Introduction to Sonar

INF-GEO4310

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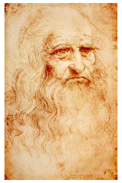
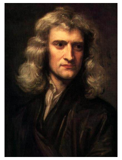
Outline

Outline

History of Underwater Acoustics

- *If you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you.*
  Leonardo da Vinci, 1490
- In 1687 Isaac Newton wrote his *Mathematical Principles of Natural Philosophy* which included the first mathematical treatment of sound
- In 1877 Lord Rayleigh wrote the *Theory of Sound* and established modern acoustic theory





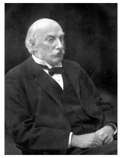
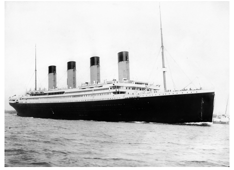


Image from wikipedia.org.

History of SONAR



- **SO**und **N**avigation **A**nd **R**anging
- A lot of activity after the loss of British passenger liner RMS Titanic in 1912
- English meteorologist Lewis Richardson, April/May 1912: Patent on Iceberg detection using acoustic echolocation in air and water
- German physicist Alexander Behm 1913: patent on echo sounder
- Canadian engineer Reginald Fessenden, 1914: Demonstrated depth sounding, underwater communications (Morse Code) and echo ranging detecting an iceberg at two miles range
- French physicist Paul Langevin and Russian immigrant electrical engineer, Constantin Chilowski 1916/17: US patents on ultrasonic submarine detector using an electrostatic method

Image from wikipedia.org.

The masters in sonar

From wikipedia.org.

Similar technologies

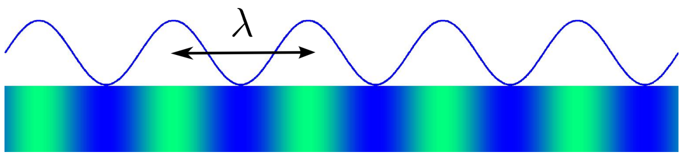
- SONAR = **So**und **N**avigation **A**nd **R**anging
- RADAR = **Ra**dio **D**etection **A**nd **R**anging
- Medical ultrasound, higher frequencies, shorter range and more complex medium
- Seismic exploration, lower frequencies, more complex medium

Literature

- Course text: `sonar_introduction_2012.pdf`
- Course presentation: `sonar_presentation_2012.pdf`
- Xavier Lurton, An introduction to underwater acoustics Springer Praxis, First edition 2002, Second edition 2010
- www.wikipedia.org
  - sonar
  - underwater acoustics
  - side-scan sonar
  - biosonar, animal echolocation
  - beamforming
- Ocean Acoustics Library http://oalib.hlsresearch.com/

Basic Physics

- Sound is waves travelling in *pressure perturbations*
- Or: compressional wave, longitudal wave, mechanical wave
- The acoustic vibrations can be characterized by
  - Wave period T [s]
  - Frequency $f = 1/T$ [Hz]
  - Wavelength $\lambda = c/f$ [m]
  - Sound speed c [m/s]



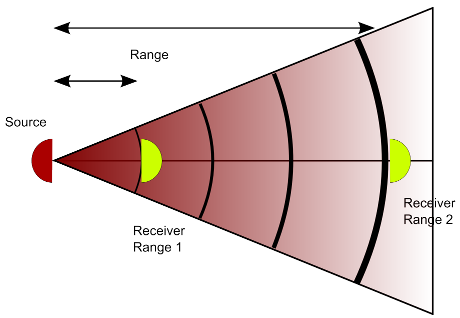
Underwater sound

- Acoustics is the only long range information carrier under water
- The pressure perturbations are very small
- Obtainable range is determined by
  - free space loss and absorption
  - the sensitivity to the receiver
- The ocean environment affects sound propagation:
  - sea surface
  - seafloor
  - temperature and salinity
  - currents and turbulence
- Underwater sound propagation is frequency dependent

