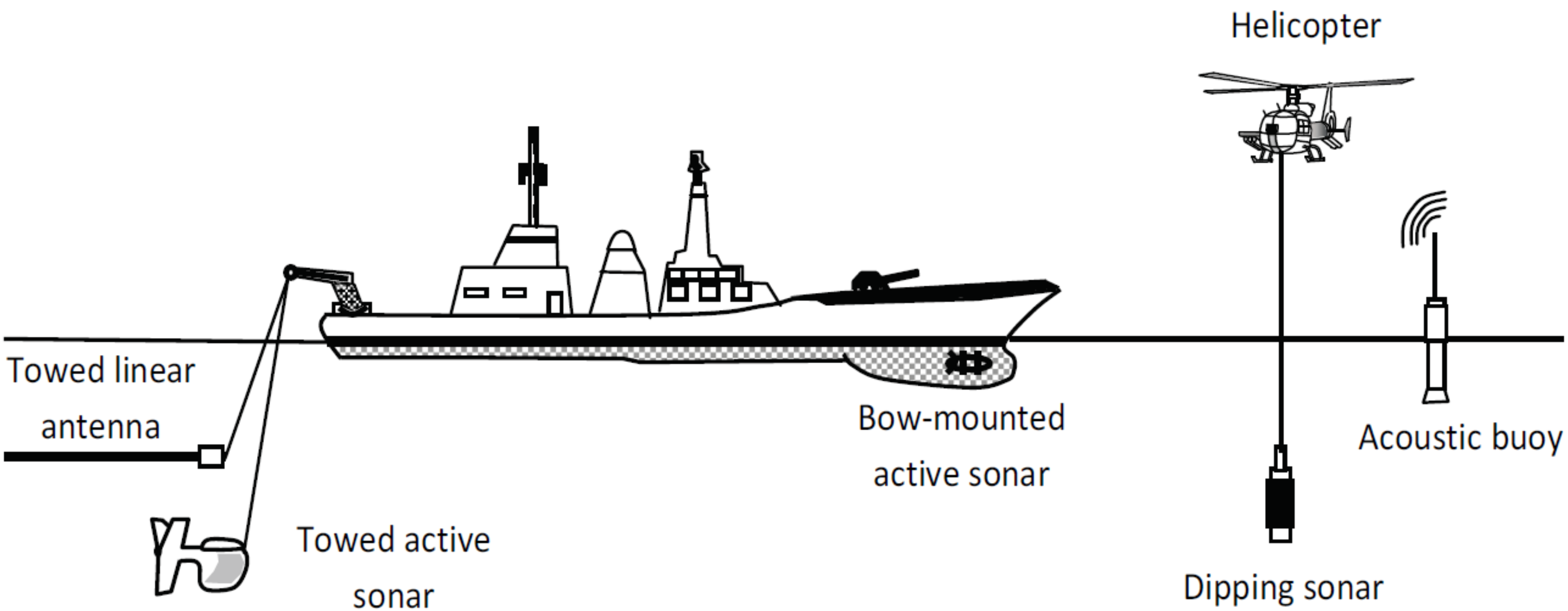
- First measurement of the velocity of sound in water was carried out in 1827
- They obtained a value of 1435 m/s

Why is Radar not used to detect Underwater Targets



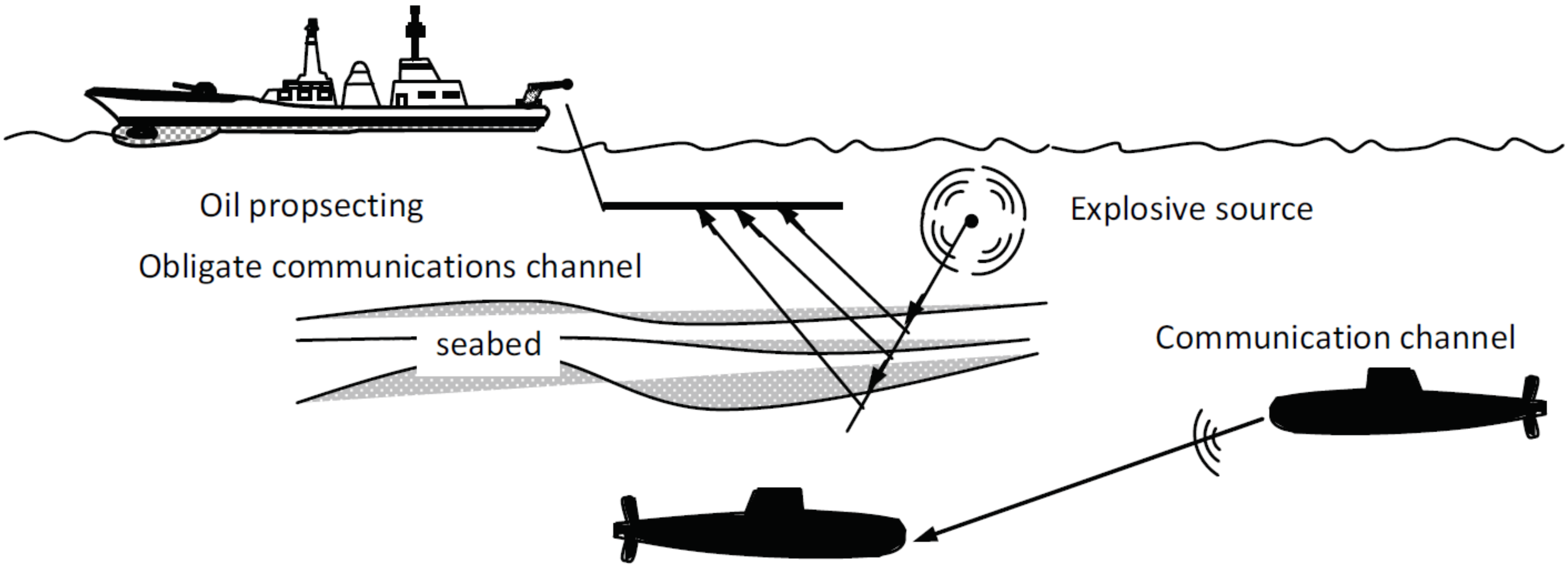
EM wave attenuate fast in water ~200000 dB/ 100m for 2GHz EM wave

Underwater Acoustic for Target Detection



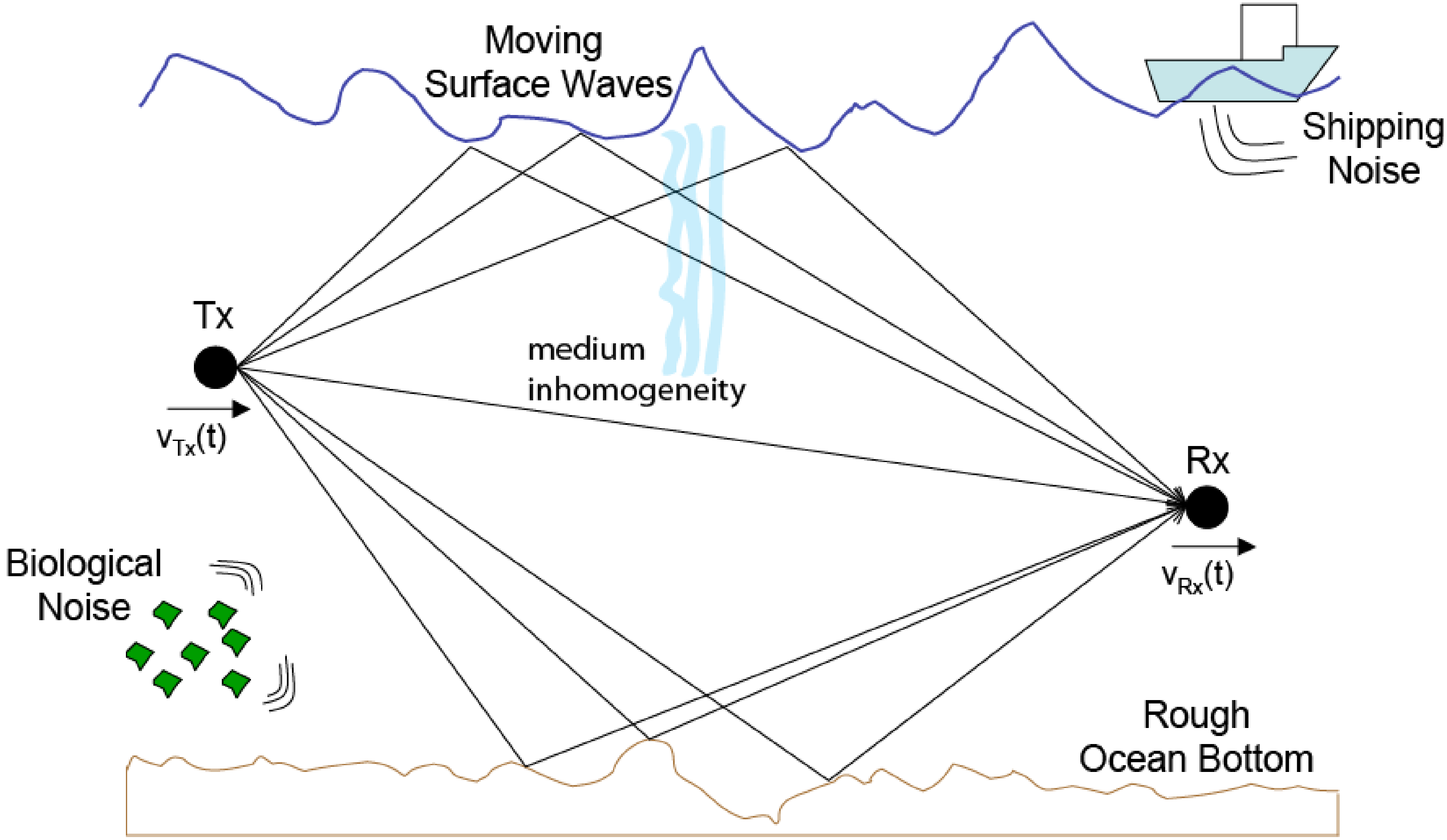
- SONAR (SOund Navigation And Ranging) systems for submarine detection.
- Focus of Information Processing with emphasis on post-treatment algorithms

The Acoustic Channel

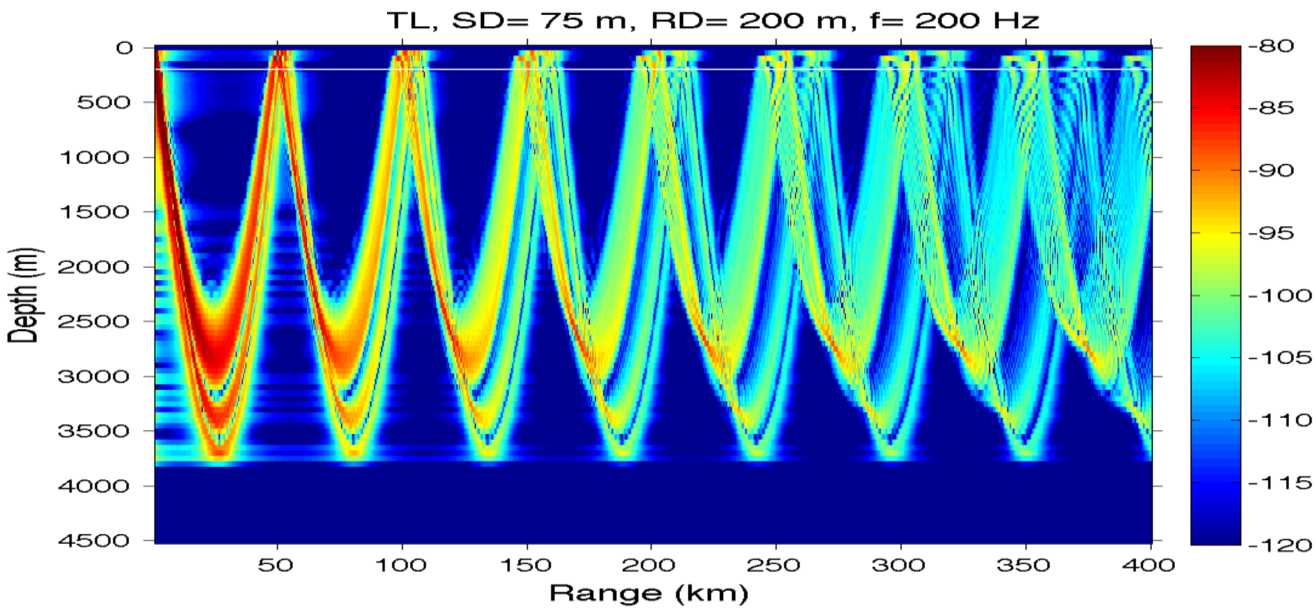


1. The Communication Channel
2. Obligate Communications Channel

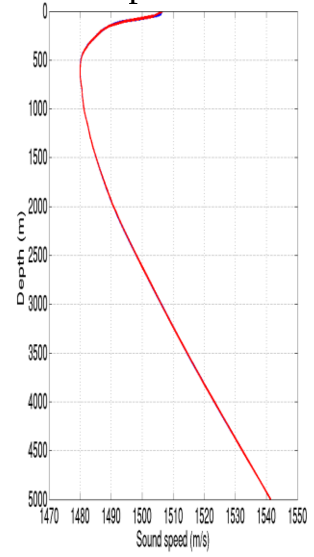
Multipath Acoustic Channel

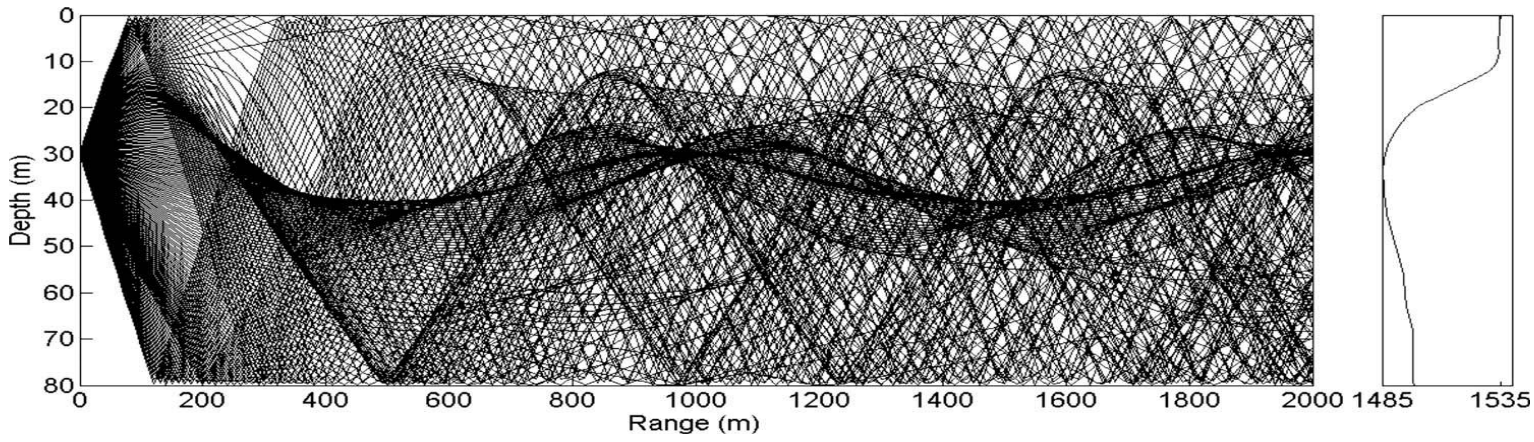


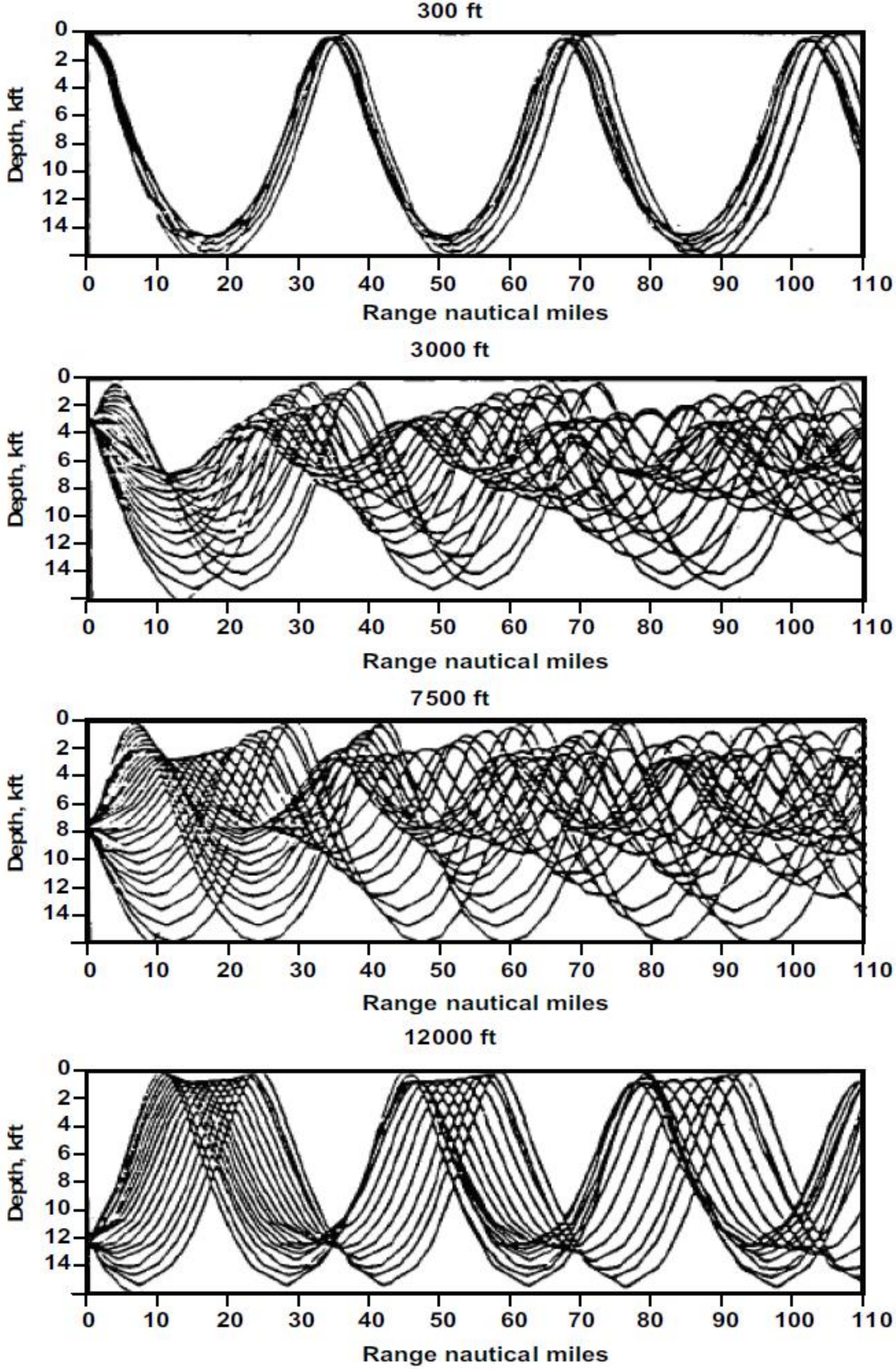
Sound Propagation Underwater



Sound speed Profile







Propagation types depends on the depth of source immersion.

The ideas of variable depth SONAR (VDS).

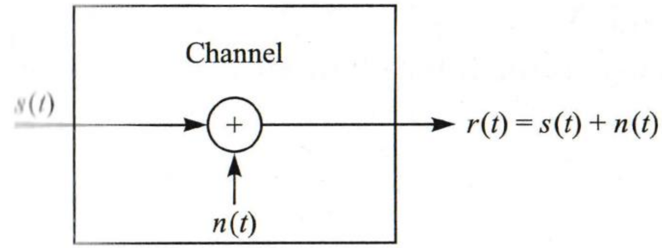
Underwater acoustic channels v.s. radio channel

	Wireless Radio Channels	Underwater Acoustic Channels
Propagation Behavior	EM Waves	Acoustic Waves
Propagation Speed (c)	$3 \times 10^8 m/s$	$1500 m/s$
Carrier Frequency	GHz Order	Around 10 kHz
Wave Length	0.3 m	0.15 m
Bandwidth (w)	1 MHz	2 kHz
Narrow or Wide	Narrow Band $\frac{w}{f_C} = \frac{10^6}{10^9} = 10^{-3}$	Wide Band $\frac{w}{f_C} = \frac{2 \times 10^3}{10 \times 10^3} = 0.2$
Velocity of Mobile / Mach number M=v/c	Assume v=100 km/hr = 27.8 m/s $M_{radio} = 9.3 \times 10^{-8}$	Assume v = 5 m/s $M_{water} = 3.3 \times 10^{-3} > 10^4 \cdot M_{radio}$
Delay spread Time	$1 \sim 3 \mu s$	up to 500 ms
Delay spread in Symbol	$1 \sim 3 symbols$	upto 100 symbols

Mathematical Model for Communication Channel

- Additive noise channel

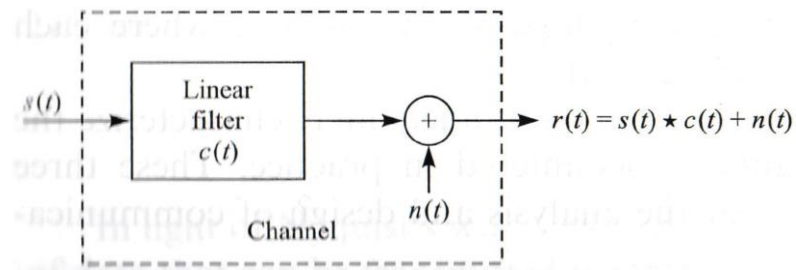
$$r(t) = s(t) + n(t)$$



- Liner filter channel

$$r(t) = s(t) * c(t) + n(t)$$

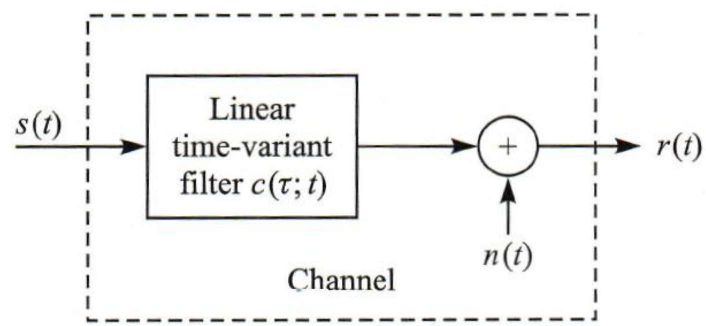
$$= \int_{-\infty}^{\infty} c(\tau)s(t-\tau)d\tau + n(t)$$



- Linear time-variant (LTV) filter channel

$$r(t) = s(t) * c(\tau;t) + n(t)$$

$$= \int_{-\infty}^{\infty} c(\tau;t)s(t-\tau)d\tau + n(t) \qquad (1)$$



Convolution Review

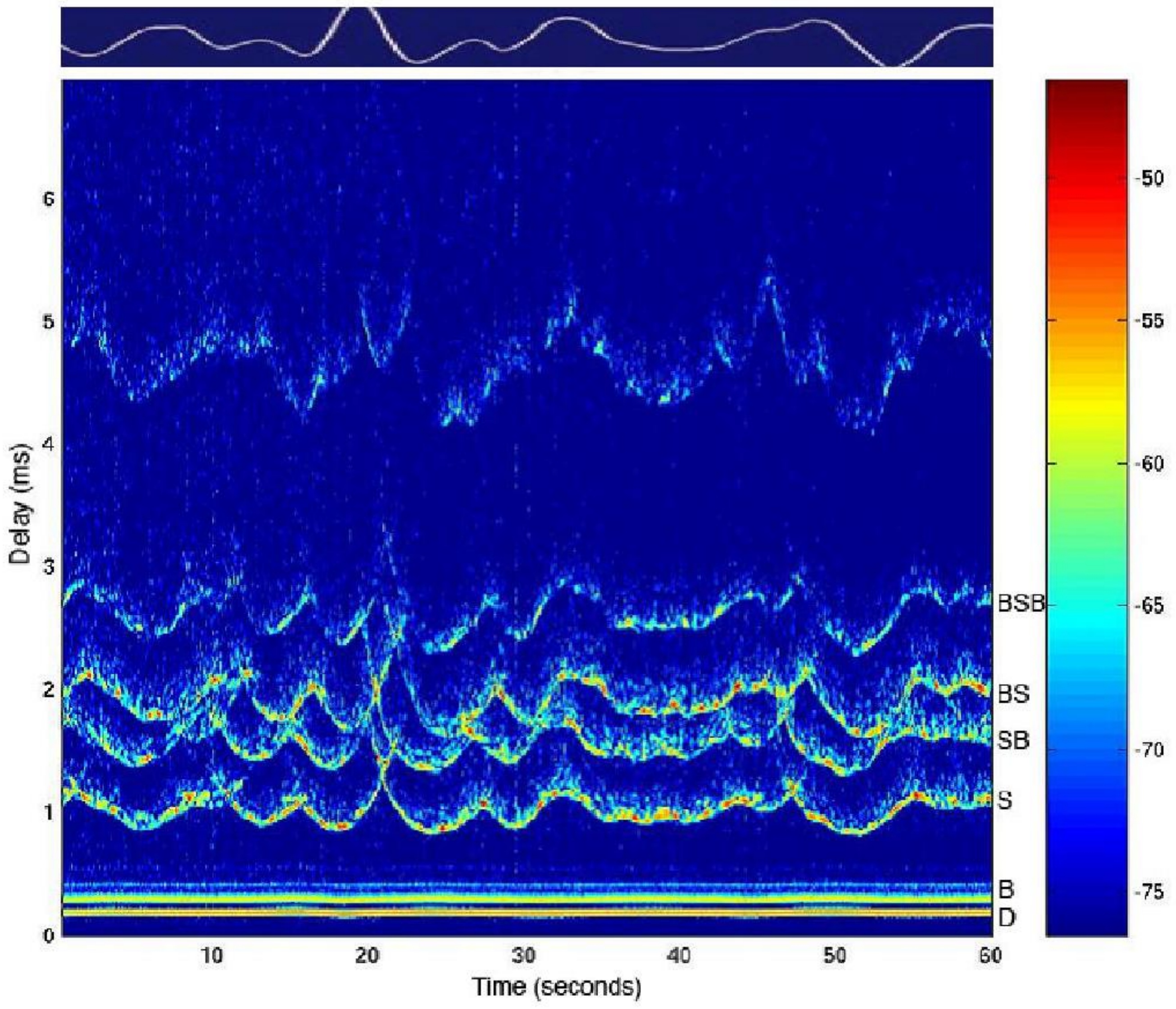
- The convolution of f and g is written $f * g$, it is a particular kind of integral transform:

$$(f * g)(t) = \int_0^t f(\tau) g(t - \tau) d\tau$$

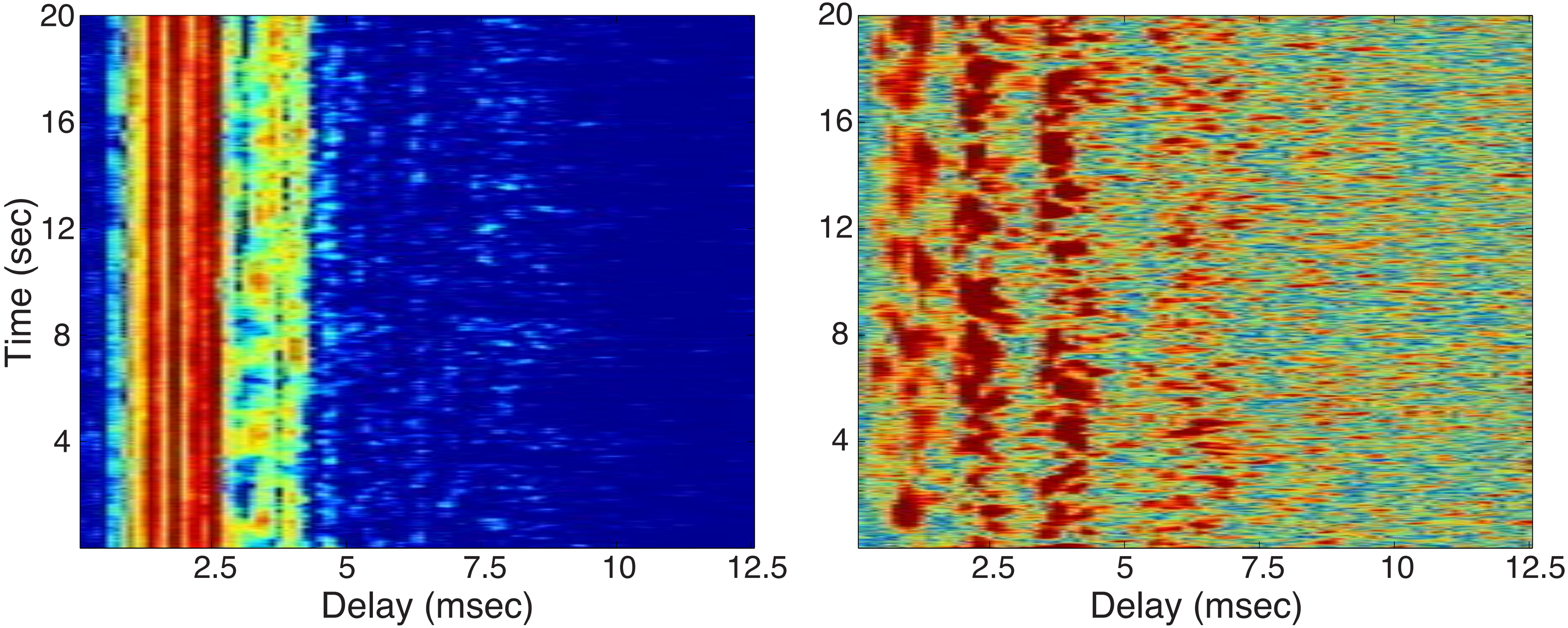
$$= \int_0^t f(t - \tau) \mathrm{g}(\tau) \mathrm{d}\tau \quad \text{(commutativity)}$$

- Convolution describes the output (in terms of the input) of linear systems.

LTV Channel due to surface wave

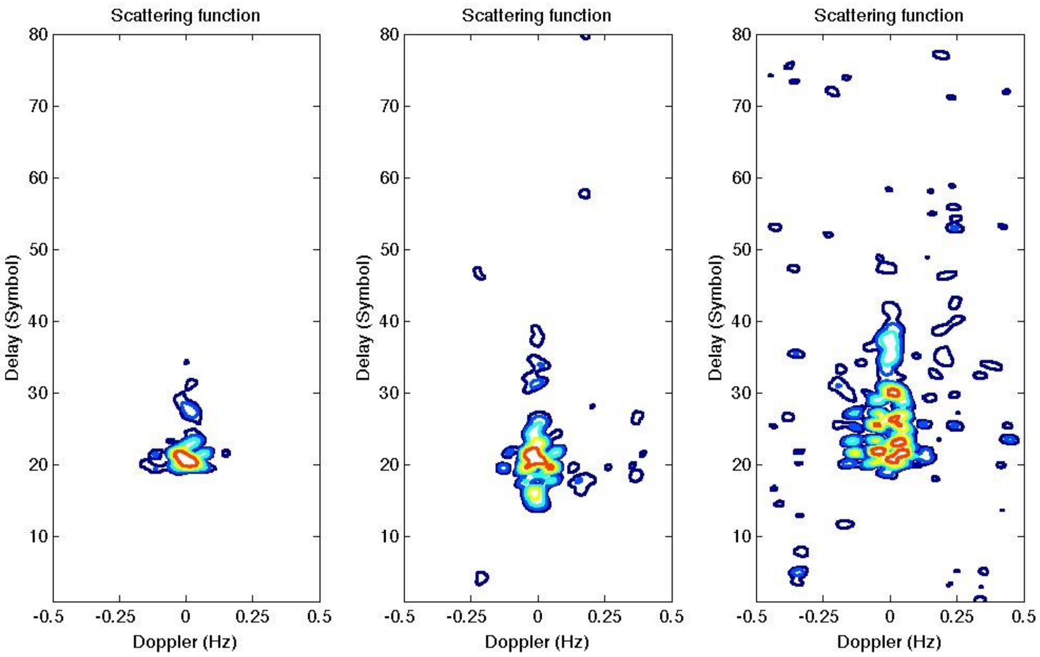


AUVFest07 Calm and Rough sea Experiment



- In around 20m depth of coast water under calm (sea state 0) and rough sea (sea state 3) conditions.
- Range was 5 kM (calm) and 2.3 kM (rough).
- Fc=17 kHz, BW=4 kHz, Fs=80 kHz.

Challenges in UWA Channel

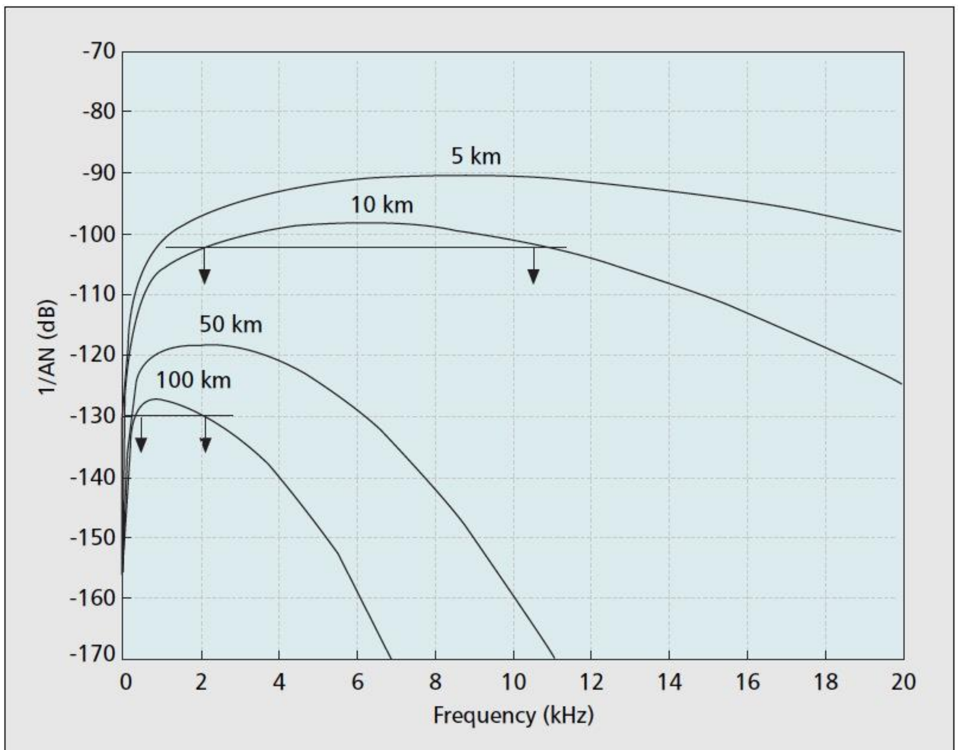


Scattering function -- ASIAEX Experiment

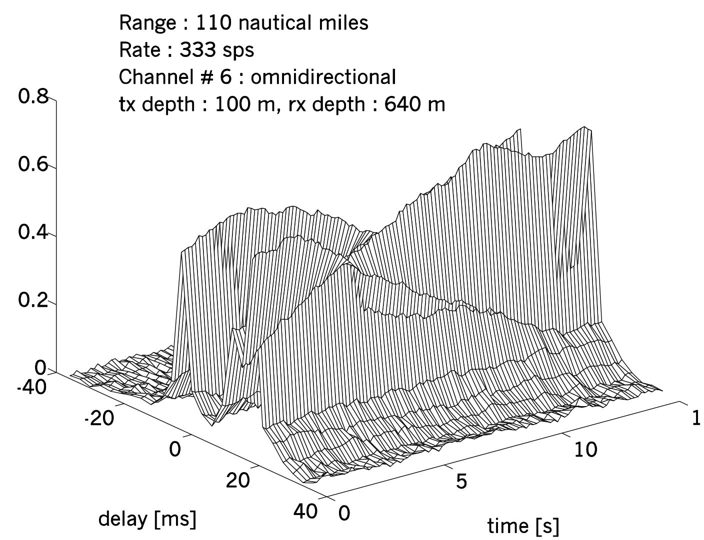
Communication Channel / Summary

<u>Physical constraints of acoustic propagation</u>:
- limited and range-dependent bandwidth
- time-varying multipath
- low speed of sound (1500 m/s)

<u>System constraints</u>:
- transducer bandwidth
- battery power
- half-duplex

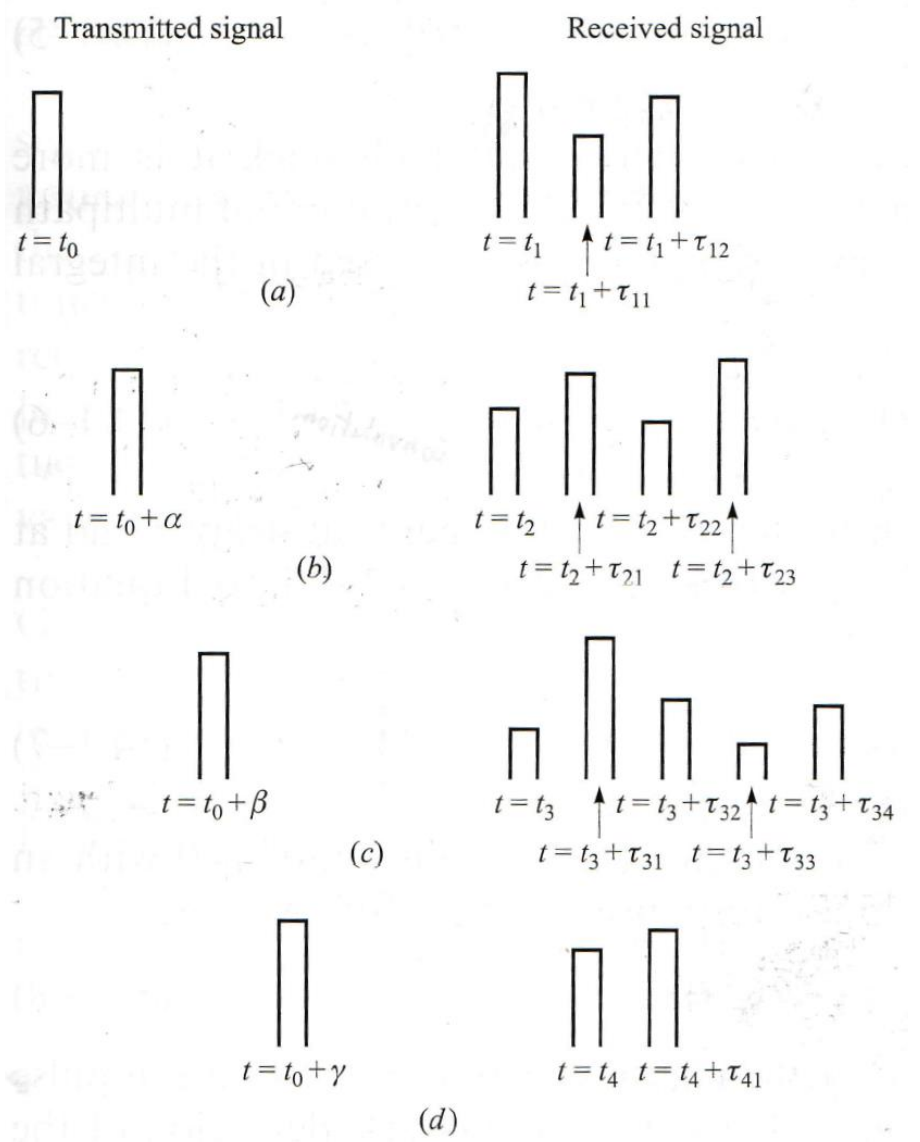


<u>Worst of both radio worlds (land mobile / satellite)</u>



Propagation Model & Statistical Characterization

- Delay spreading causes extensive inter-symbol interference (ISI).

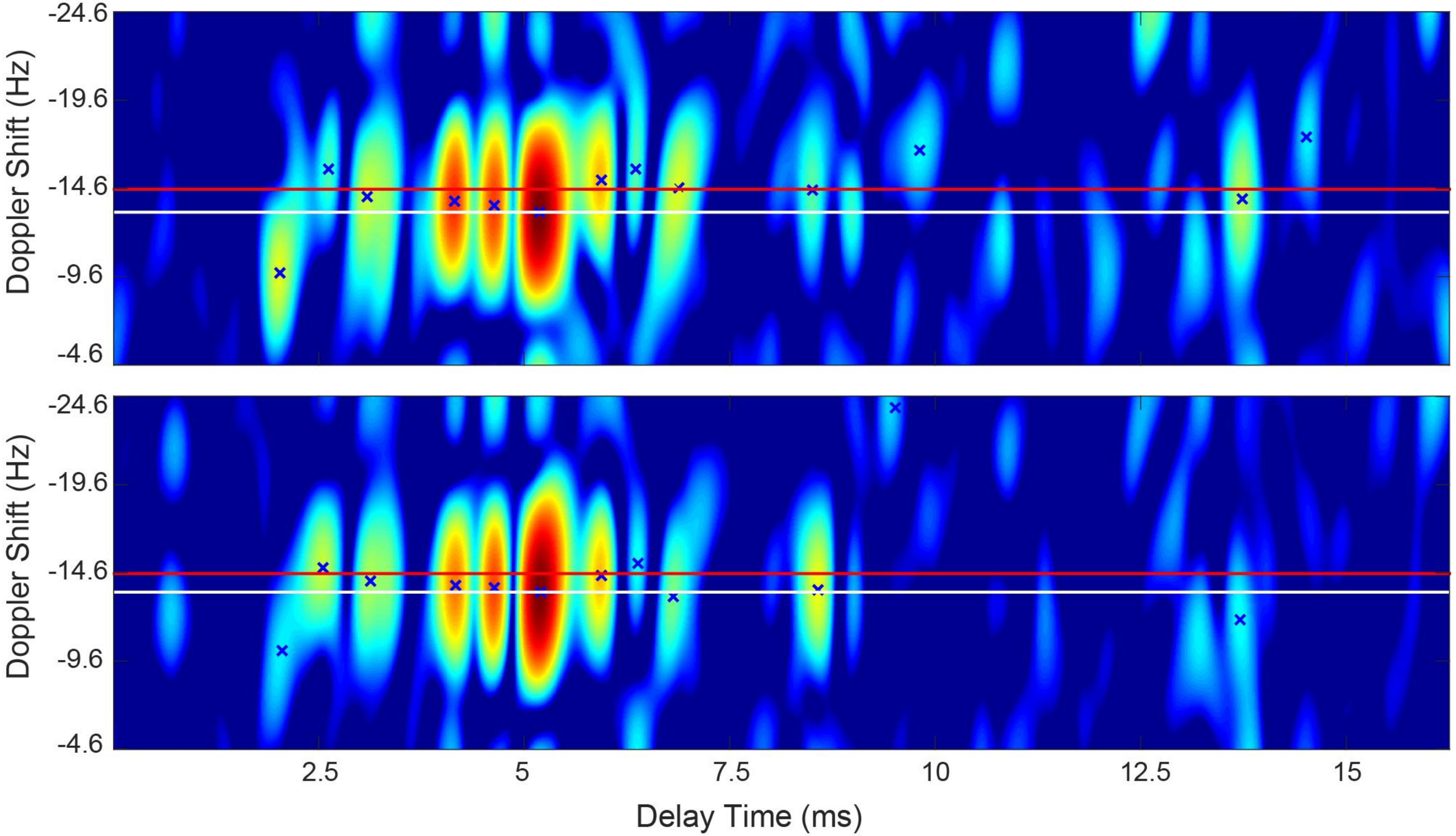


Propagation Model & Statistical Characterization

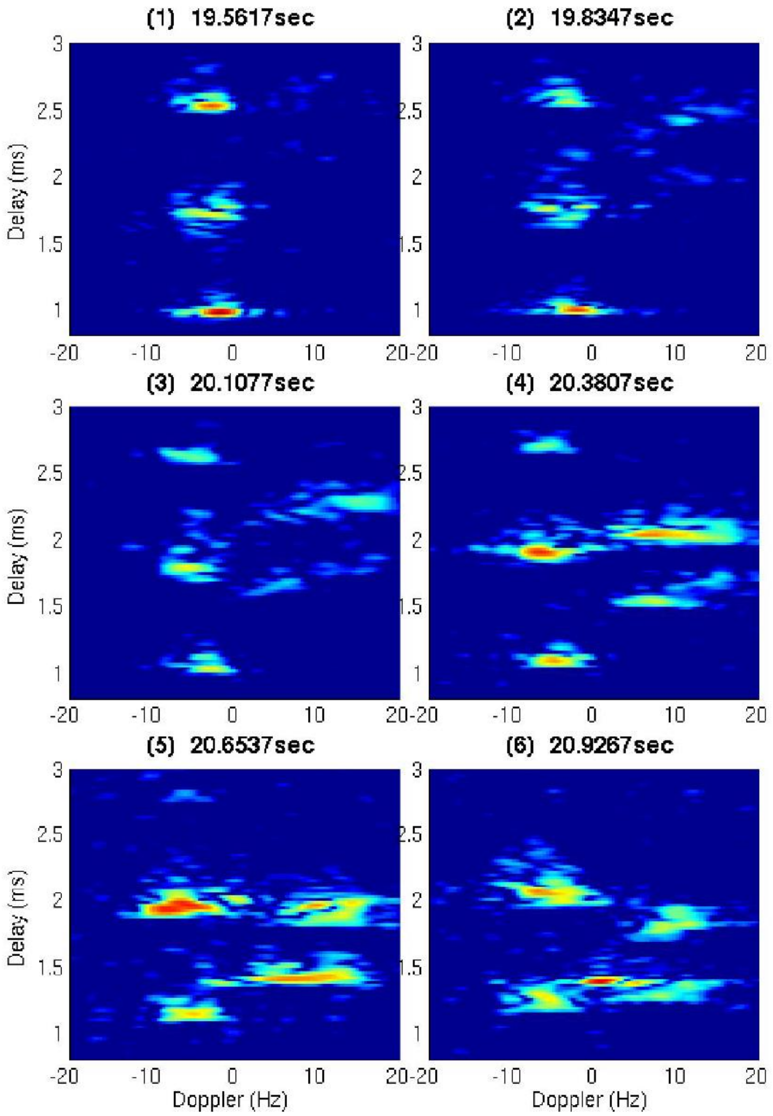
- Complex time-varying oceanographic process and ocean surface waves often produce a channel with short coherence time (or large Doppler spread) making channel tracking difficult.

- Doppler-shift is several orders higher than that in the RF channel making symbol synchronization difficult.

Doppler shift & Doppler spread (due to motion)



Doppler shift & Doppler spread (due to surface wave)



Attenuation

- Overall path loss (Absorption + spreading loss)

$$A(l,f) = (l/l_r)^k a(f)^{l-l_r} \qquad l : \text{distance}, \ l_r : \text{reference}$$

k : pass loss exponent, (k=1 for cylindrical spreading, k=2 for spherical spreading)

a(f) : absorption coefficient

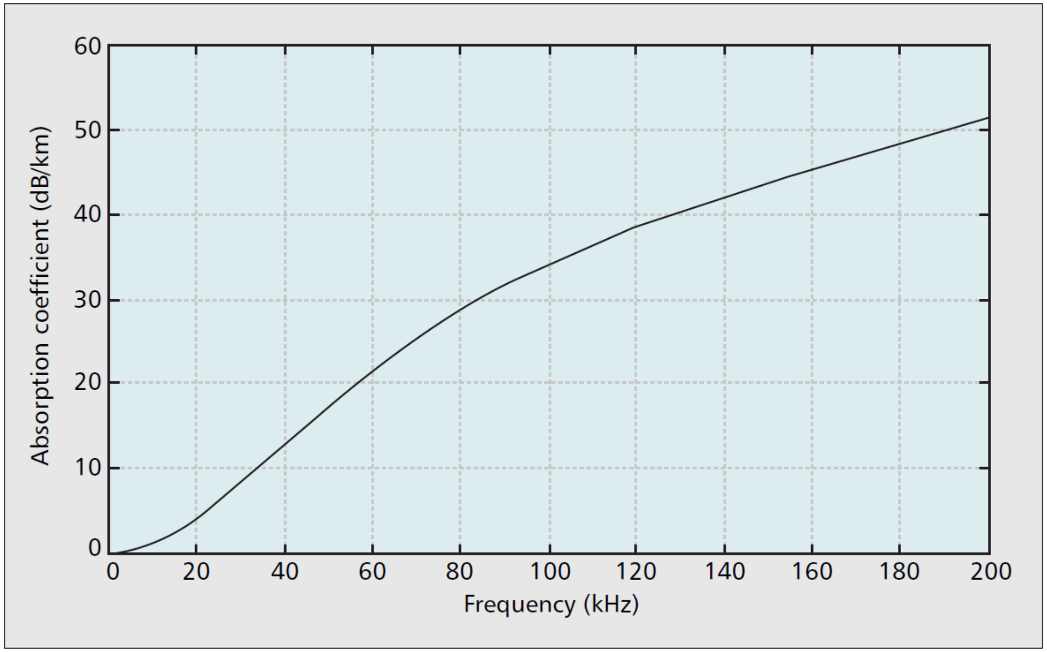


Figure 1. *Absorption coefficient, 10 log* a(f) *in dB/km.*

Noise

- Ambient noise
  - Turbulence, breaking waves, rain, shipping
  - Gaussian, non-white
- Site-specific noise
  - Ice cracking
  - Snapping shrimp
  - Non-Gaussian

$$SNR(l, f) = S_l(f) / A(l, f)N(f)$$

$S_l(f)$ is the power spectral density of Tx signal

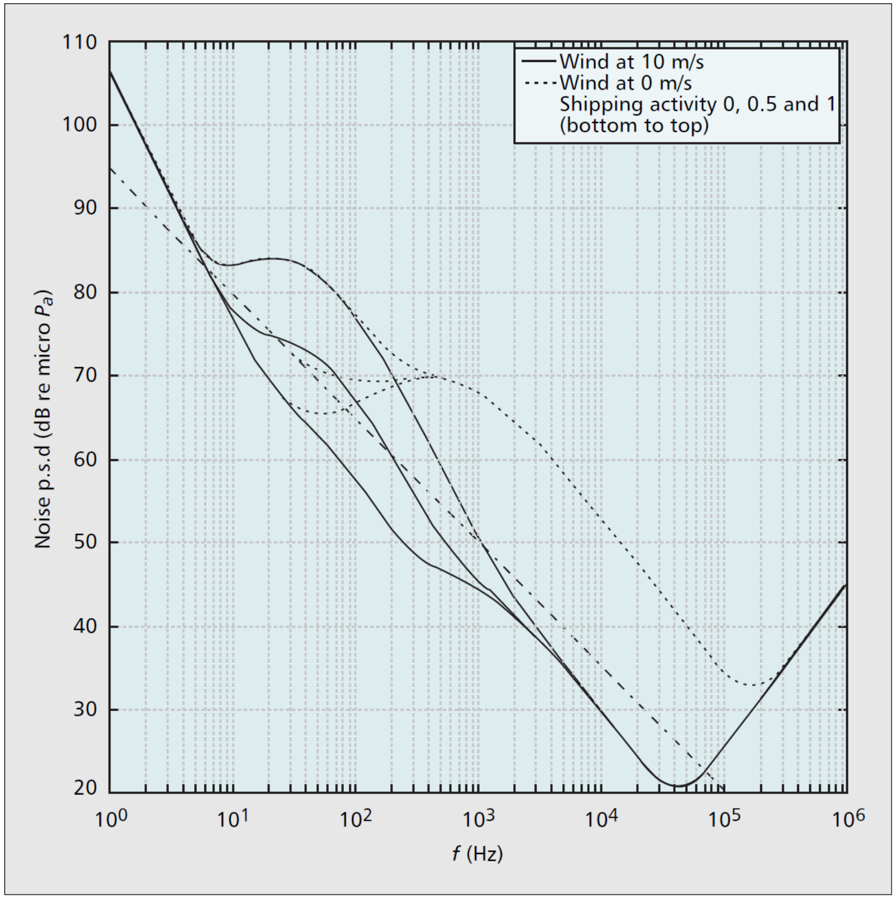


Figure 2. *Power spectral density of the ambient noise.*

SNR as a function of frequency

- For a given distance, the SNR is a function of frequency.

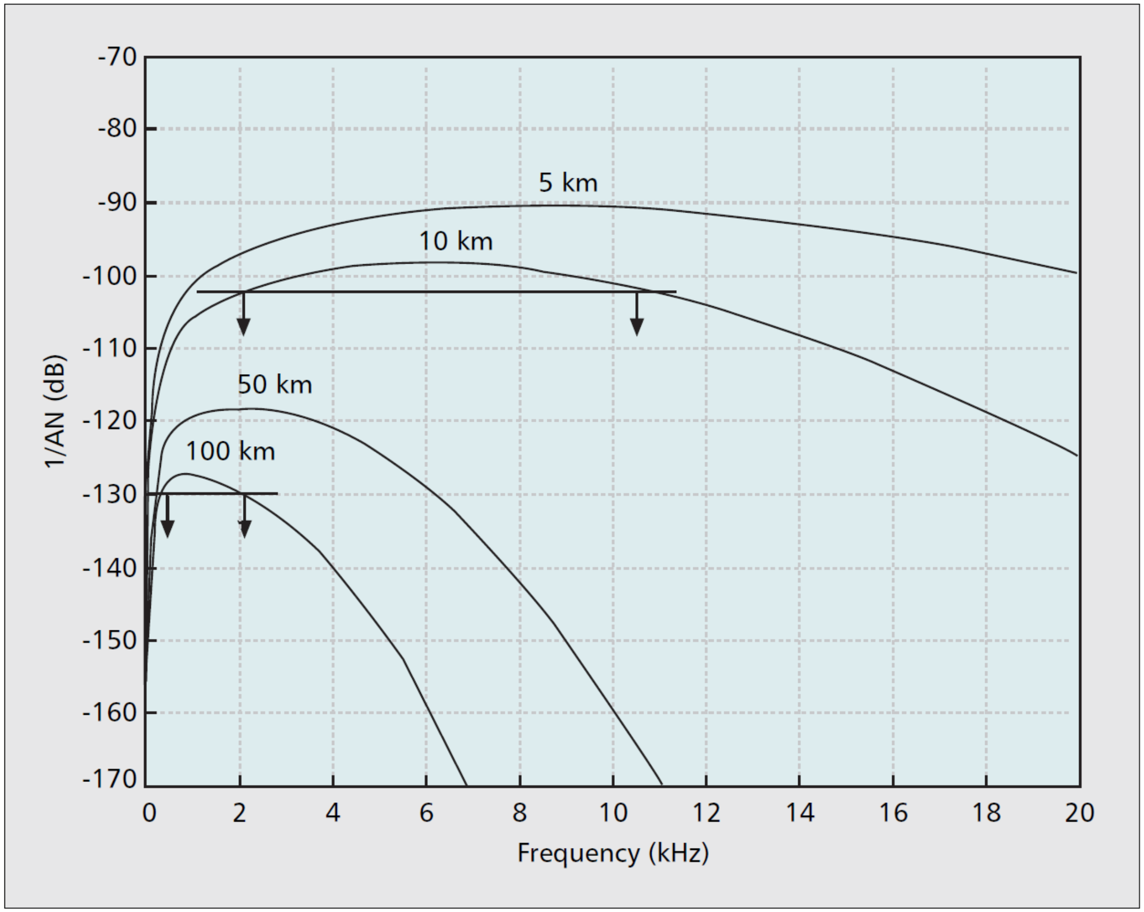


Figure 3. *Signal-to-noise ratio in an acoustic channel depends on the frequency and distance through the factor 1/A(l, f)N(f).*

The fact that bandwidth is limited implies the need for band-width efficient modulation methods.

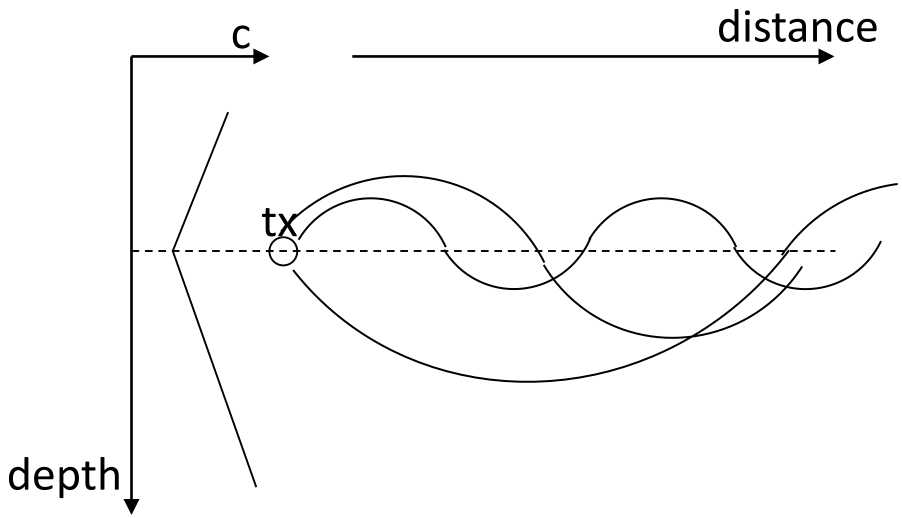
Bandwidth is limited → ultra wide band communications

Multipath

- Multipath in the ocean is governed by
  - Sound reflection
  - Sound refraction (due to spatial variability of sound speed, obey Snall’s law)
- Sound speed depends on
  - Temperature
  - Salinity
  - Pressure
- Ray traveling over a longer path may do so at higher speed.
  - Non-minimum phase channel response

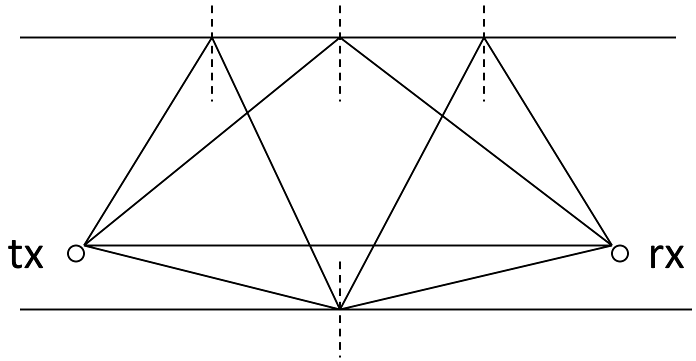
Mechanisms of multipath formation

Deep water: a ray, launched at some angle, bends towards the region of lower sound speed (Snell's law).
Continuous application of Snell's law → ray diagram (trace).



Deep sound channeling:
-rays bend repeatedly towards the depth at which the sound speed is minimal
-sound can travel over long distances in this manner (no reflection loss).

Shallow water: reflections at surface have little loss; reflection loss at bottom depends on the type (sand,rock, etc.), angle of incidence, frequency.



Multipath gets attenuated because of repeated reflection loss, increased path length.

Length of each path can be calculated from geometry:

l_p: p^{th} path length

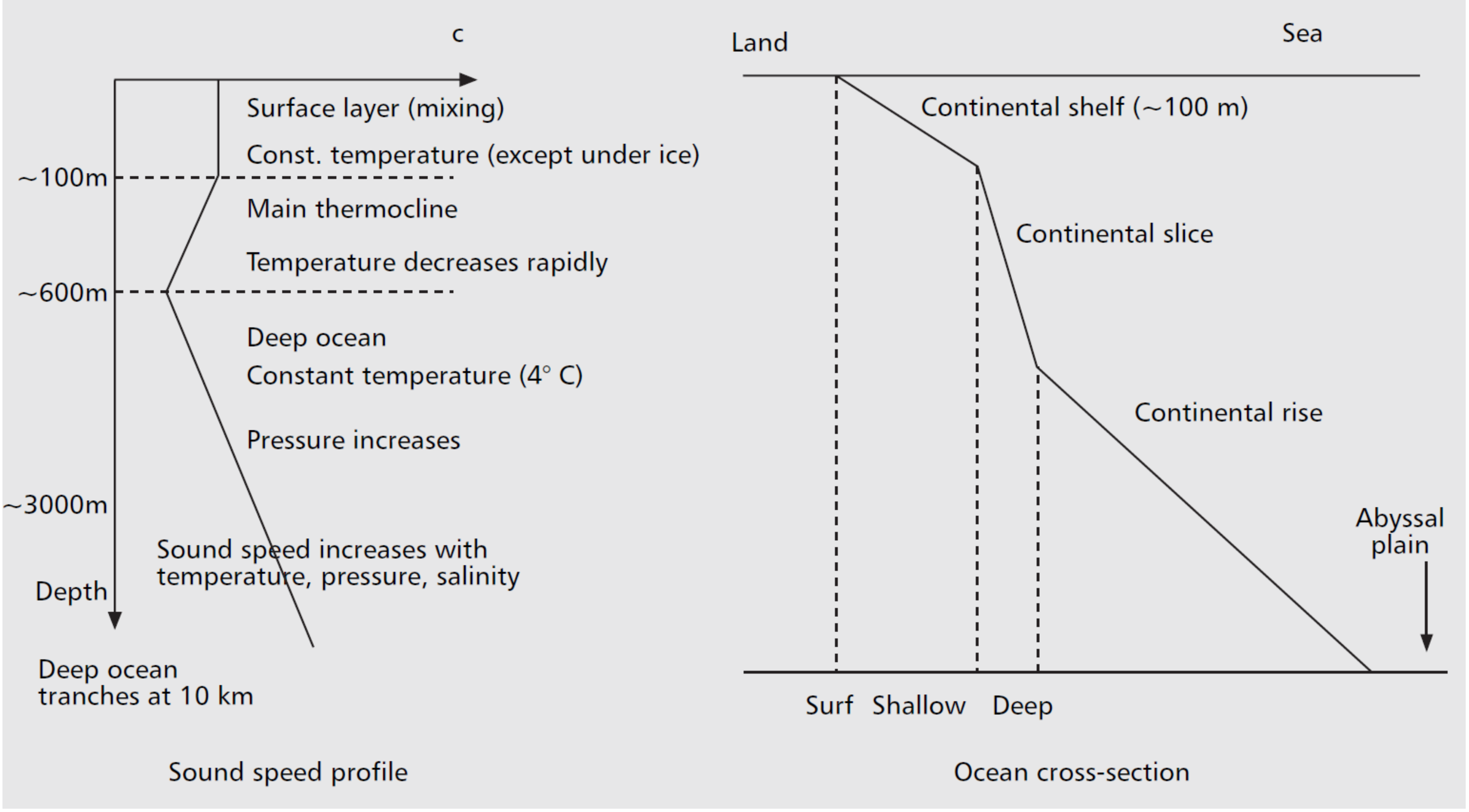
$\tau_p = l_p / c$: p^{th} path delay

$A_p = A(l_p, f)$: p^{th} path attenuation

Γ_p: p^{th} path reflection coefficient

} $G_p = \Gamma_p / A_p^{1/2}$: path gain

Sound speed profile



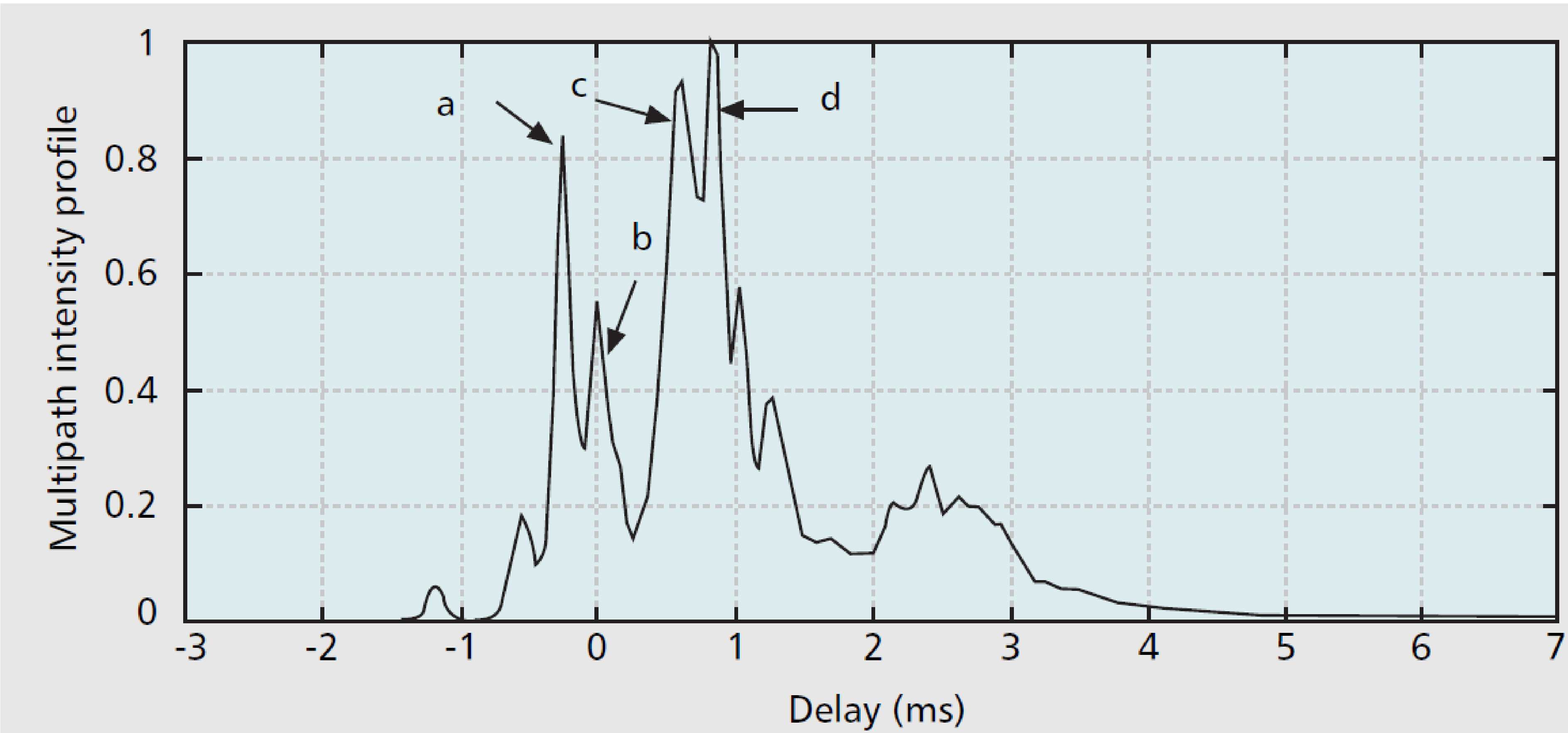
Channel time variability

- Due to Medium inhomogeneity
- Due to motion
- No consensus on statistical characterization of acoustic communication channels
  - Rice fading or Rayleigh fading
- Channel coherence time as low as 100 *ms*
  - *Very challenge for coherent communication*

UWAC experiment an example

- Shallow water, Distance @ 1 km
- Tx signal
  - PN sequence of length 4095
  - BPSK modulated @ 13 kHz carrier
  - BW: 10 kb/s
- Rx signal
  - 2x samples/symbol
  - Correlated with replica of PN signal
  - Phase exhibits random fluctuation around a constant slope (Doppler shift)

CIR From the experiment



Doppler Effect

- There is always some motion present in the system.
  - Doppler effect is proportional to v/c
    - $a = 1.5 \cdot 10^{-7}$ at 160 km/h motion in radio channels
    - $a = 3 \cdot 10^{-4}$ at 0.5 m/s motion underwater
  - Consider synchronization and channel estimation
    - Explicit phase and delay synchronization (due to signal compression/dilation)
    - Particularly severe in multicarrier systems (non uniform Doppler)

Convolution Review

- Discrete convolution

$$(f*g)[n] = \sum_{m=-\infty}^{\infty} f[m]g[n-m]$$

$$= \sum_{m=-\infty}^{\infty} f[n-m]g[m]$$

- If f and g are rapidly decreasing functions, then so is the convolution $f*g$.

Convolution Review

- Properties
  - Commutativity $f * g = g * f$
  - Associativity $f * (g * h) = (f * g) * h$
  - Distributivity $f * (g + h) = (f * g) + (f * h)$
  - Associativity with scalar multiplication

    $$a(f * g) = (af) * g$$
  - Multiplicative identity $f * \delta = f$

- Convolution Theorem

$\Im\{f*g\}=k\cdot\Im\{f\}\cdot\Im\{g\}$, where $\Im\{f\}$ denotes

Fourier transform or Laplace transform or Z-transform.

Correlation Review

- **Cross-correlation** : measure of similarity of two series as a function of the lag to the other.

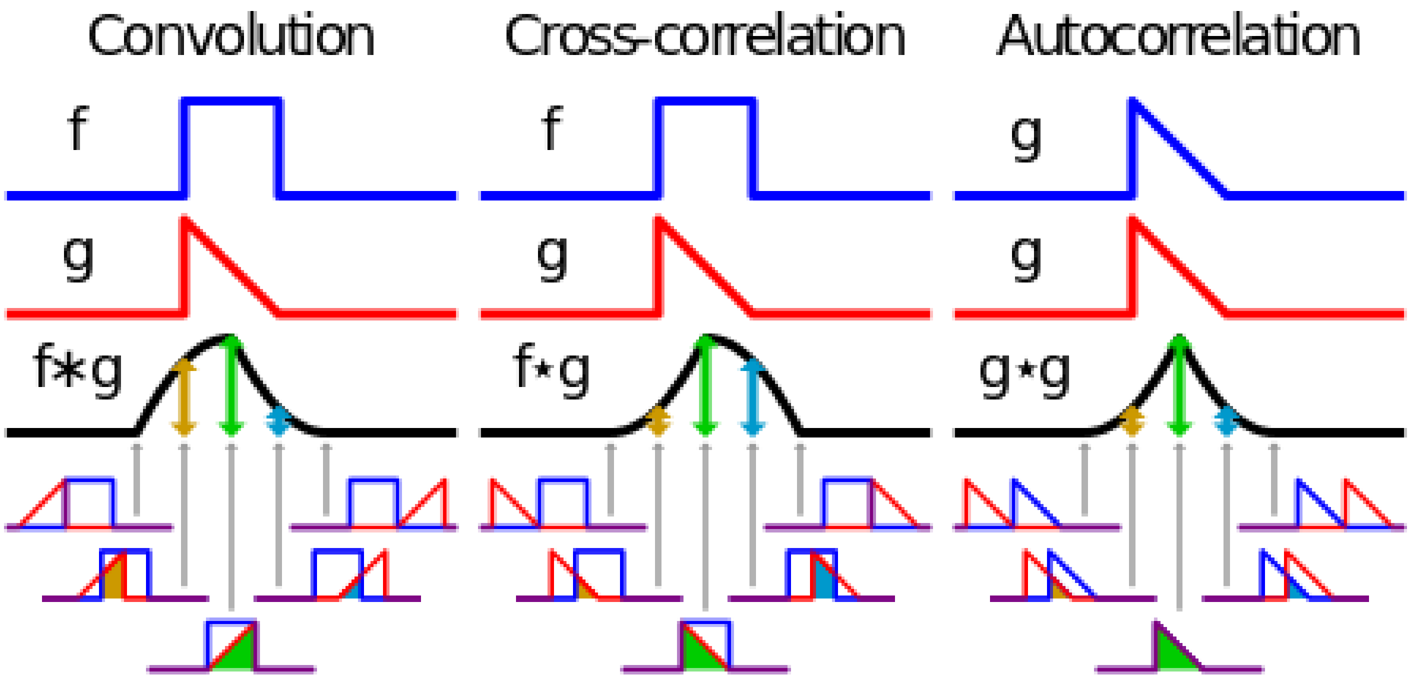
$$(f \times g)(\tau) = \int_{-\infty}^{\infty} f^*(t) g(t+\tau) dt$$, where f^* denotes the complex conjugate of f.

- **Cross-correlation** in discrete form:

$$(f \times g)[n] = \sum_{-\infty}^{\infty} f^*[m] g[m+n]$$

- **Autocorrelation** is the cross-correlation of a signal with itself, there will always be a peak at a lag of zero, and its size will be the signal power.

An example



Convolution
Cross-correlation
Autocorrelation
f
g
f∗g
f
g
f⋆g
g
g
g⋆g

Applications of Underwater Acoustics

Civil Application

1. Measure sea bed with sounders
2. Detection of fish by fishing sonars
3. Information transmission using acoustic modems
4. Marine mapping
5. hydrography

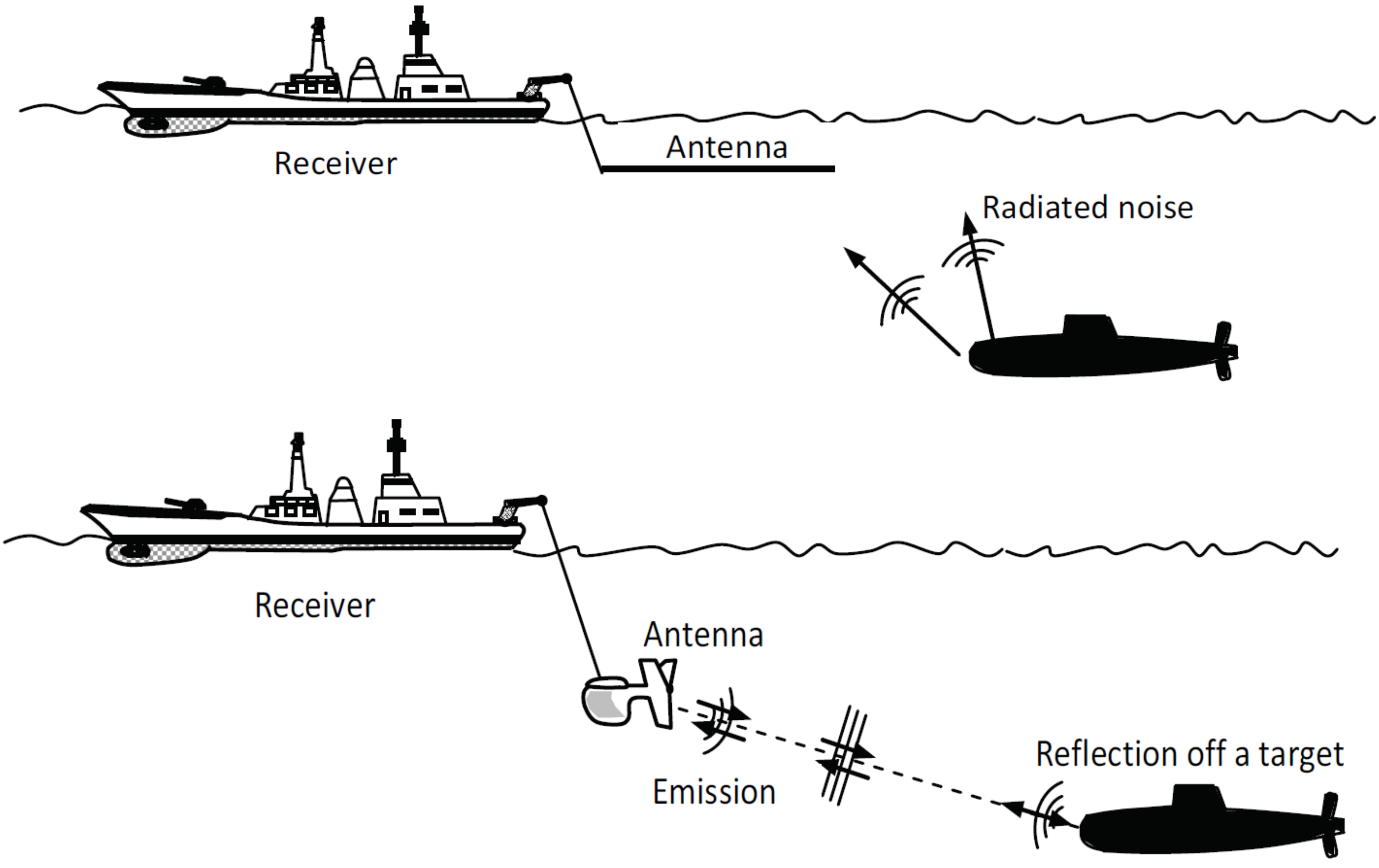
Military Applications

1. Detection, localization and recognition of underwater objects
2. Torpedo Guiding
3. Sonar emissions interception

Suspended Sediment measurement by Acoustic Backscattering

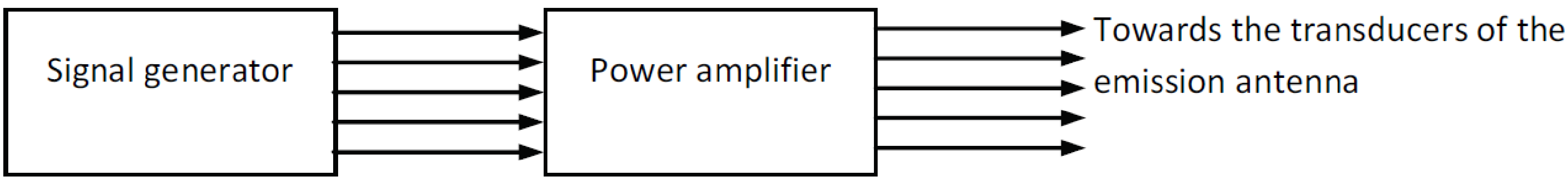
Using ultrasonic acoustic back scattering to measure suspended sediment concentration

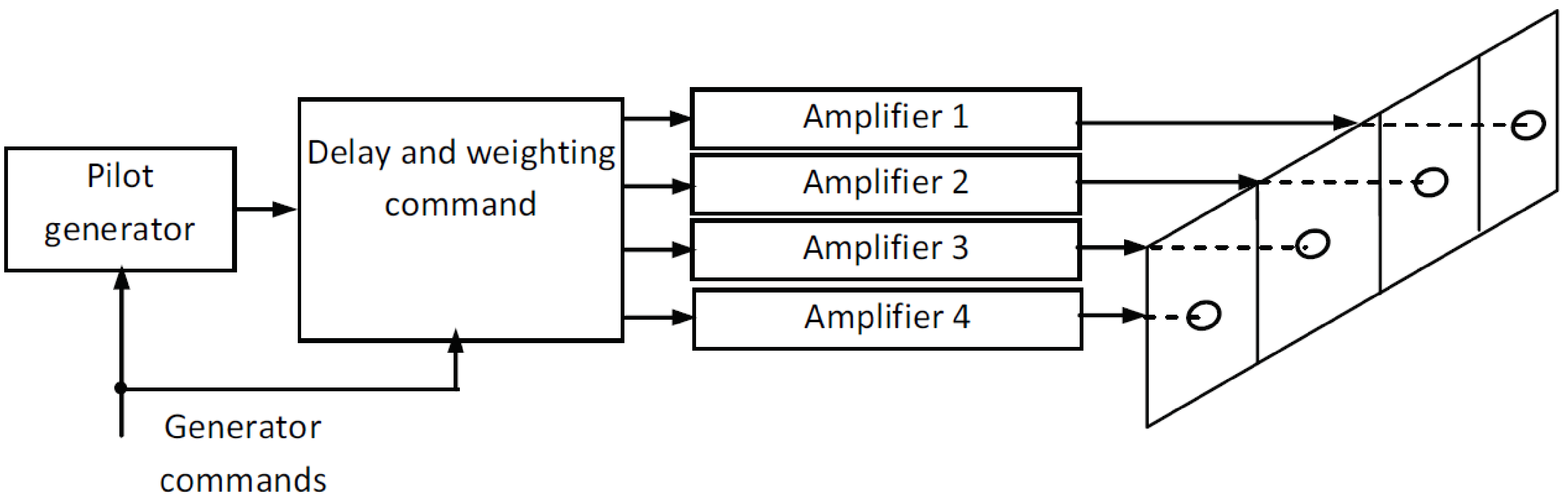
Passive and Active SONAR



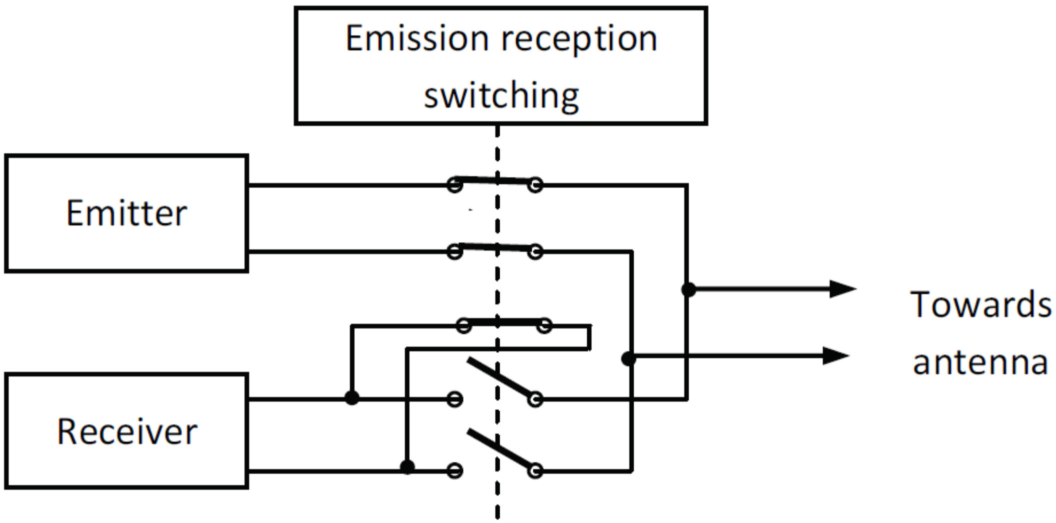
Processing Chain in Active Sonar

Signal Emission

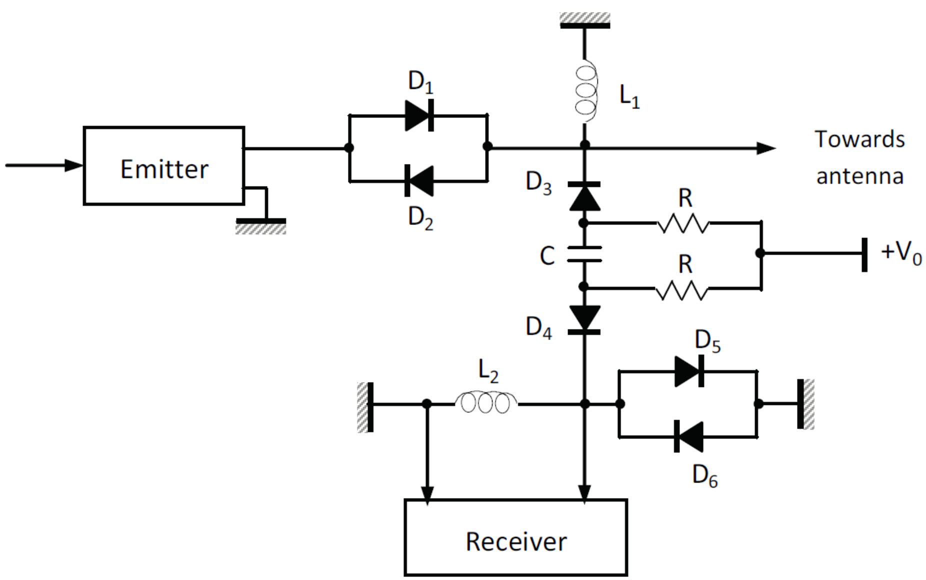




Emitter/Receiver switch

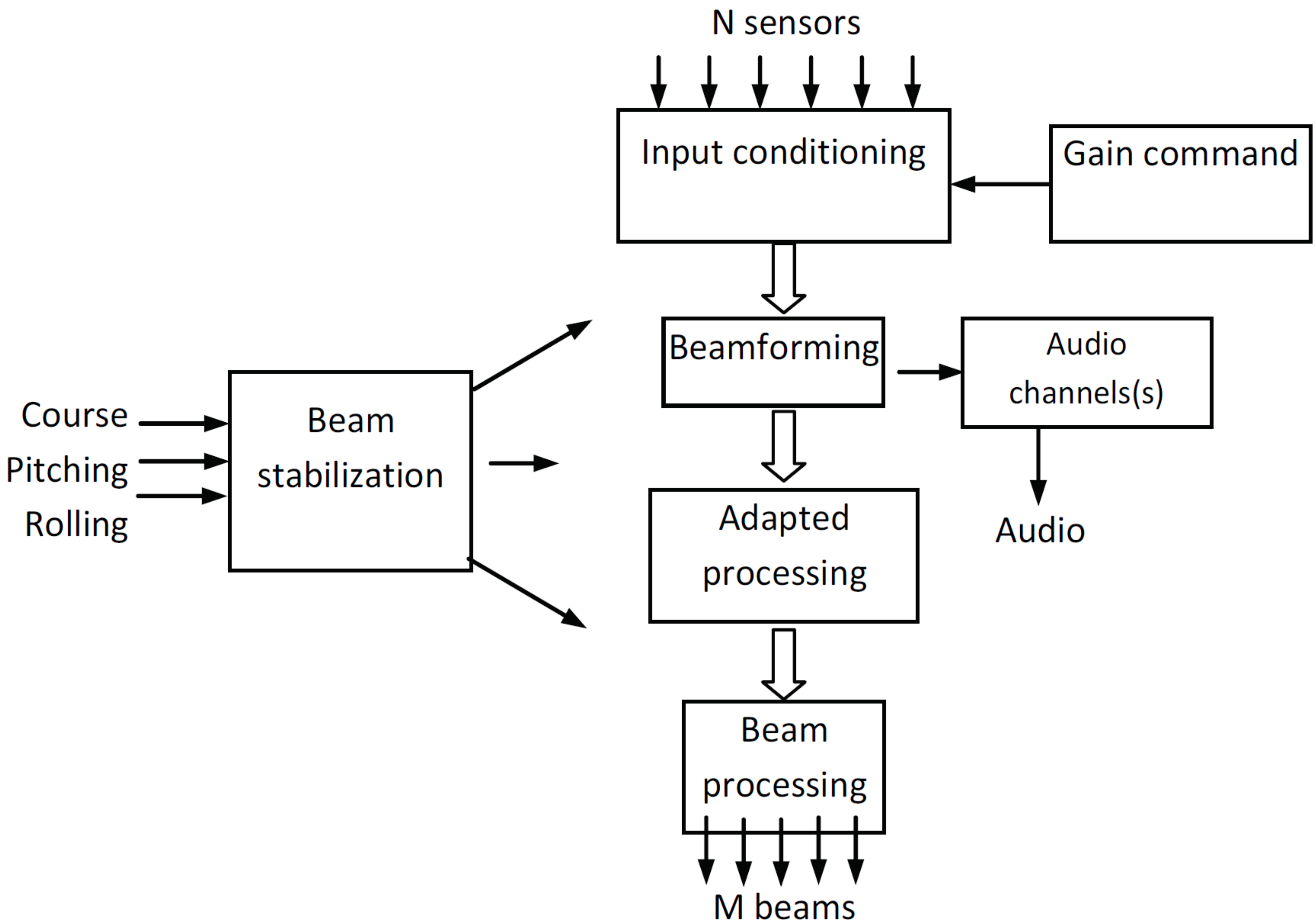


Relay based



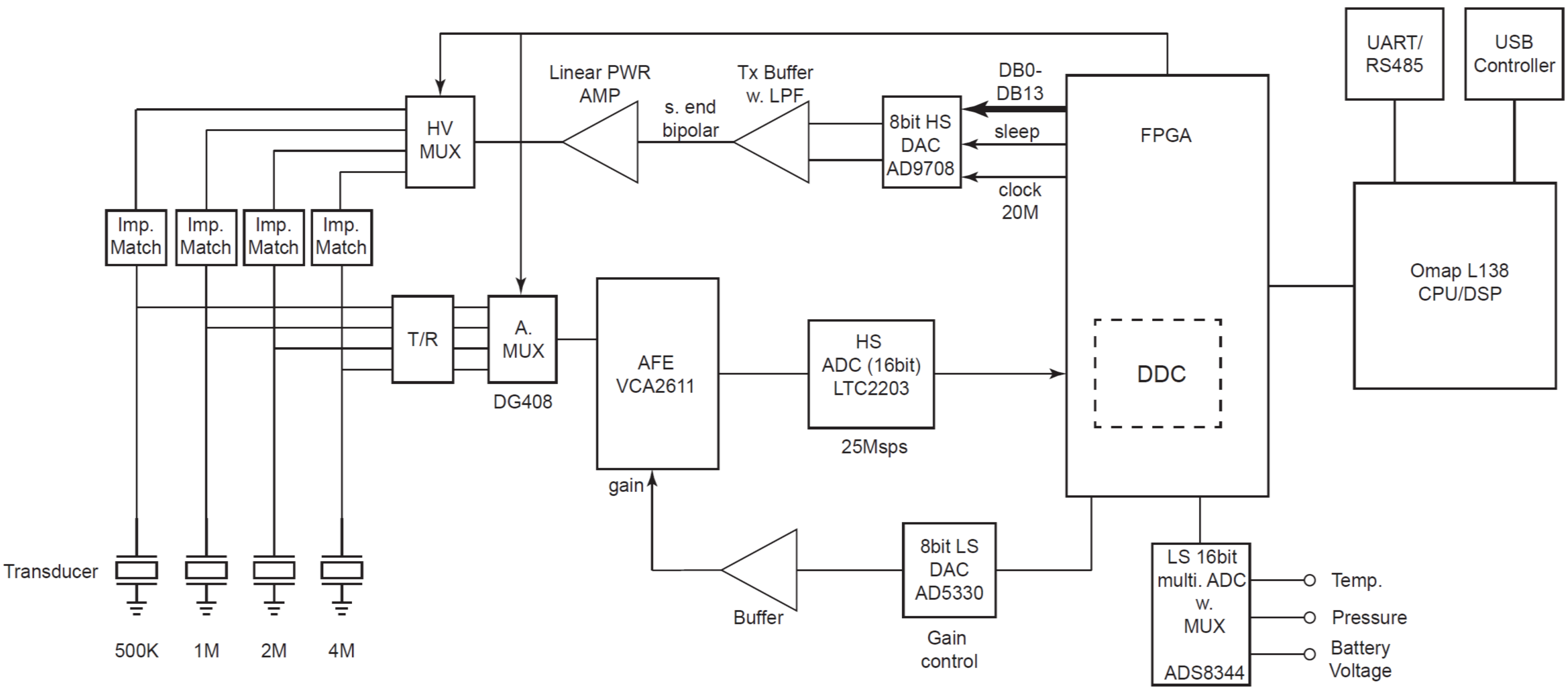
Diode based

Reception



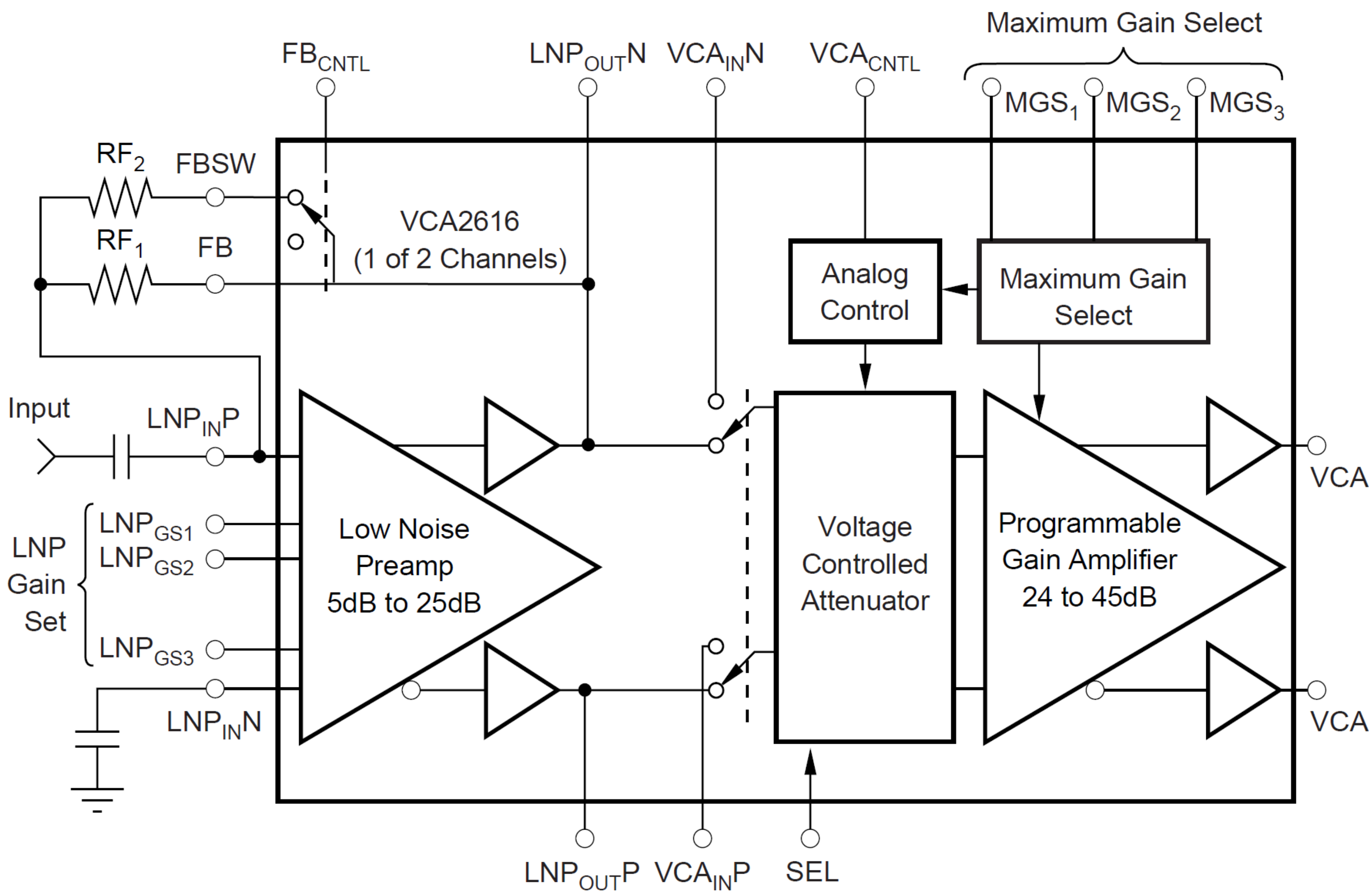
N sensors
Input conditioning
Gain command
Beamforming
Audio channels(s)
Audio
Course
Pitching
Rolling
Beam stabilization
Adapted processing
Beam processing
M beams

An Example for suspended sediment measurement system



AFE: Analog Front End

Inside Analog Front End



Frond End Signal Processing

– Suspended sediment concentration measurement example

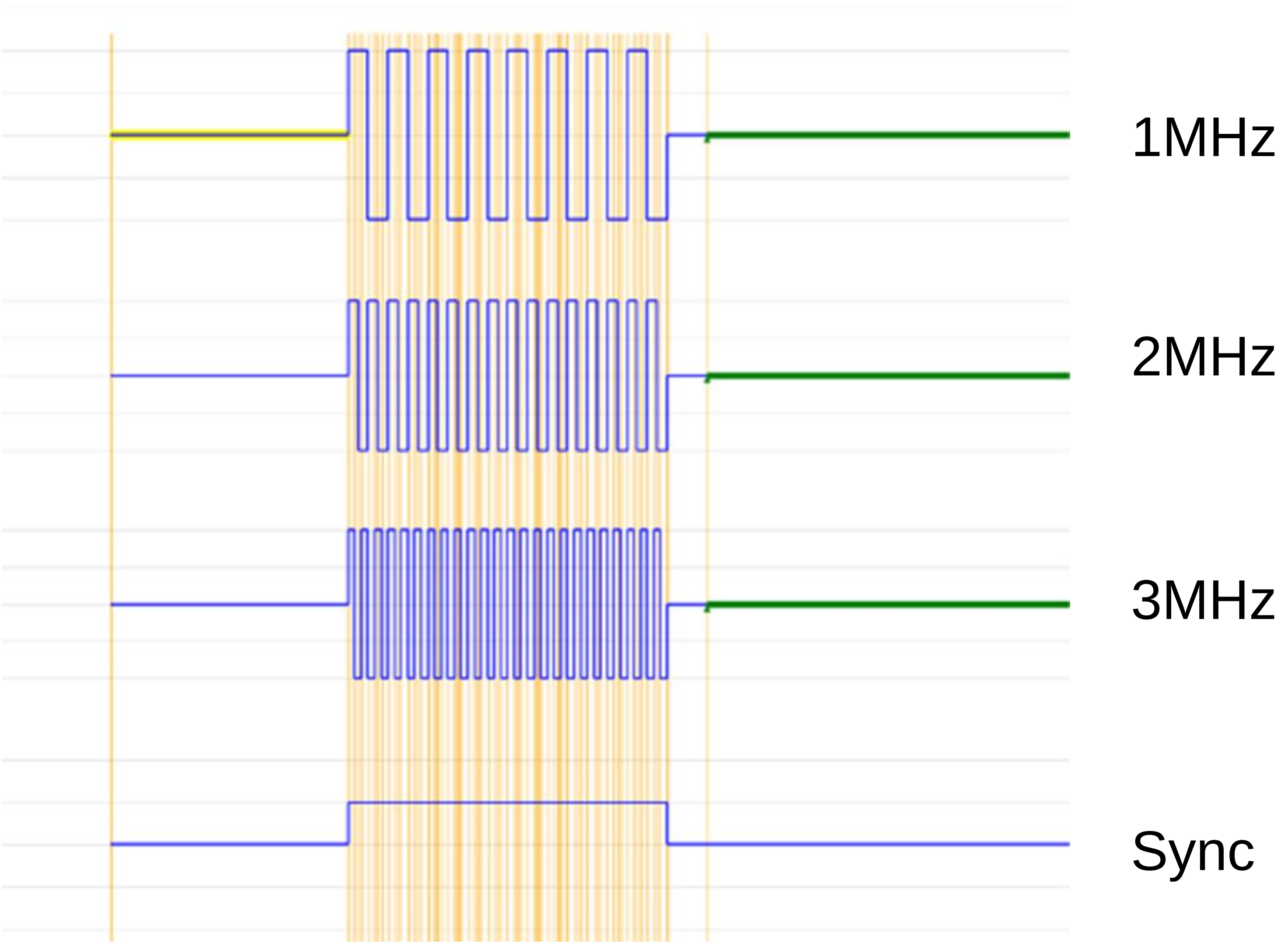
4 transducers in this sediment tank (500k, 1M, 1M, 2M and 3 MHz)

Transducers generate short pulses(@ 20Hz) simultaneous

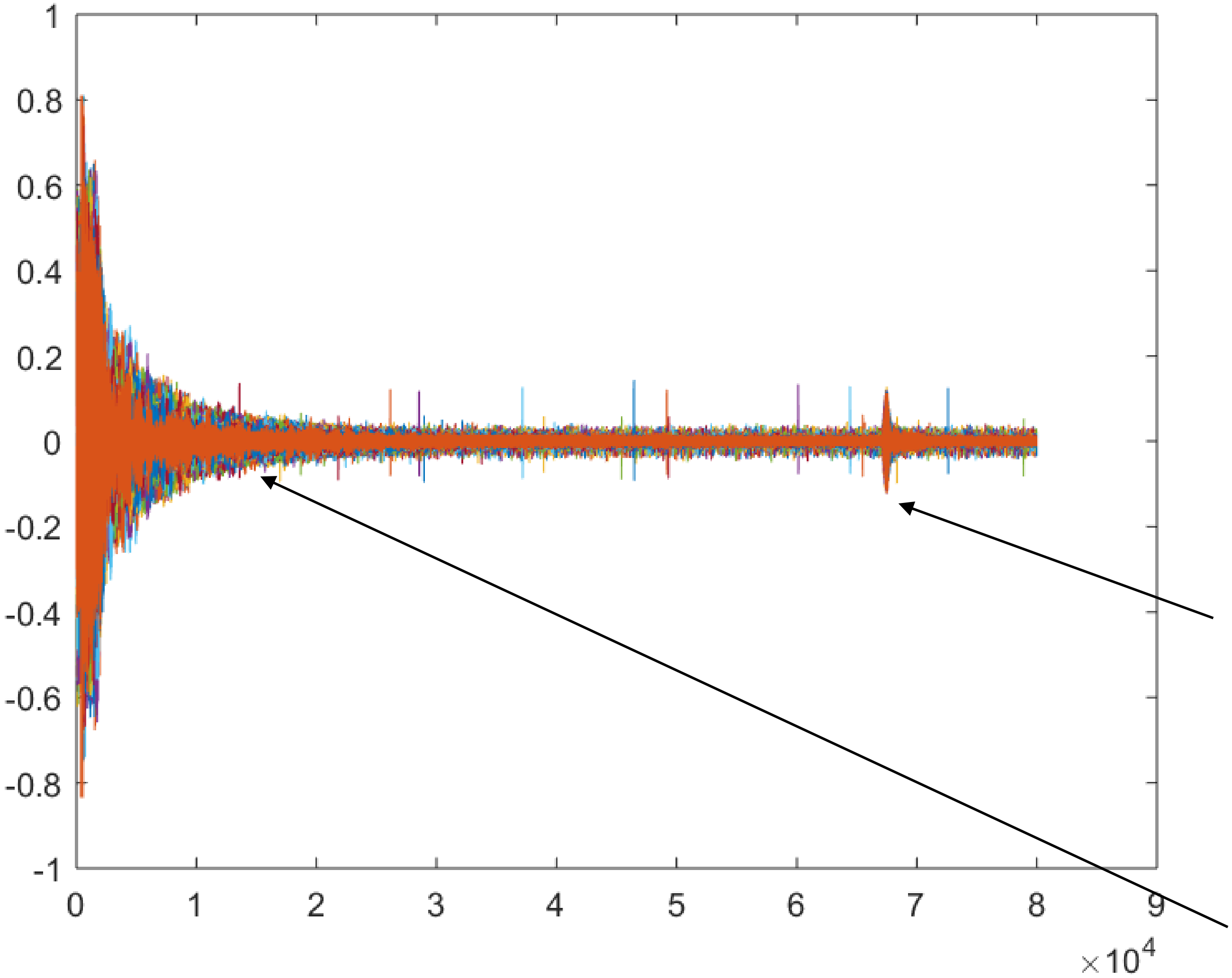
Calculate sediment concentration from backscattered signal

Generated short pulses

Why square waves instead of pure sinusoidal ?



Received backscattered signal @ 1MHz



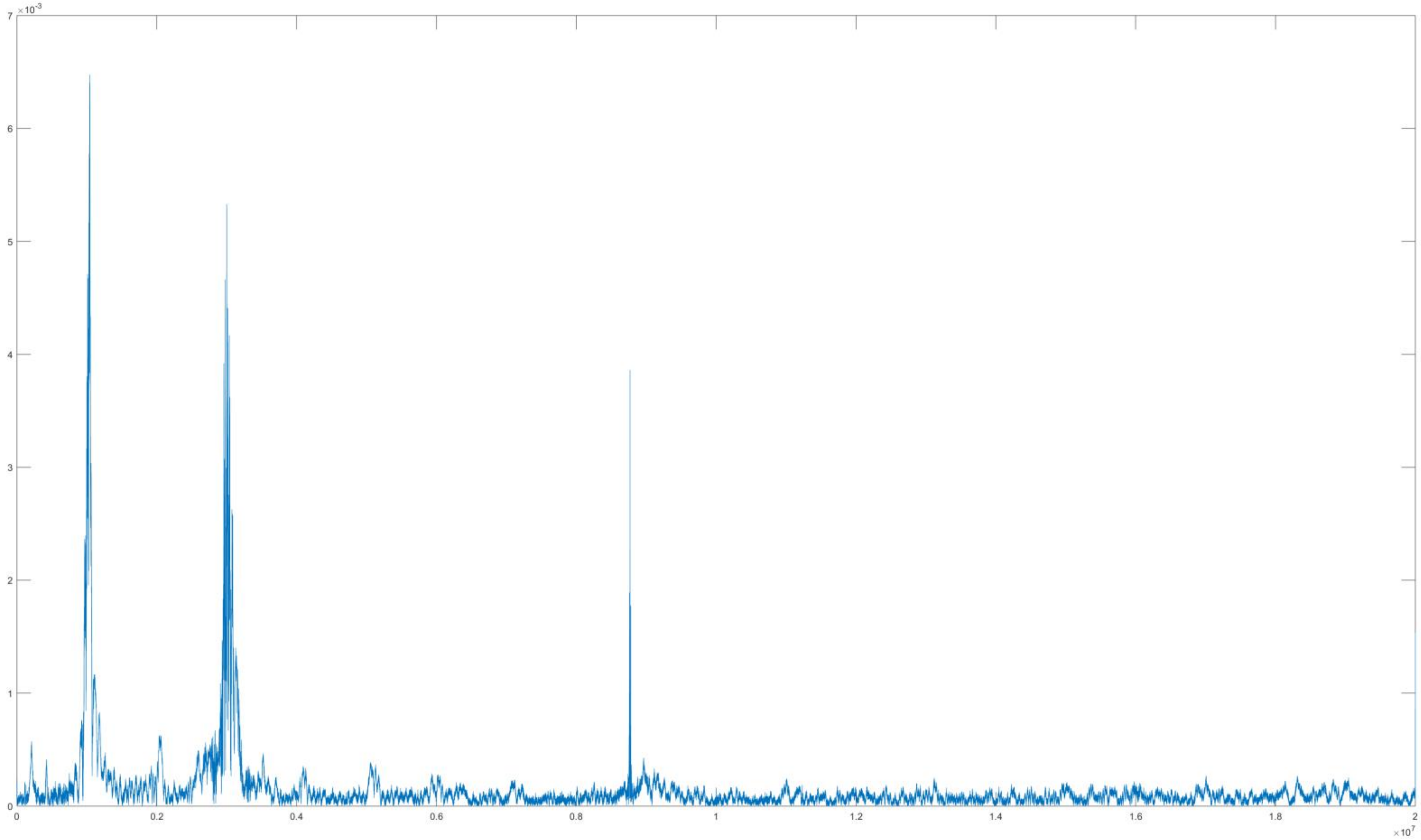
200 instances, 80000 samples for each instance

Return from mixing blades

Return from suspended particle

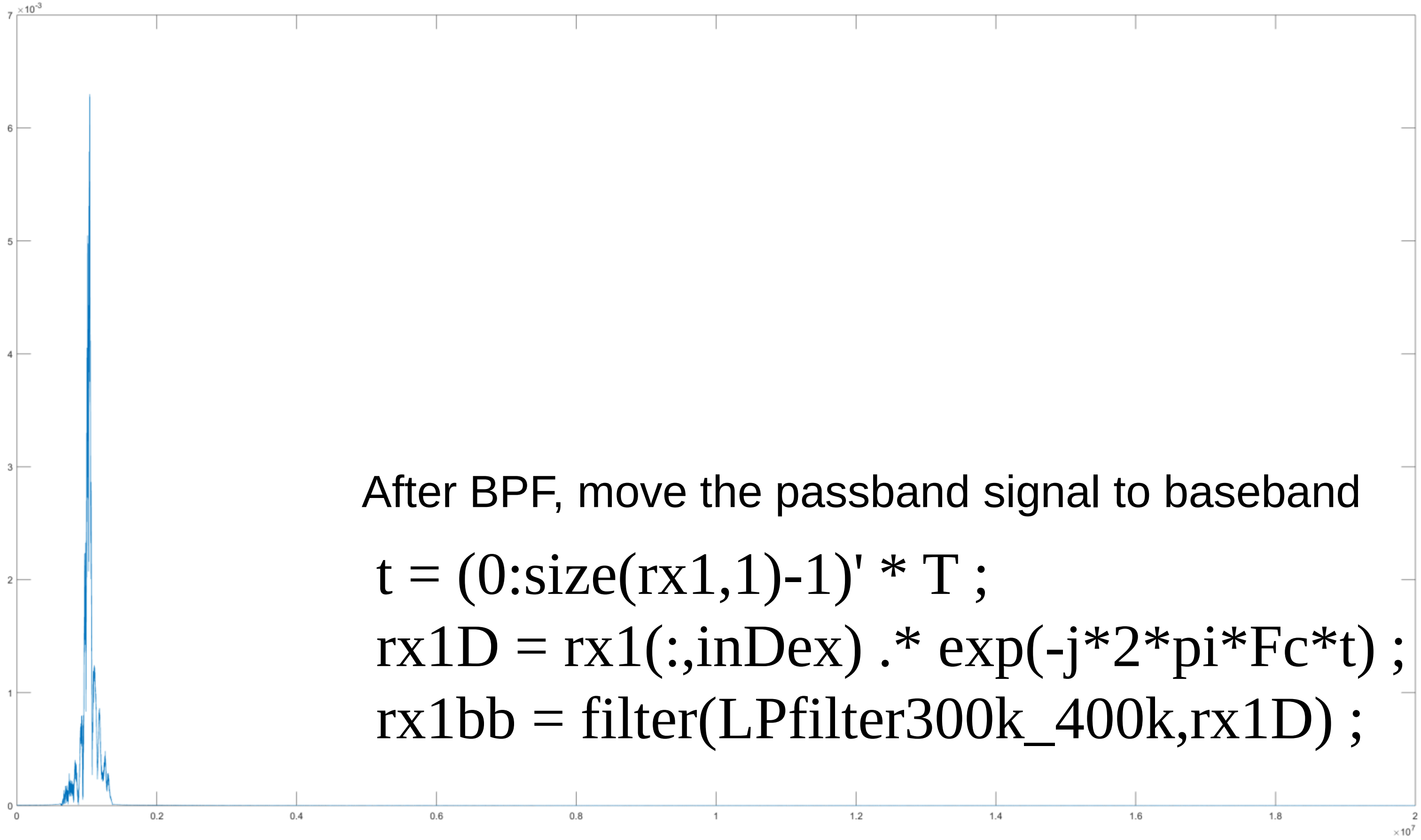
RAW data cannot be used directly. Why?

FFT of received signal



Need to remove side tone.

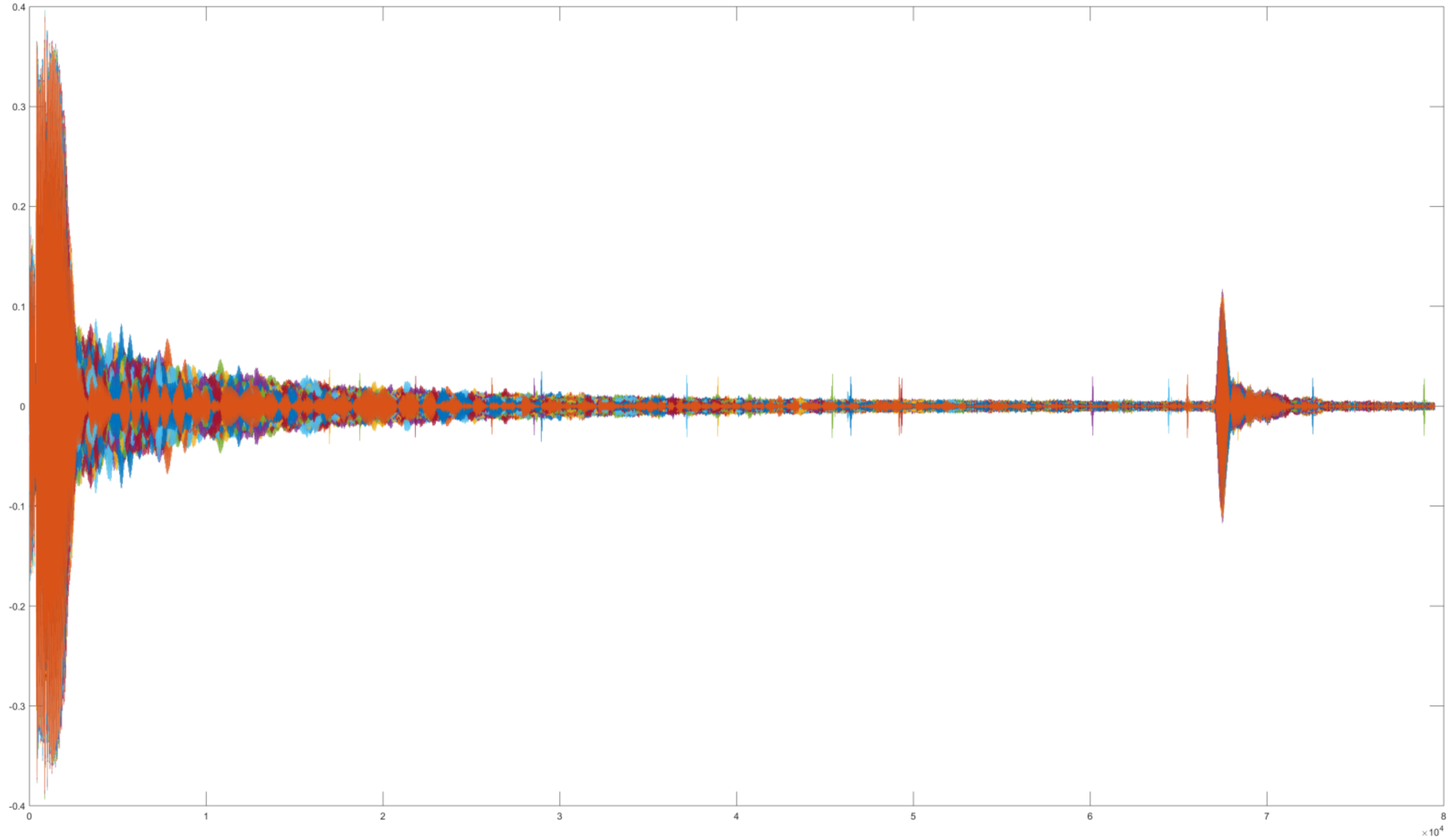
Out of band signal filtering by a Band-pass (BPF) filter



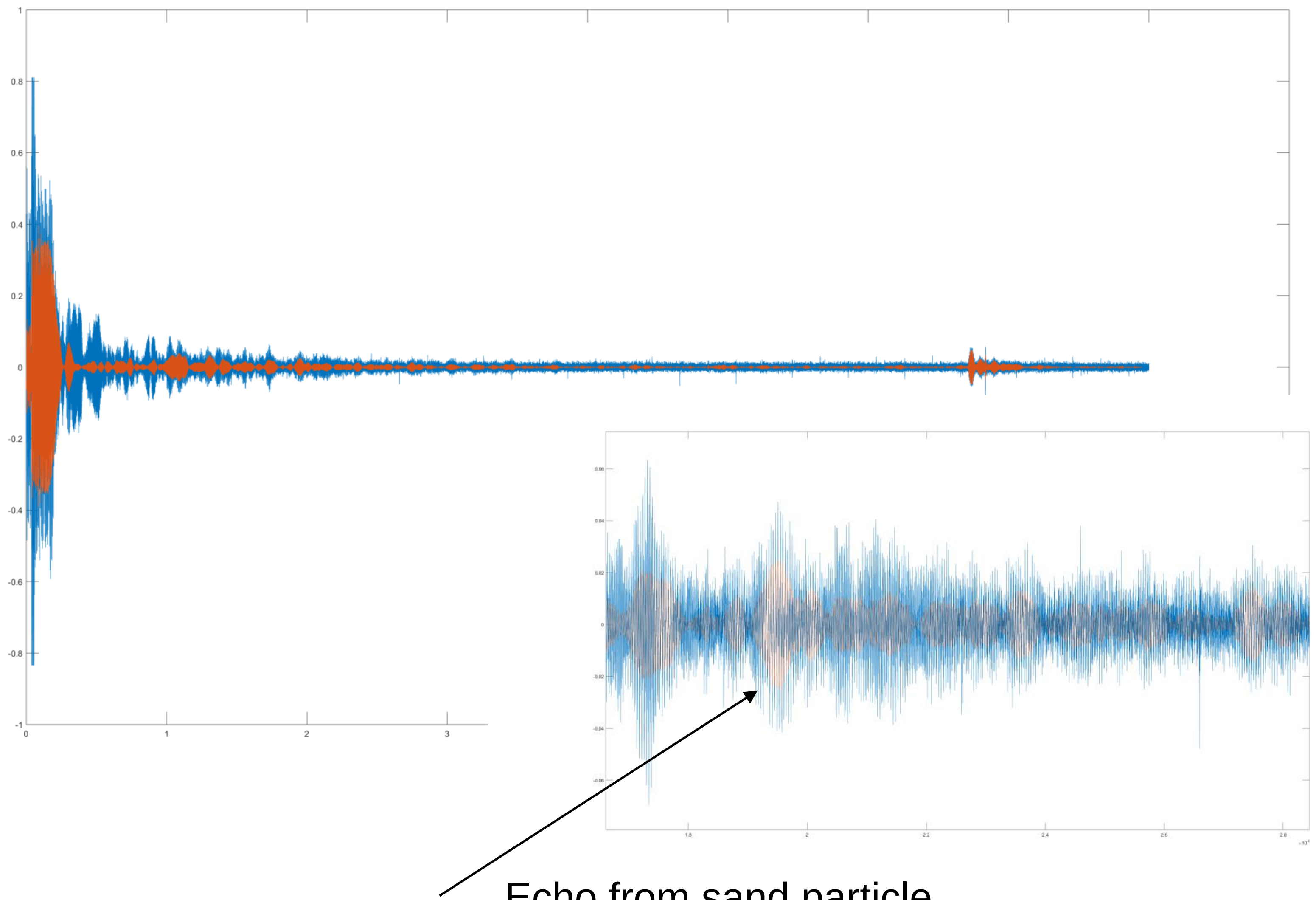
After BPF, move the passband signal to baseband

```
t = (0:size(rx1,1)-1)' * T ;
rx1D = rx1(:,inDex) .* exp(-j*2*pi*Fc*t) ;
rx1bb = filter(LPfilter300k_400k,rx1D) ;
```

Received Signal in Passband (after BPF)

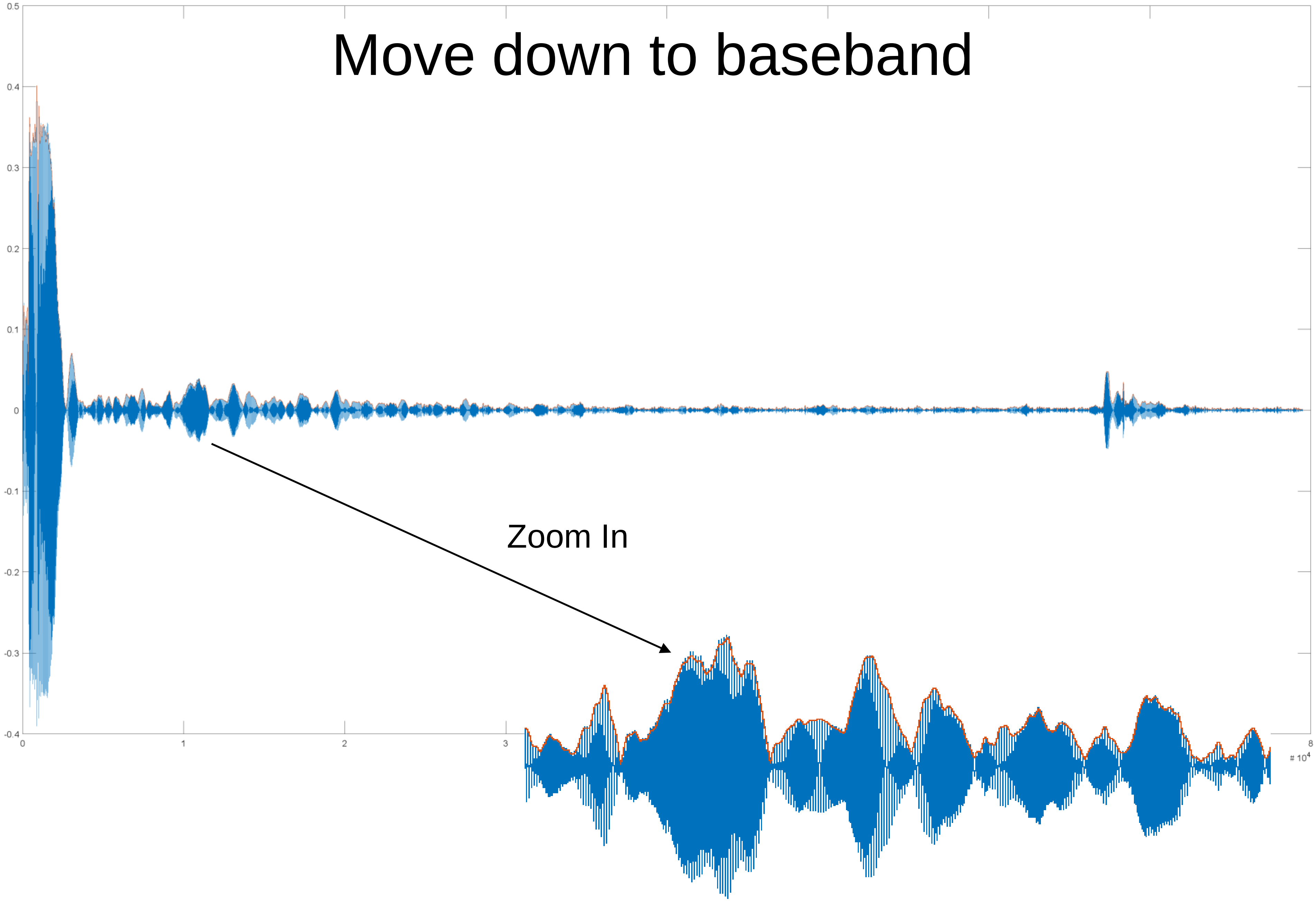


Comparison of received signal before(blue) and after BPF(orange)

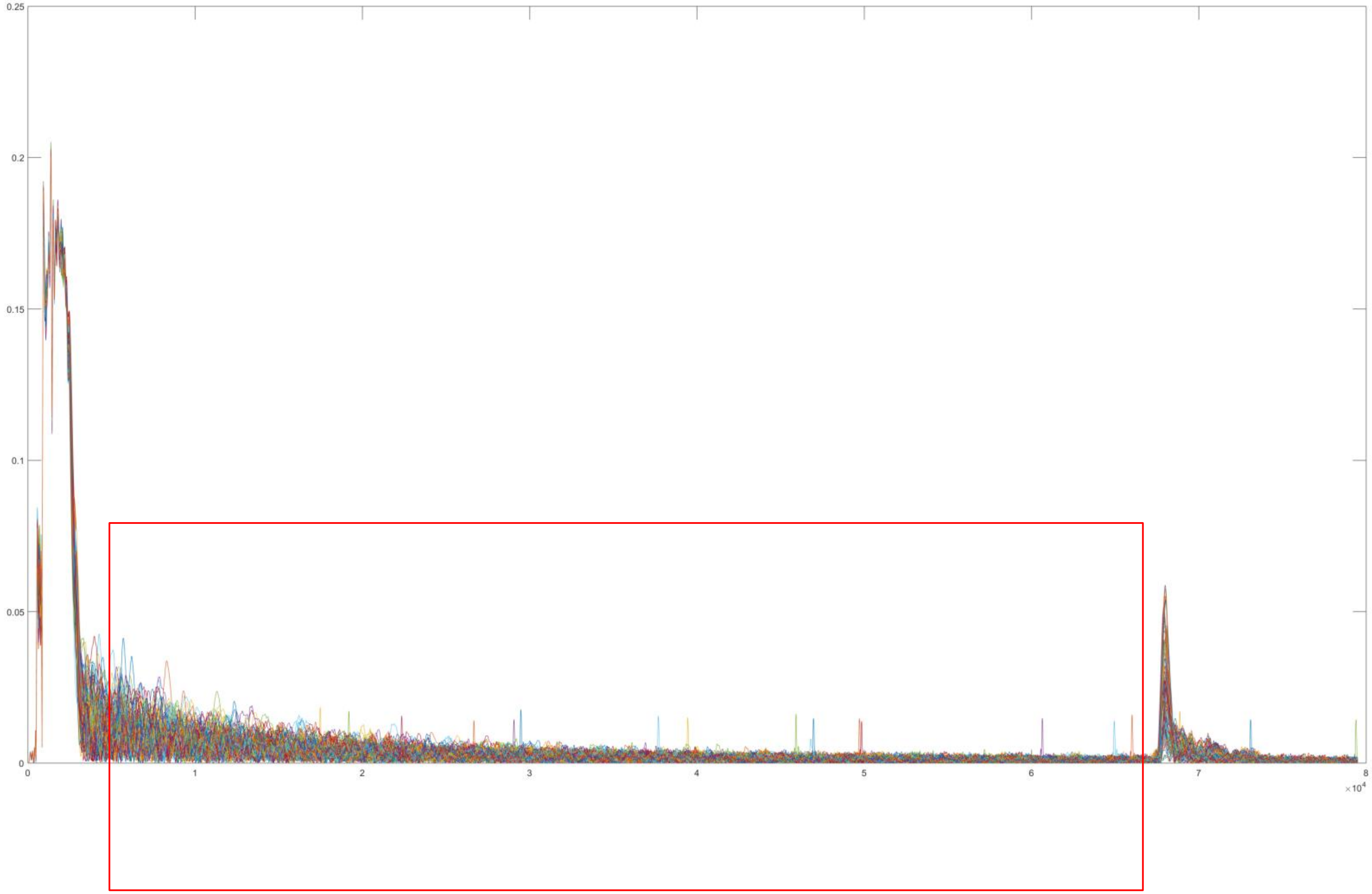


Echo from sand particle

Move down to baseband

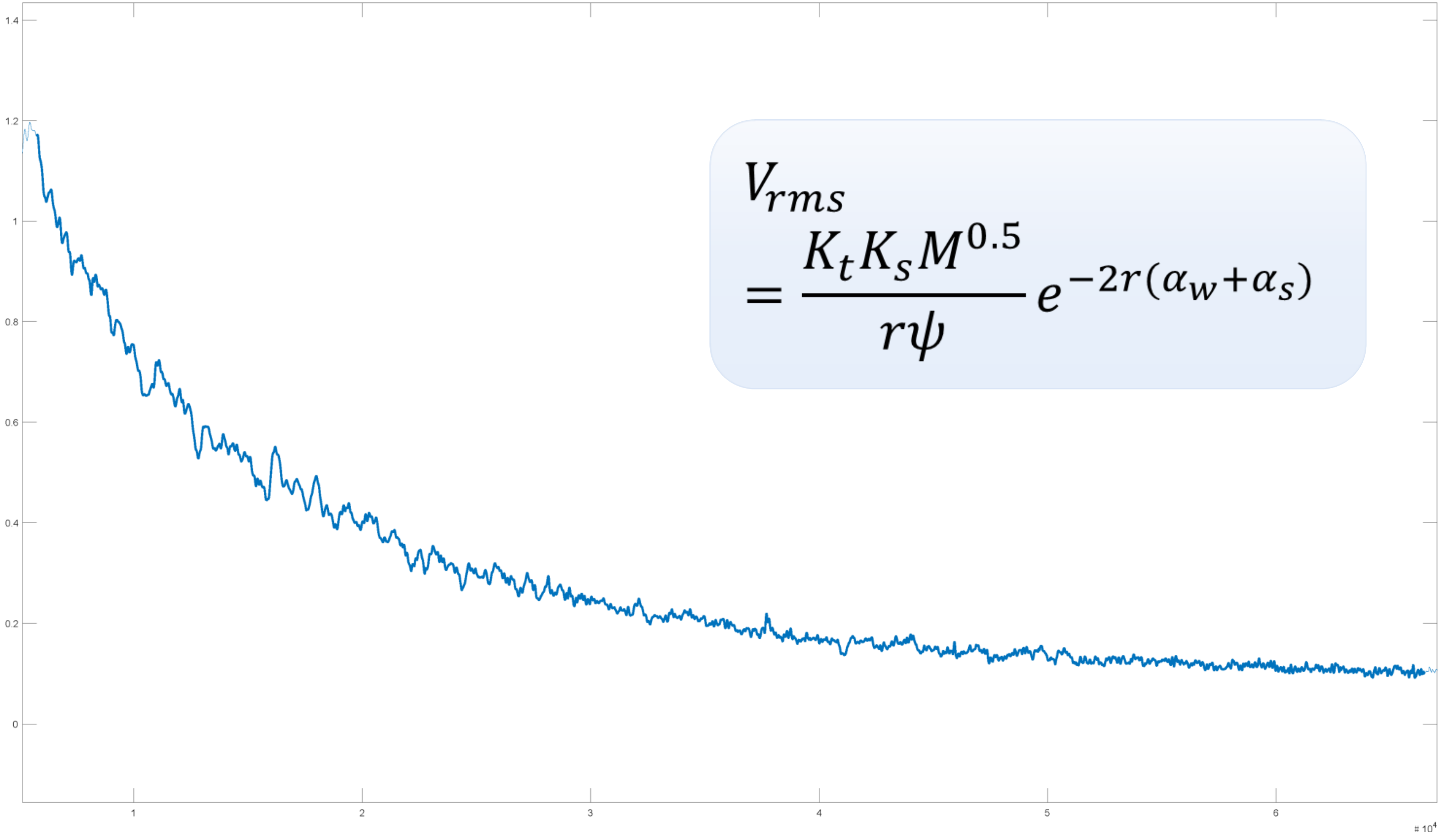


Average all the received instances



Results for 1 MHz @ 0.4g/1L water

$$V_{rms} = \frac{K_t K_s M^{0.5}}{r\psi} e^{-2r(\alpha_w+\alpha_s)}$$

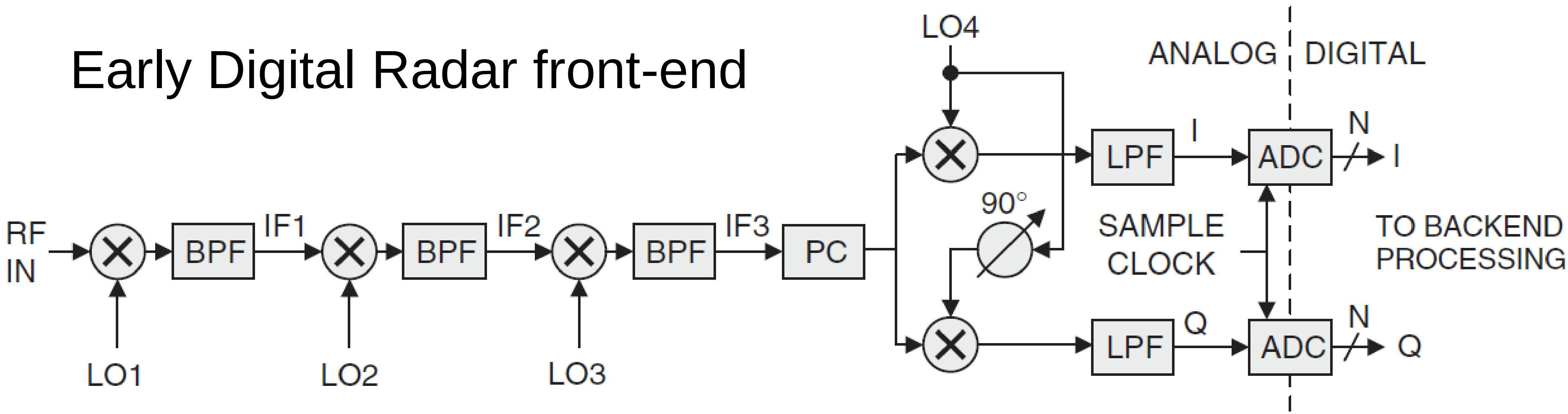


Signal Processing Chain

Conventional Signal Processing Chain

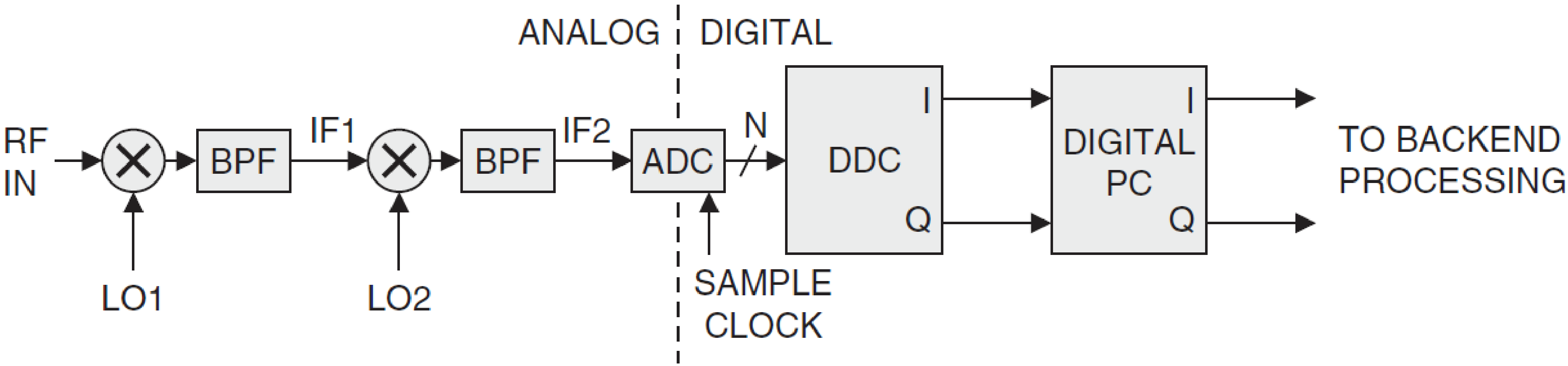
- •Cost
- •Performance & flexibility
- •Advance in ADC/DAC

Early Digital Radar front-end



LO: Local Oscillator, BPF: Band Pass Filter, LPF: Low Pass Filter, PC: Pulse Compression

Modern Digital Radar front-end

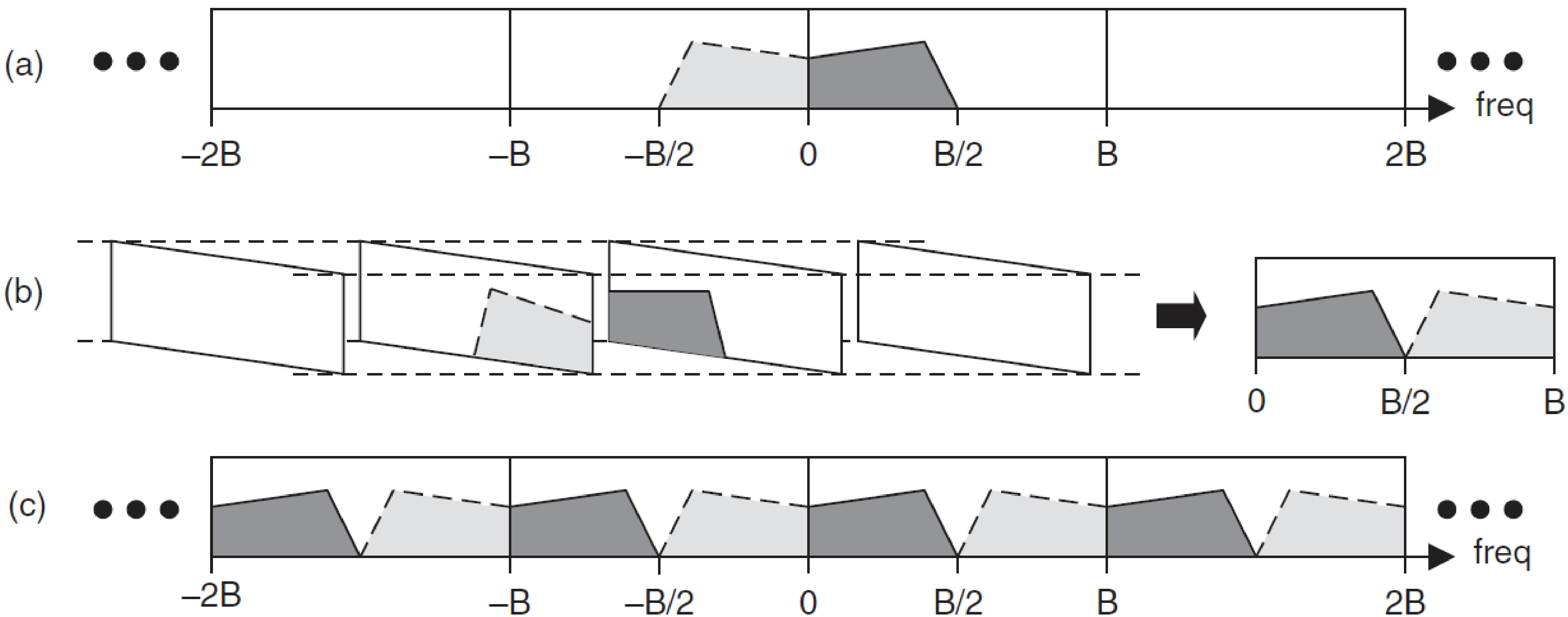


DDC: Digital-Down-Converter

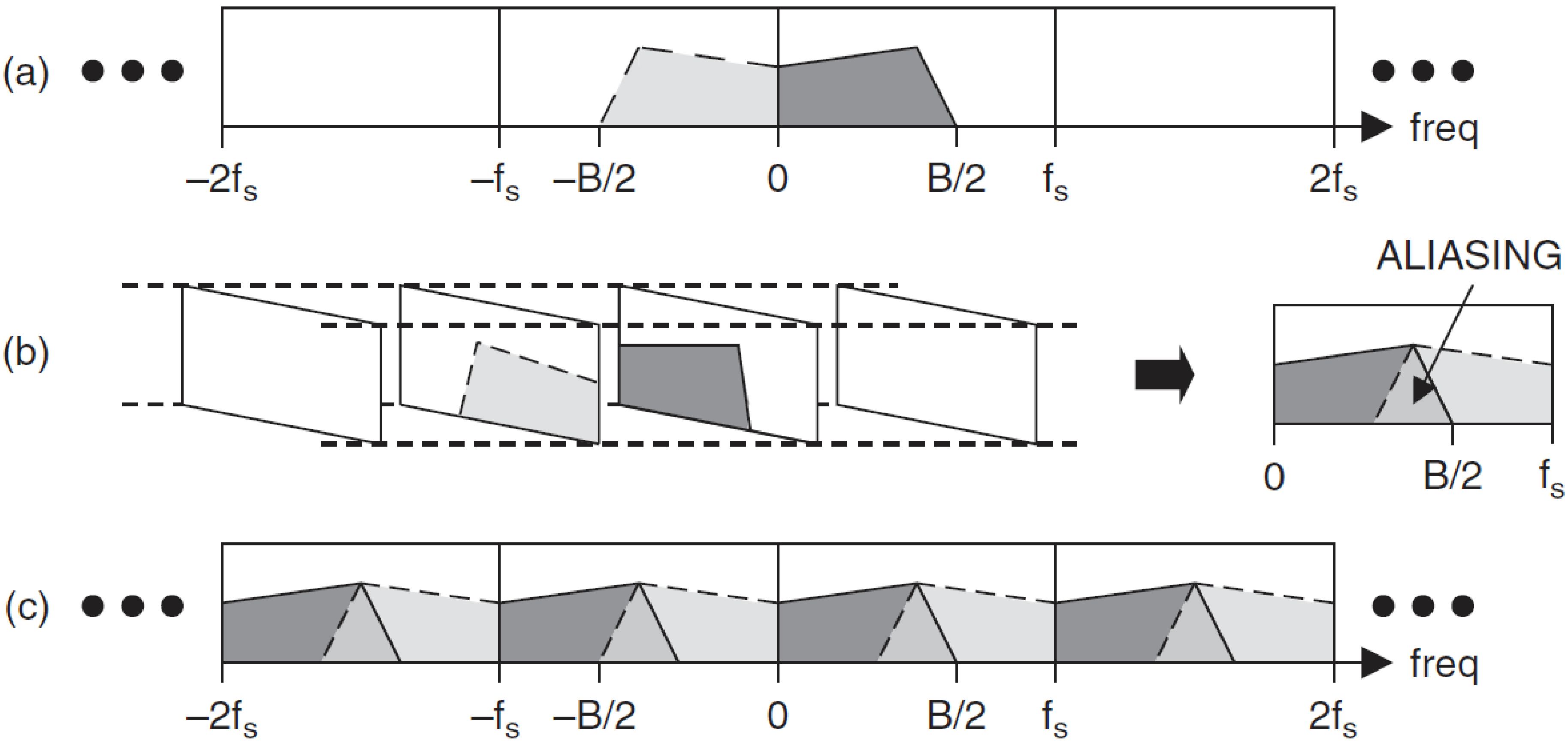
Signal Sampling Basis -- Revisit

- *Nyquist frequency lower bounds the sampling rate at which reconstruction is possible without aliasing.*
- *Nyquist frequency is equal to the two-sided signal bandwidth B.*

Sampling @ Baseband --No Aliasing



Sampling @ baseband -- With Aliasing



Sampling real bandpass signal --No Aliasing

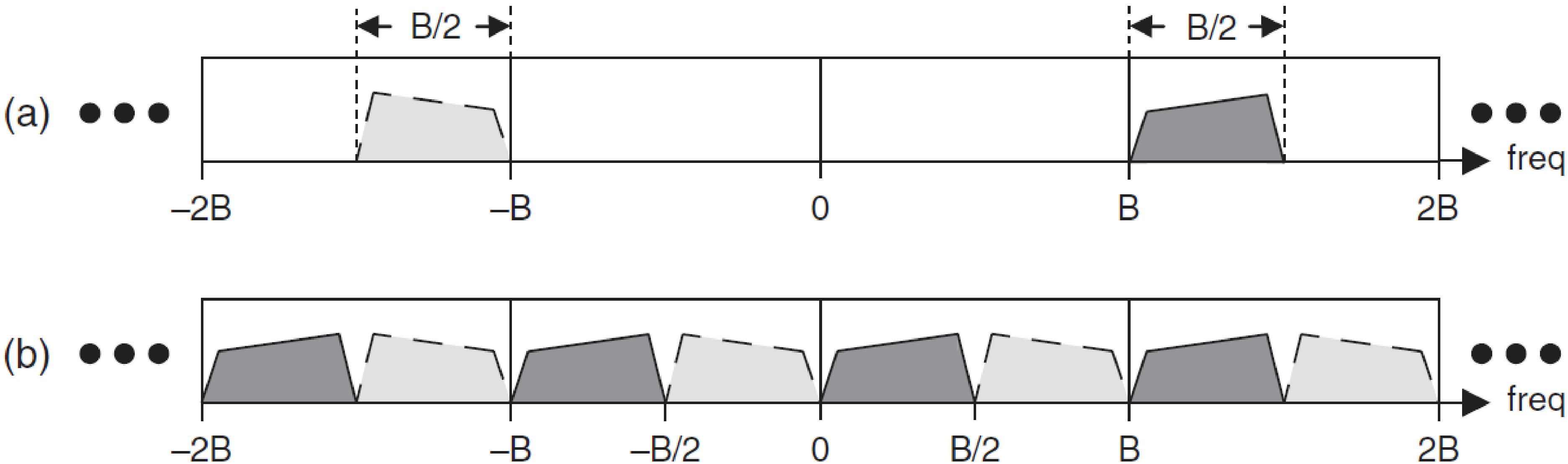


FIGURE 25.5 (*a*) Bandlimited, real passband signal spectrum before sampling and (*b*) signal spectrum after sampling

The Nyquist frequency is B even though the signal contains components at actual frequencies greater than B.

Bandpass sampling leads to considerable cost savings.

Sampling complex bandpass signal --No Aliasing

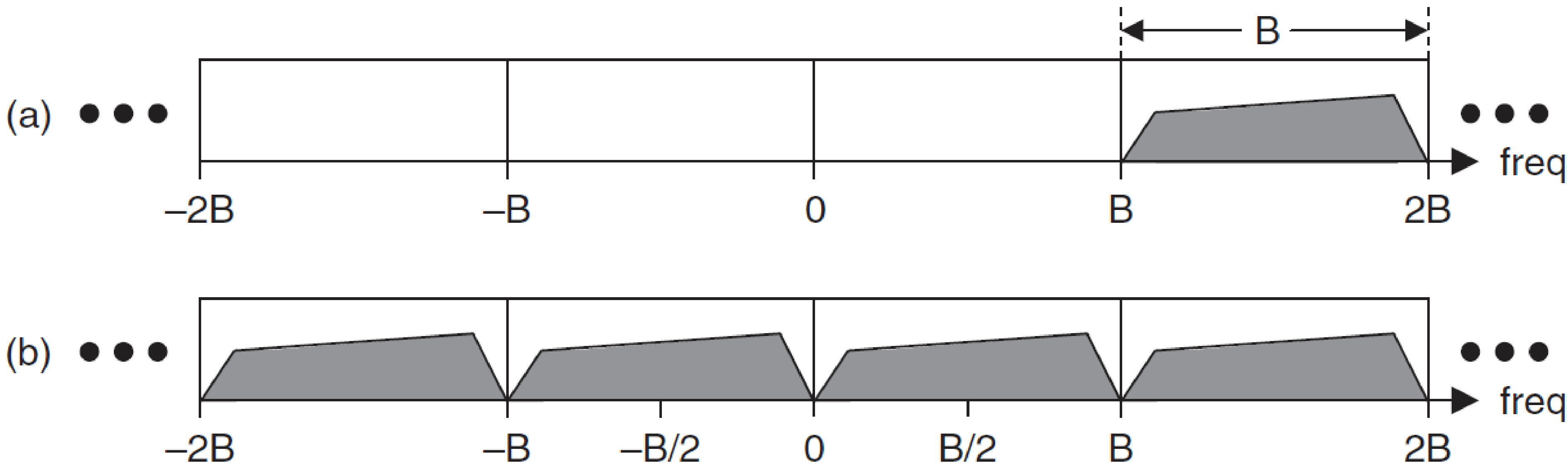


FIGURE 25.6 (*a*) Non-real signal spectrum before sampling by Nyquist frequency, *B*, and (*b*) signal spectrum after sampling

Sampling real bandpass signal --With Aliasing

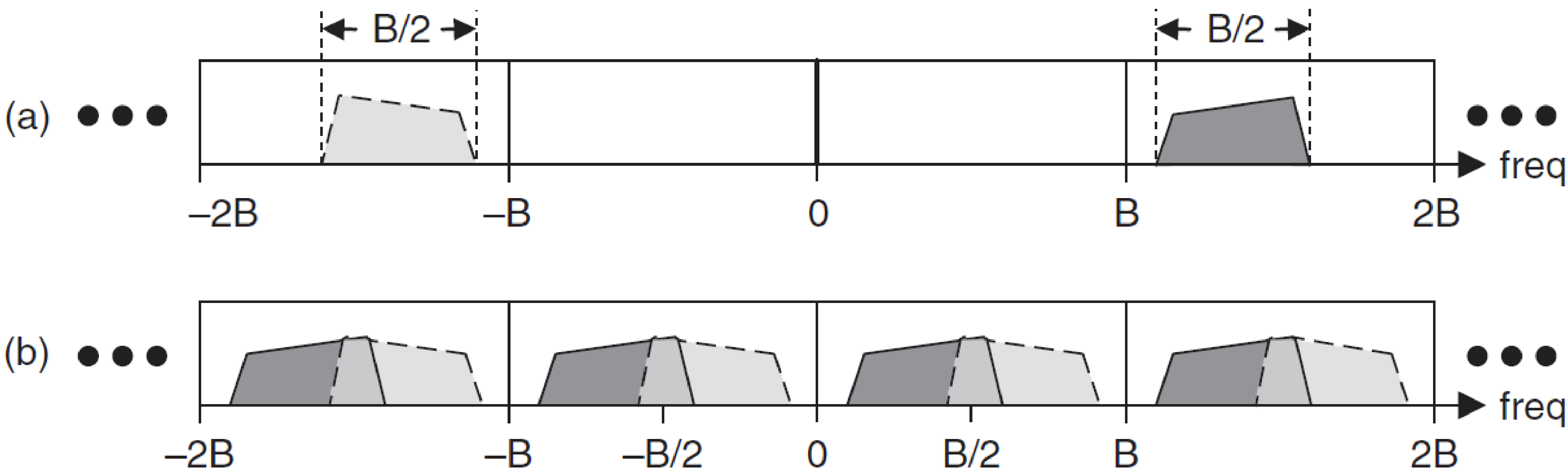


FIGURE 25.7 (*a*) Bandlimited, real passband signal spectrum before sampling and (*b*) signal spectrum after sampling

To solve this problem, one may:

1. Move the signal
2. Increase sampling rate

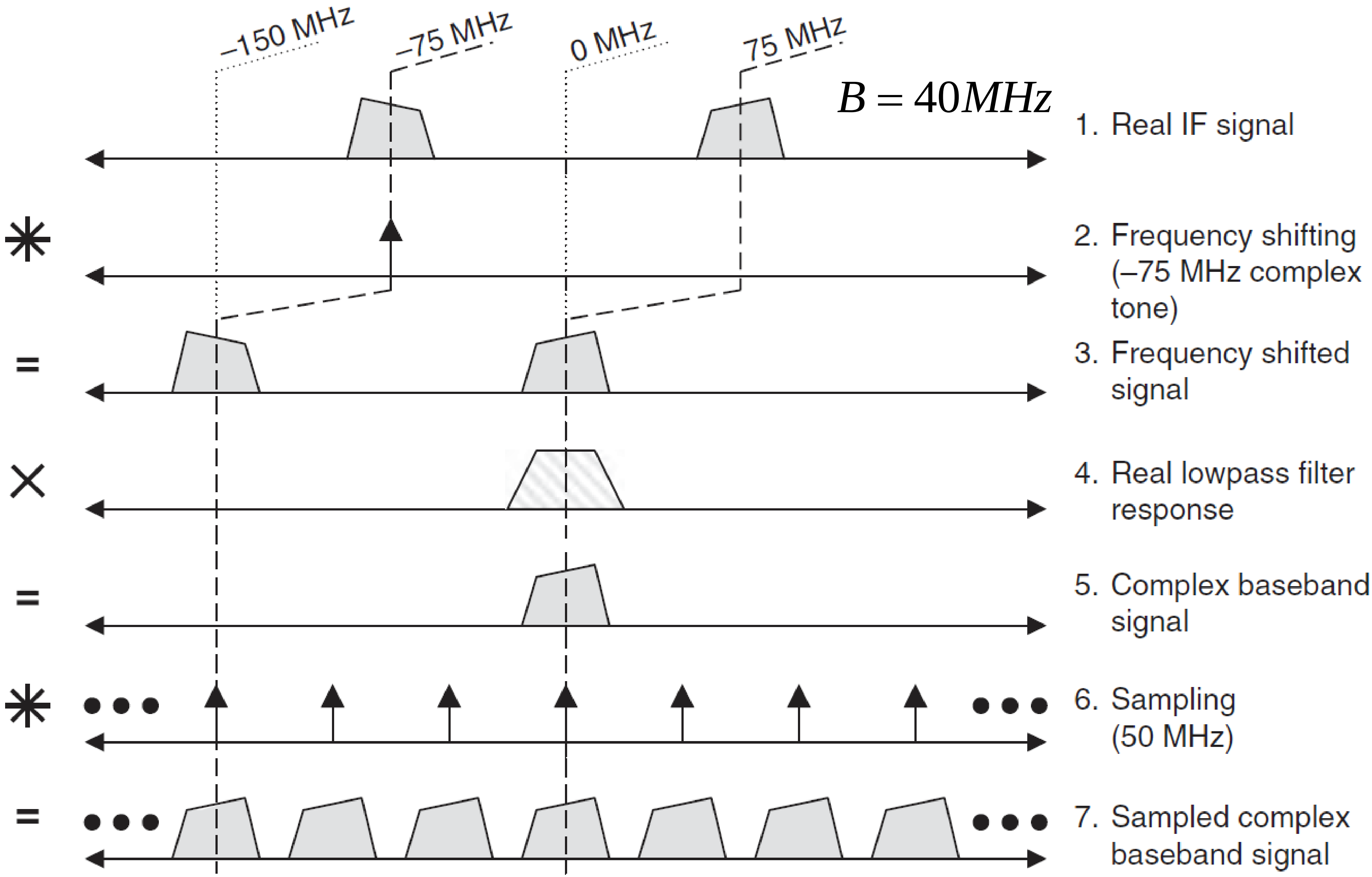
Digital Downconversion (DDC)

Bring down IF signal to complex baseband.

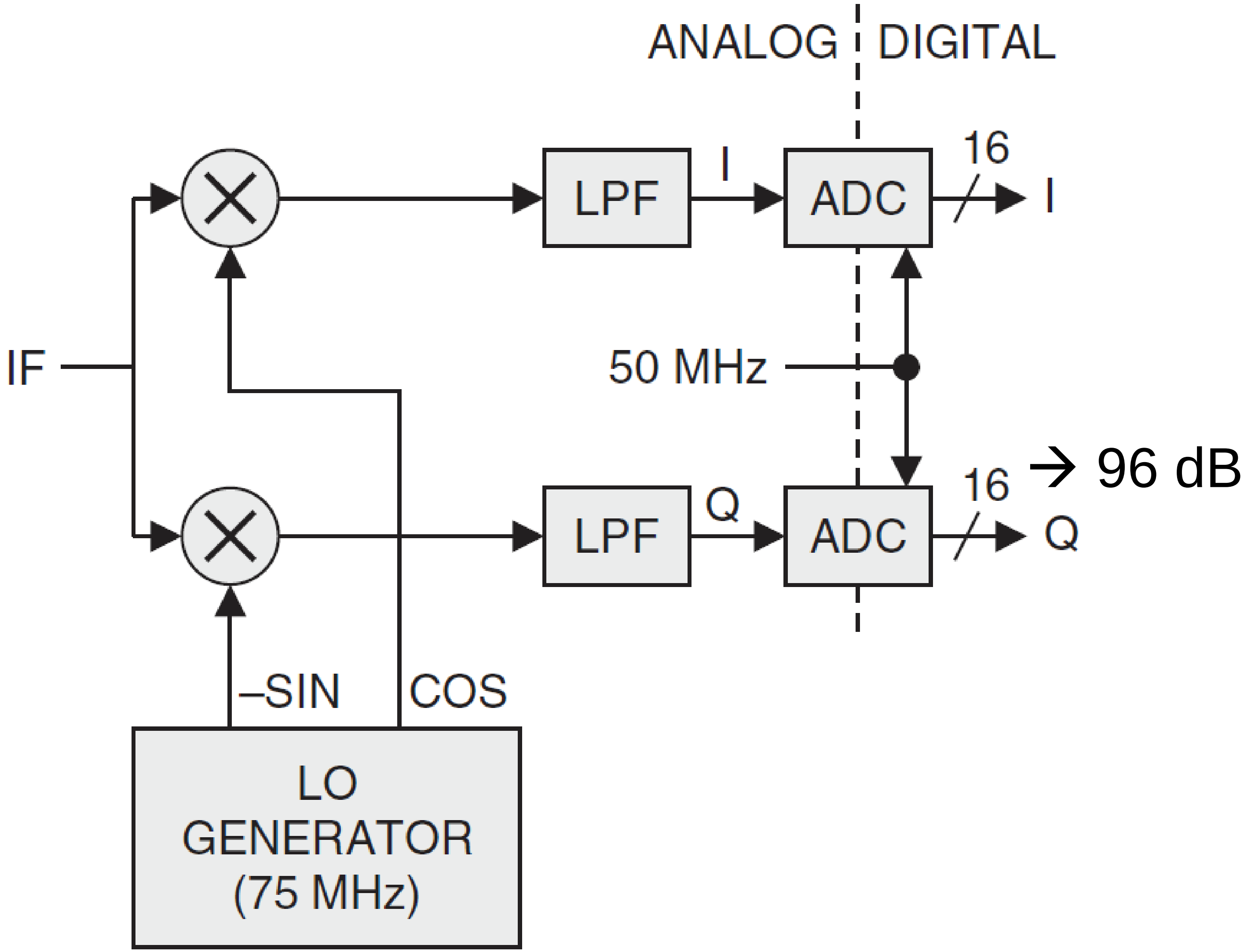
1. Analog Downconversion and Sampling (traditional approach)

2. Digital Downconversion (modern approach)

Analog Downconversion and Sampling



How it is implemented in hardware.



Digital Downconversion and Sampling

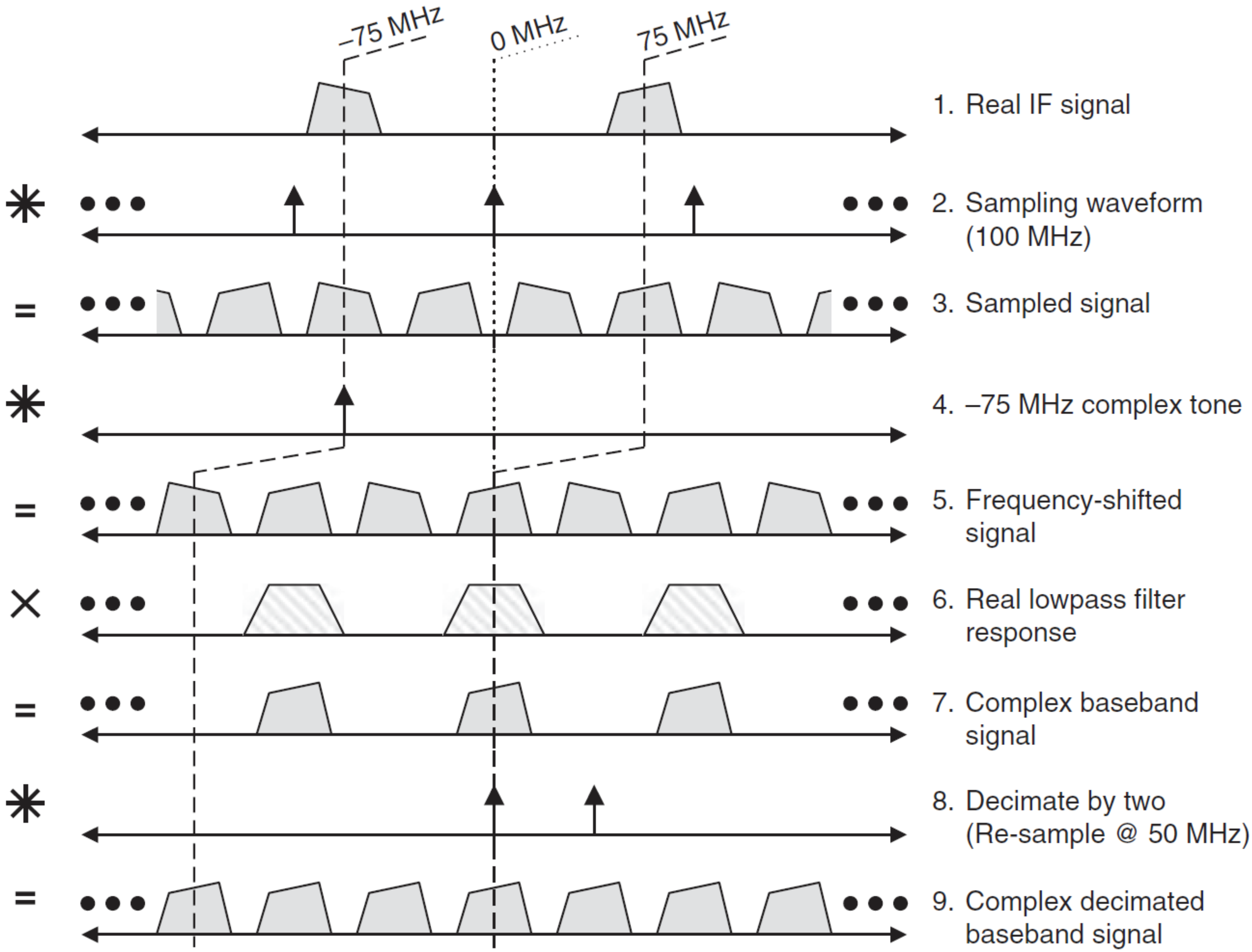
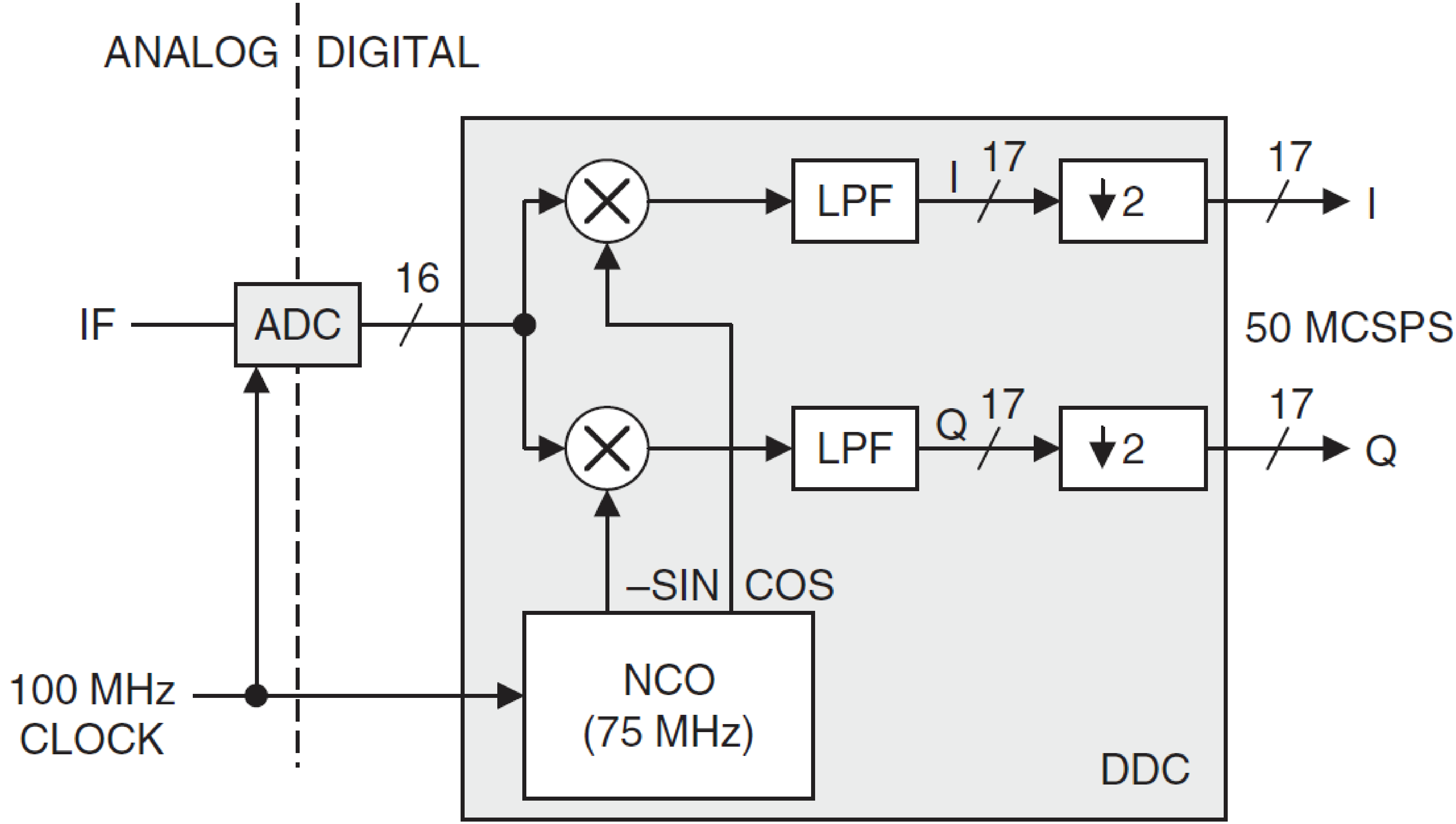


FIGURE 25.10 Digital downconversion in the frequency domain

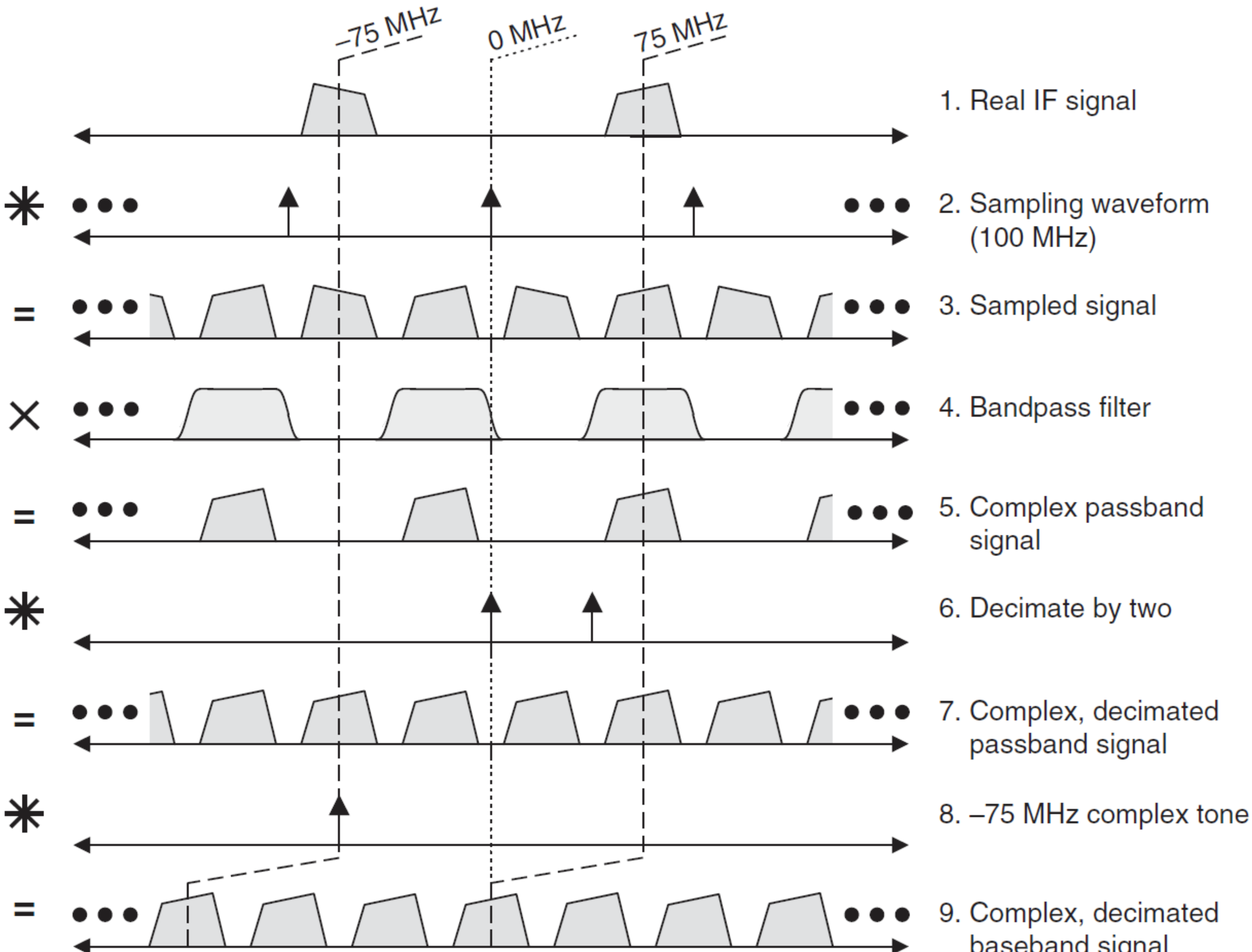
Digital Downconversion Implementation



NCO: *Numerically Controlled Oscillator*

MCSPS: *Million Complex Samples Per Second*

Direct Digital Downconversion



- Implementation of the Direct DDC

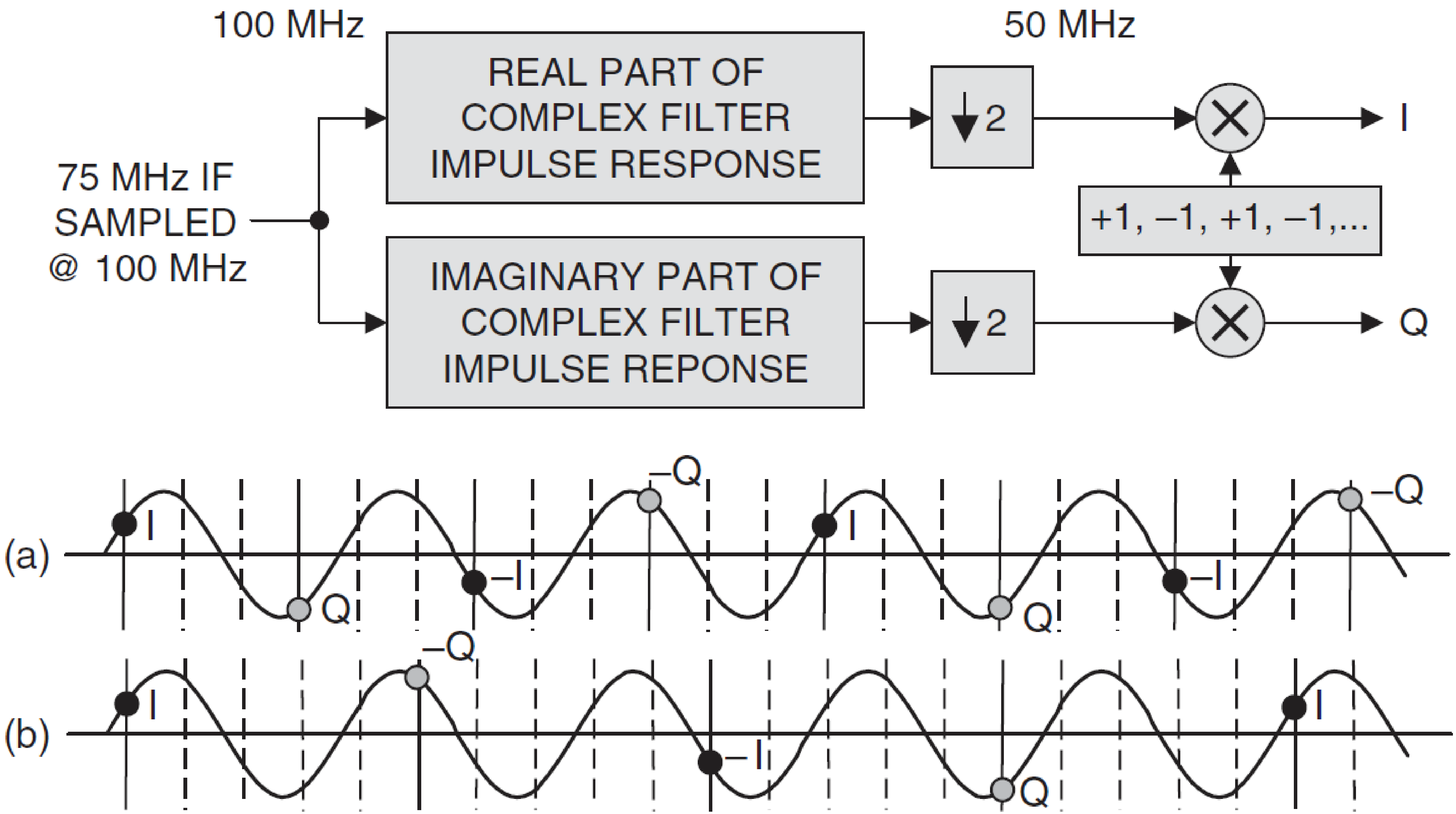
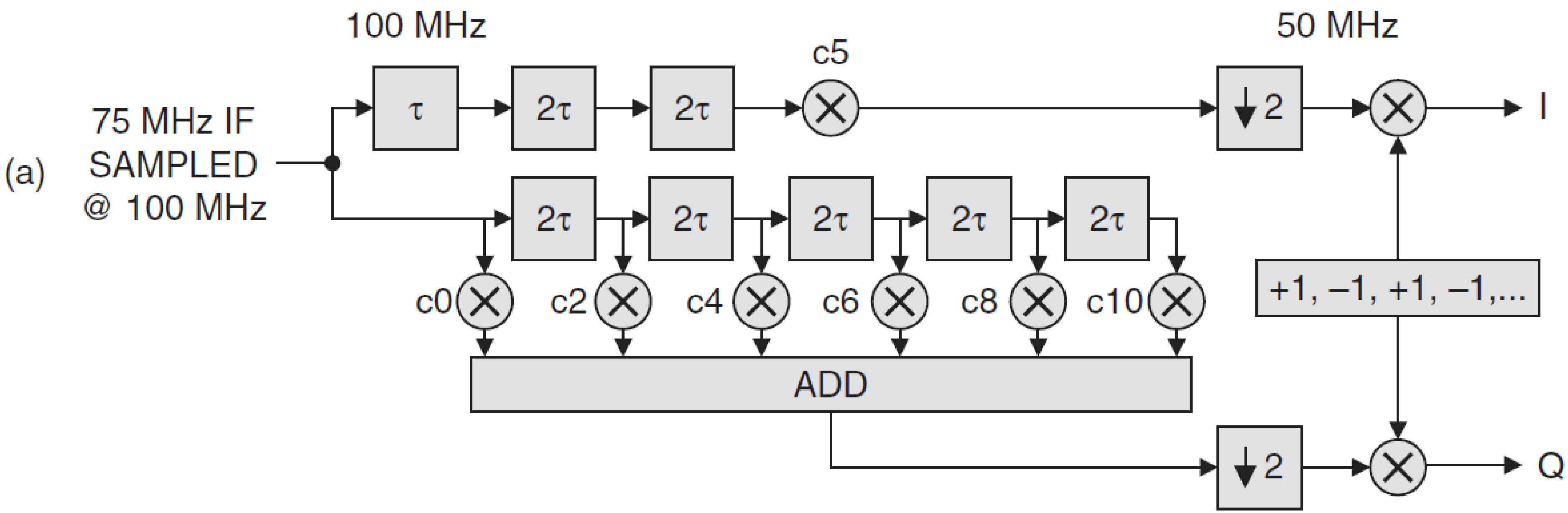
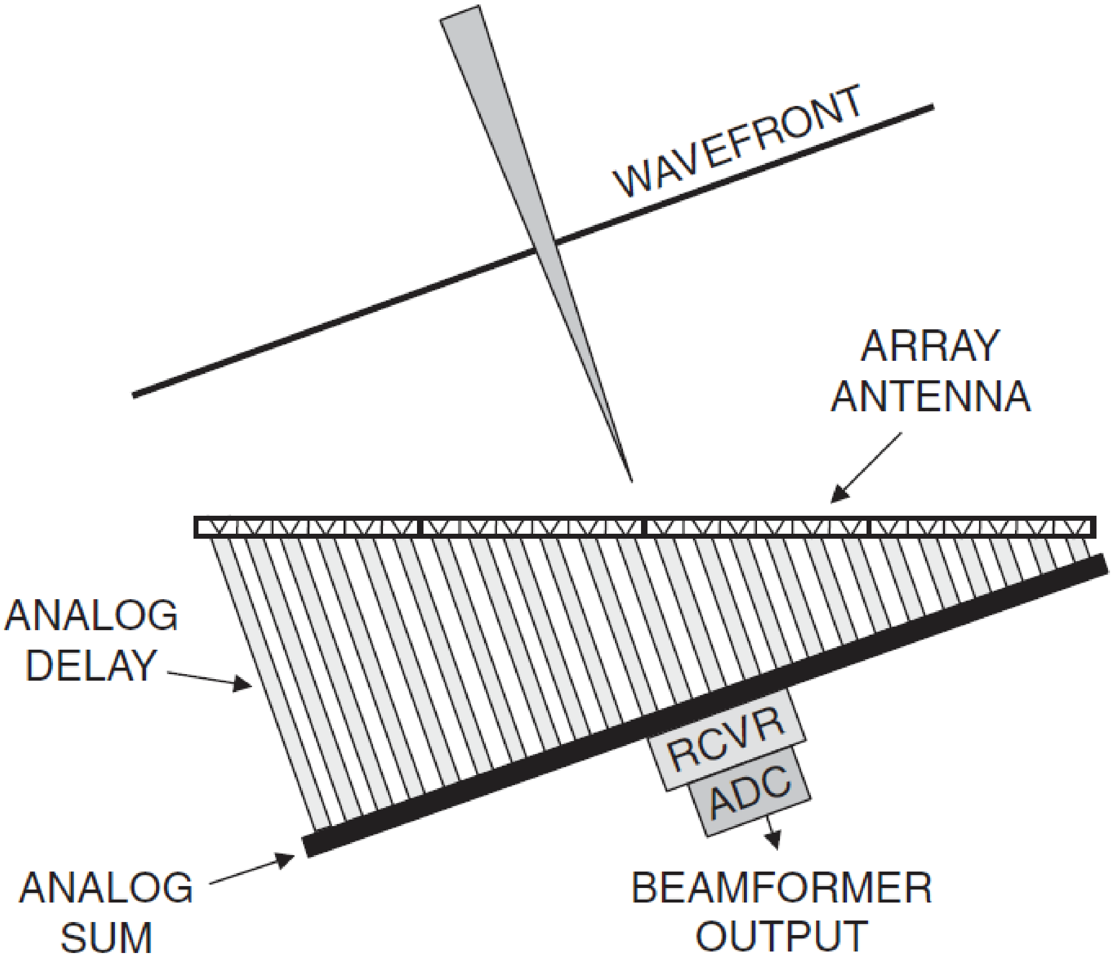


FIGURE 25.13 75 MHz tone sampled at (*a*) 100 MHz (4/3 × IF) and (*b*) 60 MHz (4/5 × IF)

- Implementation of the Direct DDC

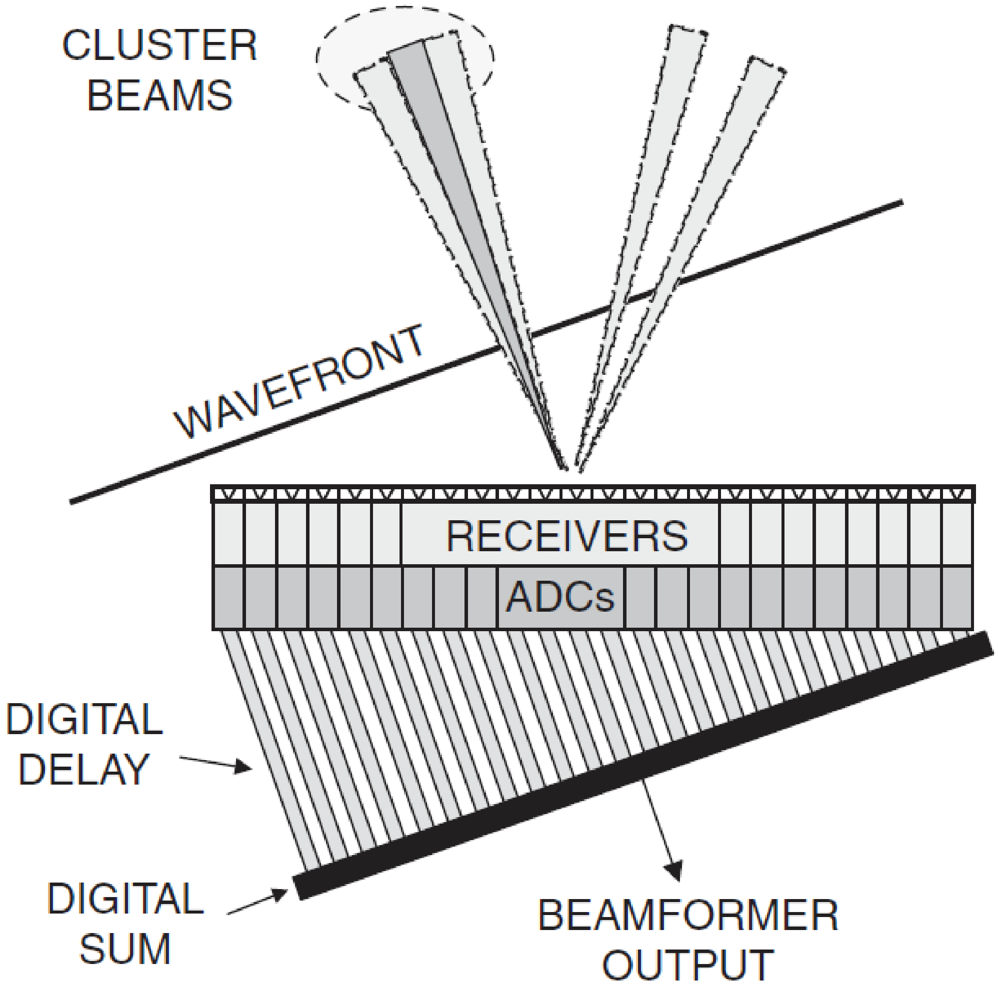


- Beamforming – Analog type



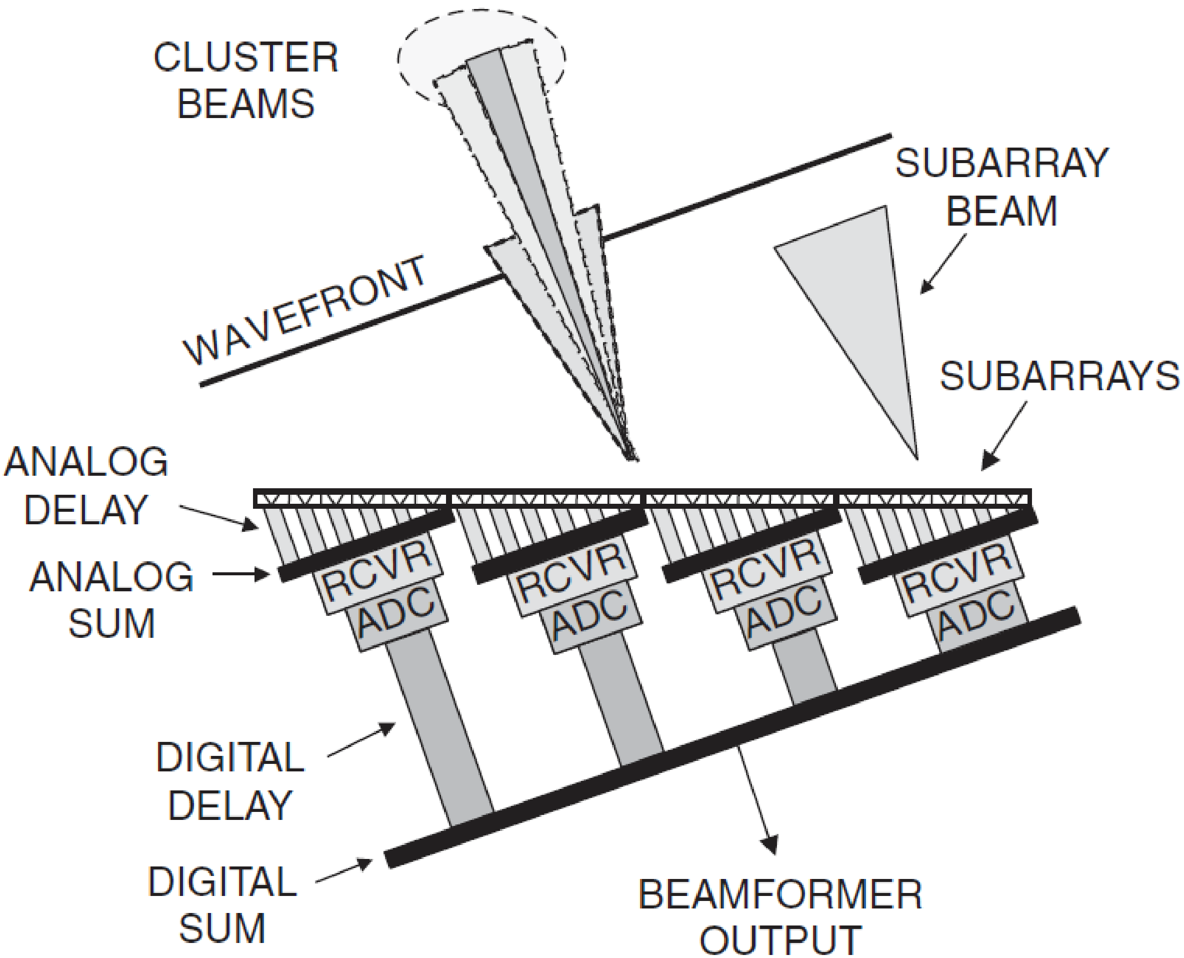
- Narrow bandwidth : Use phase shifter
- Wide bandwidth : Use true time delay
- Single beam at a time

- Full Digital Beamforming



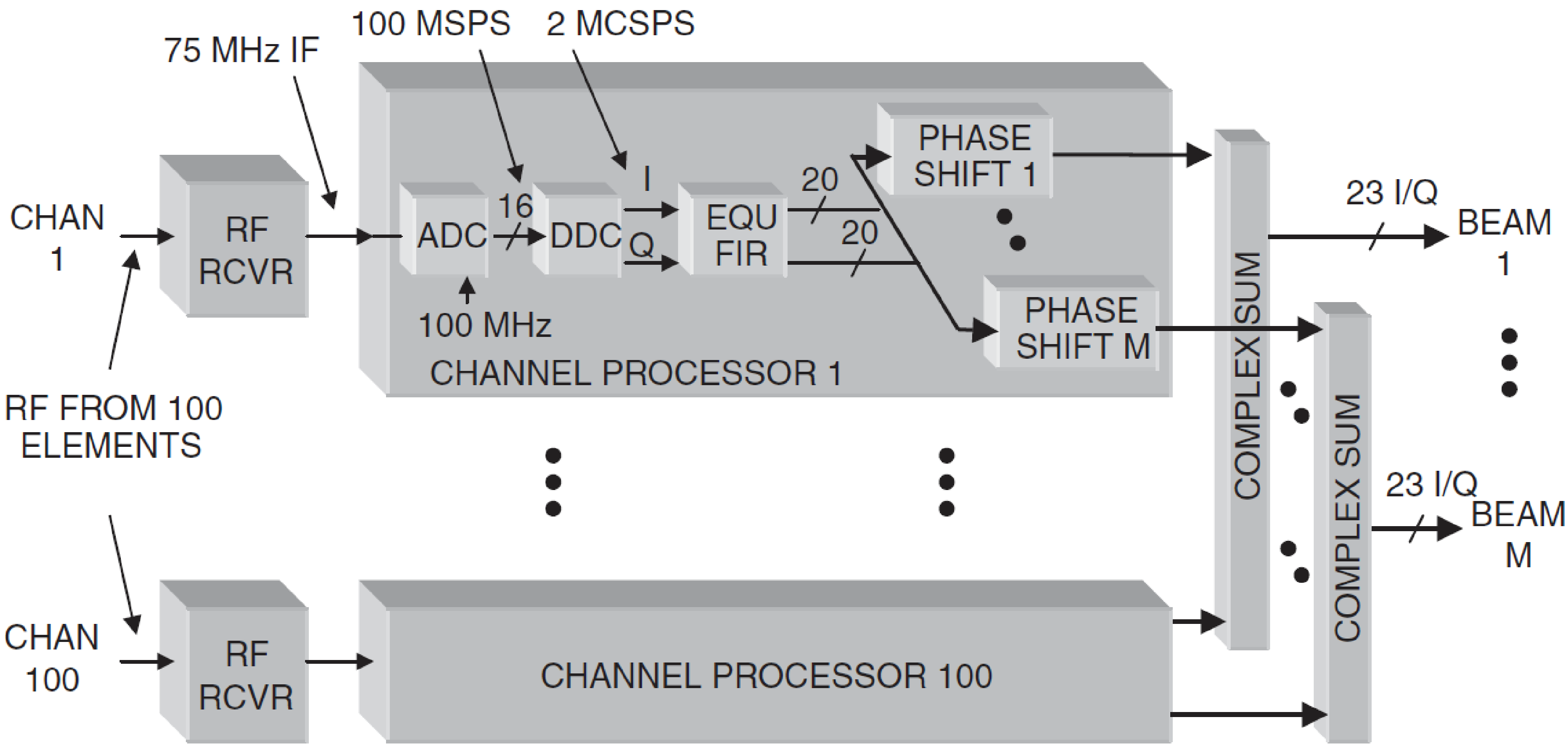
- Multiple beams can be formed simultaneously
- Expensive in implementation

- Hybrid Beamforming



- Analog beamforming is used for subarrays, followed by digital receivers.

- Typical Digital Beamformer



Phase shift : complex multiply or CORDIC operation
Time delay : FIR filter

- Transmitter – Direct Digital Synthesizer

FIGURE 25.23 Direct Digital Synthesizer (DDS)

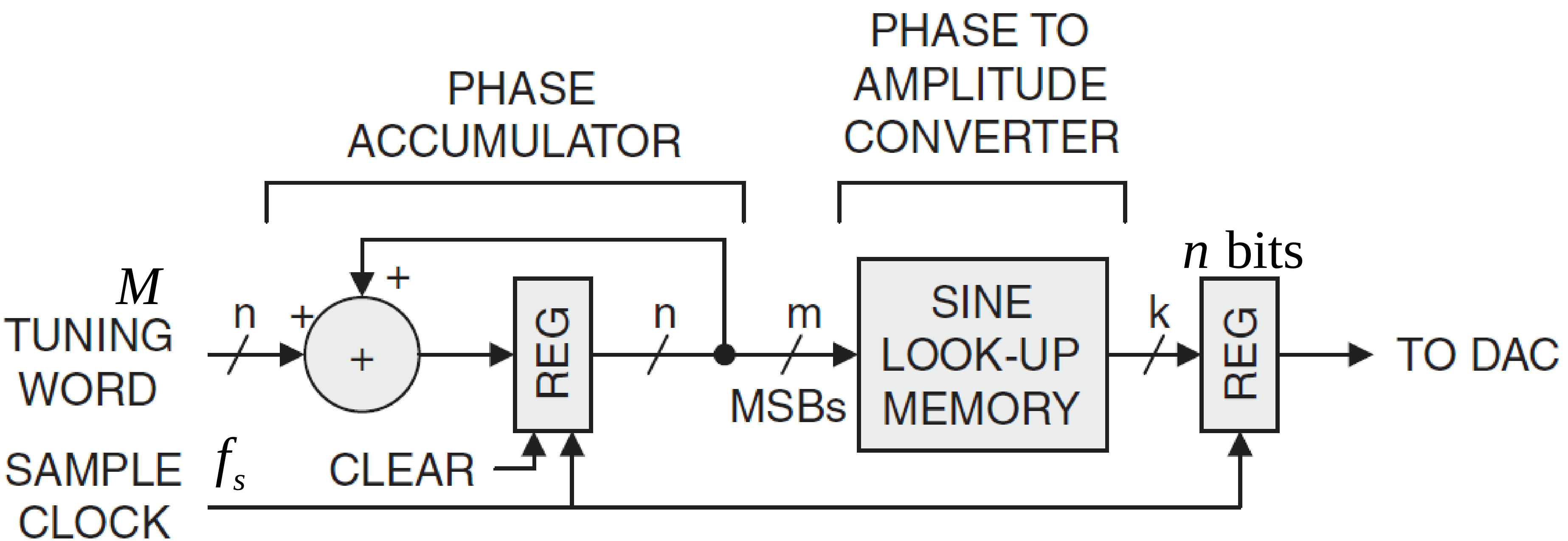


FIGURE 25.24 NCO block diagram

Output frequency = $\dfrac{Mf_s}{2^n}$

- Digital Upconverter

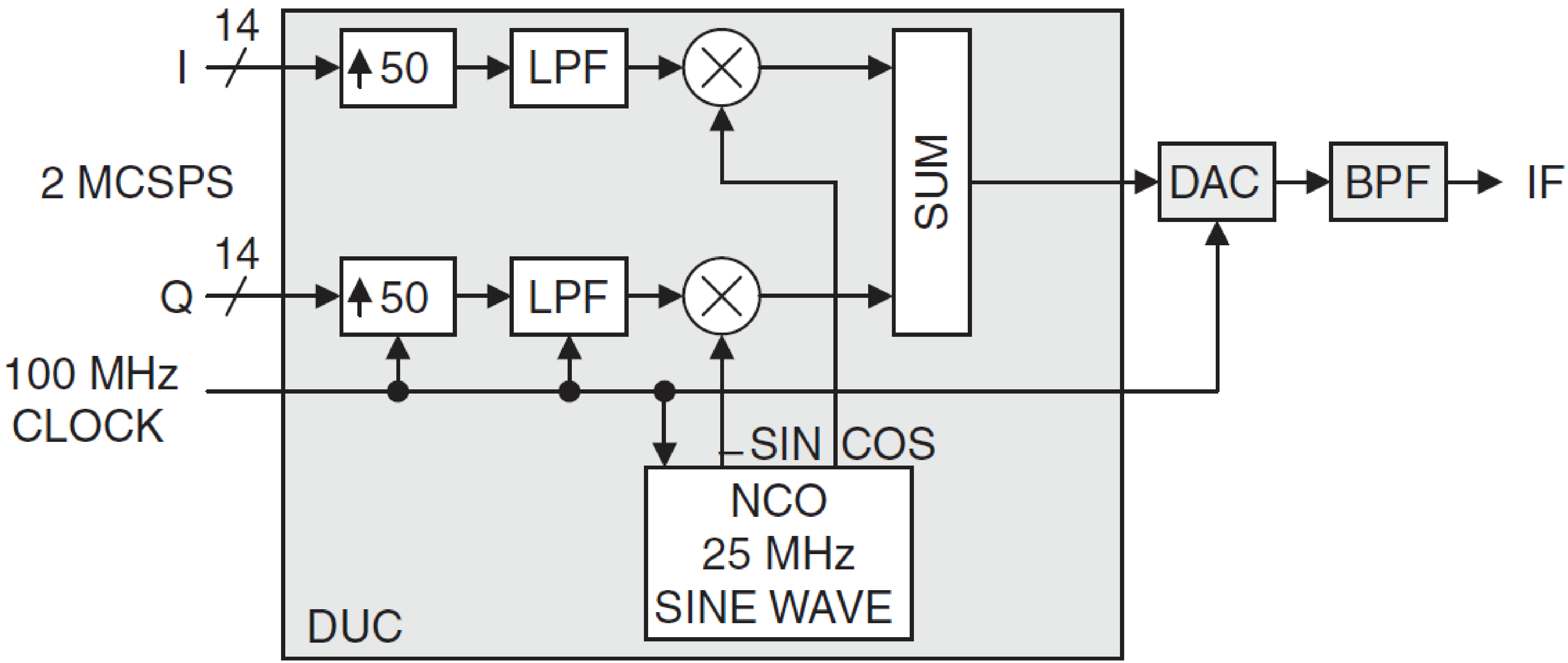
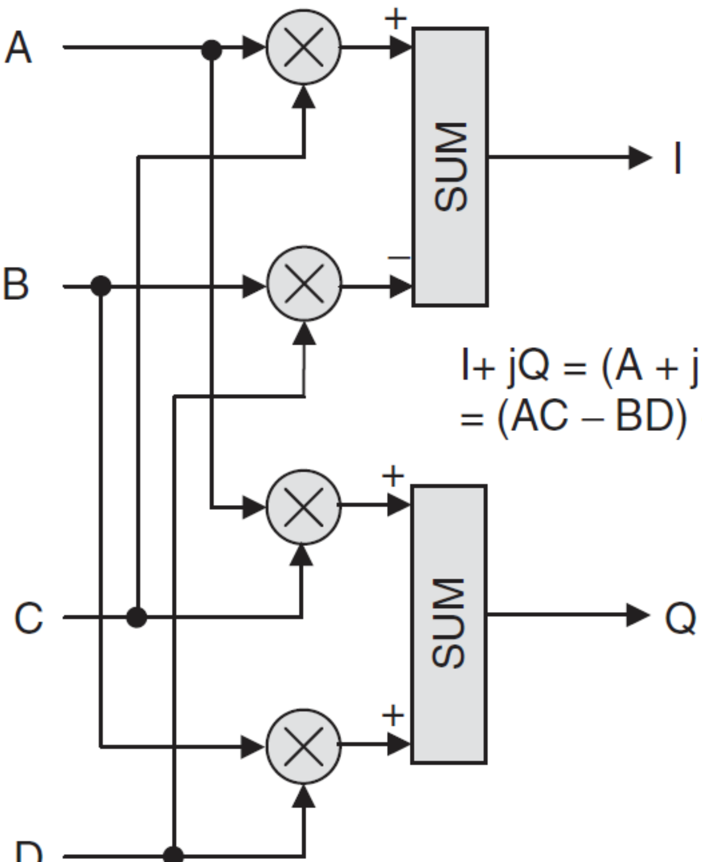


FIGURE 25.25 Digital upconverter (DUC)

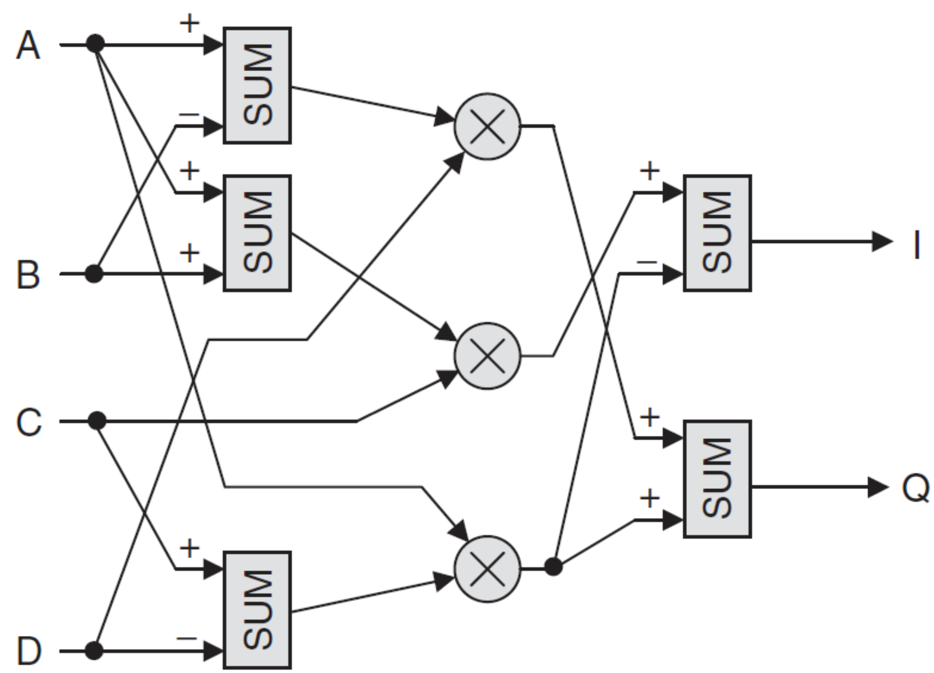
- Phase Shift -- By complex multiply

$$I = (AC - BD) = D(A - B) + A(C - D)$$

$$Q = (AD + BC) = C(A + B) - A(C - D)$$



$$I + jQ = (A + jB)^*(C + jD)$$
$$= (AC - BD) + j(AD + BC)$$



4X 4+

3X 5+

- Phase Shift -- By CORDIC Processor (**CO**ordinate **R**otation **DI**gital **C**omputer)

-- implement a phase shift without using multipliers

$$I_1 = I_0(\cos(\theta)) - Q_0(\sin(\theta))$$
$$Q_1 = I_0(\sin(\theta)) + Q_0(\cos(\theta))$$

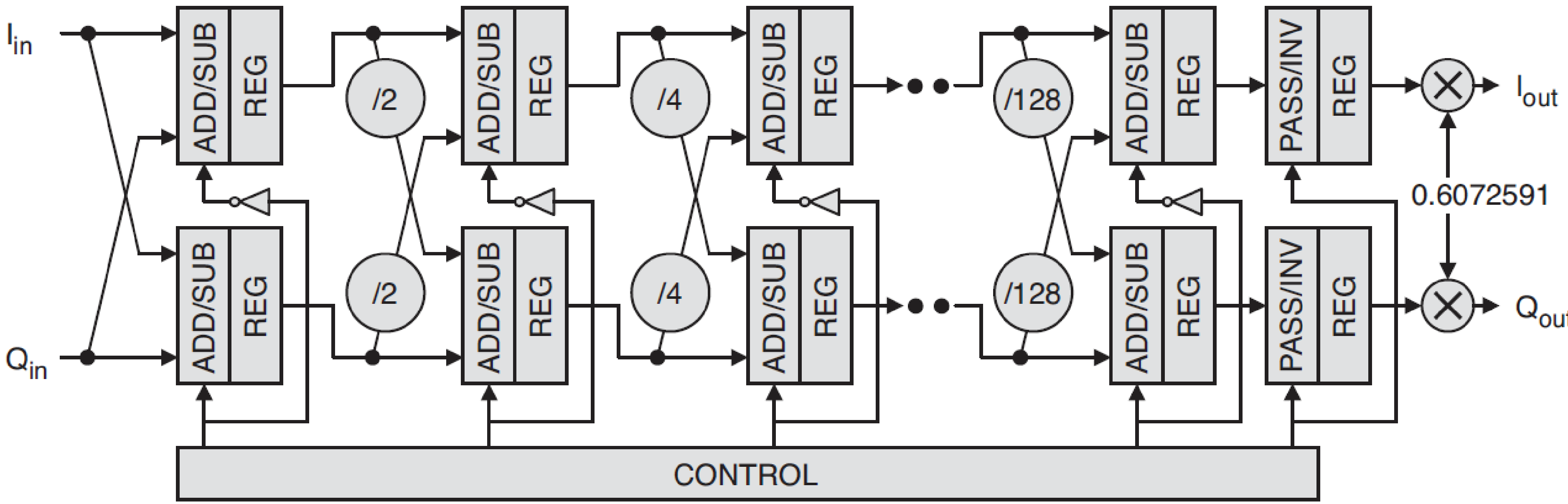
➔

$$I_1 = \cos(\theta)[I_0 - Q_0(\tan(\theta))]$$
$$Q_1 = \cos(\theta)[Q_0 + I_0(\tan(\theta))]$$

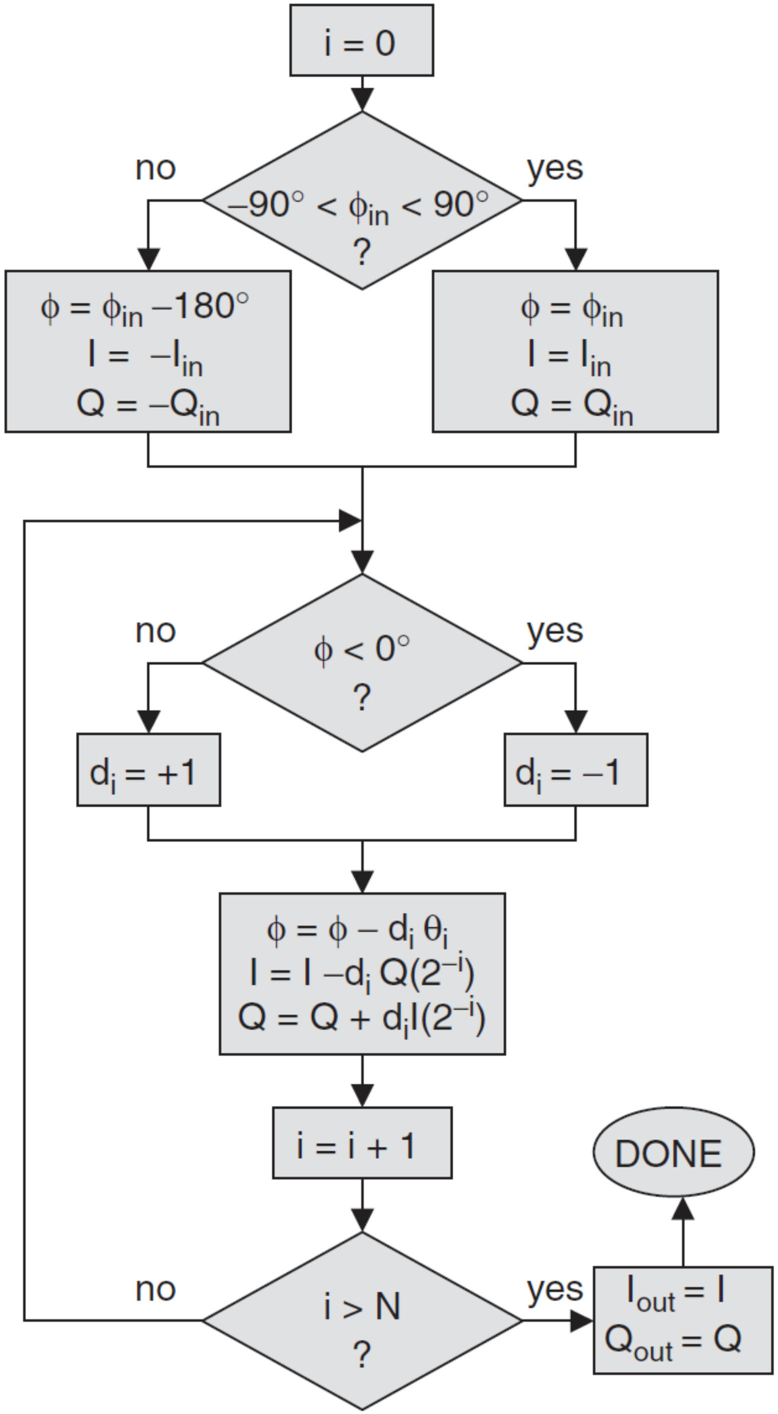
TABLE 25.1 CORDIC Parameters for First Eight Stages

i	$\tan(\theta_i)$	θ_i (deg)	$\cos(\theta_i)$	$P[\cos(\theta_i)]$
0	1	45.000	0.707107	0.707107
1	1/2	26.565	0.894427	0.632456
2	1/4	14.036	0.970143	0.613572
3	1/8	7.1250	0.992278	0.608834
4	1/16	3.5763	0.998053	0.607648
5	1/32	1.7899	0.999512	0.607352
6	1/64	0.8951	0.999878	0.607278
7	1/128	0.4476	0.999970	0.607259

- Eight-stage CORDIC processor



- CORDIC flow chart



Quiz 2

- Why we use acoustic for sensing and communication underwater.
- Draw the constellation for (1). QPSK, and (2). 2FSK modulation scheme.

- Explain what is the multipath channel. What kind of communication channel exhibits significant multipath effect.
- Explain the methods for underwater localization.