Geometrical spreading loss - one way

- The acoustic wave expands as a spherical wave
- The acoustic intensity decreases with range in inverse proportion to the surface of the sphere
- The acoustic wave amplitude A decreases with range R
- The intensity $I = A^2$
- In homogeneous media

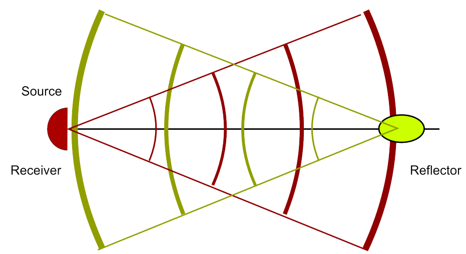
$$I \sim \frac{1}{R^2}$$



Geometrical spreading loss - two way

- The acoustic wave expands as a spherical wave to the reflector
- The reflected field expands as a spherical wave back to the receiver
- In homogeneous media, the two way loss becomes

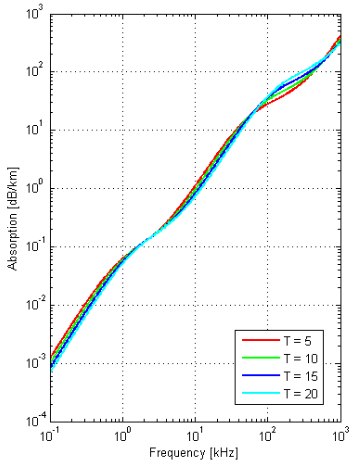
$$I \sim \frac{1}{R^2}\frac{1}{R^2} = \frac{1}{R^4}$$



Absorption

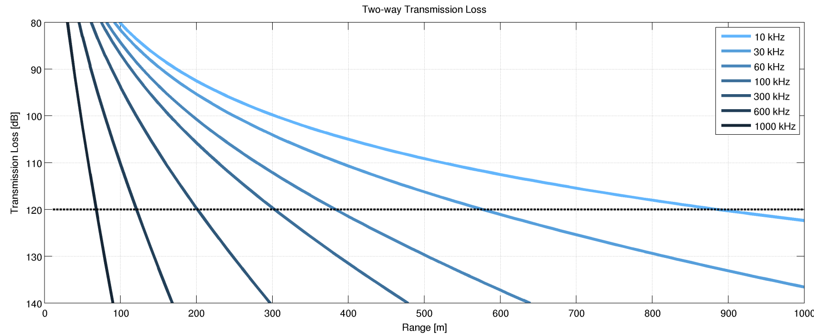
- Seawater is a dissipative medium through viscosity and chemical processes
- Acoustic absorption in seawater is frequency dependent
- Lower frequencies will reach longer than higher frequencies

f [kHz]	R [km]	λ [m]
0.1	1000	15
1	100	1.5
10	10	0.15
100	1	0.015
1000	0.1	0.0015



Transmission loss

- Transmission loss is geometrical spread + absorption
- Logarithmic (dB) scale: $I_{dB} = 10\log_{10}(I)$
- A certain frequency will have a certain maximum range
- Frequency is a critical design parameter



The Ocean as Acoustic Medium

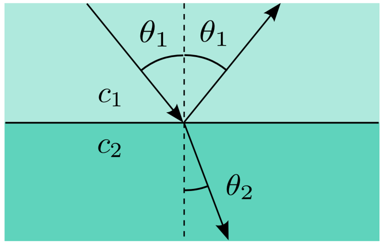
- The sound velocity - environmental dependency
- Layering and refraction - waveguides
- The sea floor and the sea surface - scattering
- Noise sources

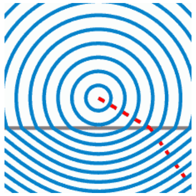
Reflection and Refraction in Acoustics

- Recall from first lecture on optical imaging
- The reflection angle is equal to the incident angle
- The angle of refraction is given by Snell's law

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}$$

- The index of refraction $n = c_2/c_1$
- Snells law can be derived from *Fermats principle* or from the general *boundary conditions*





From Wikipedia

Refraction and the underwater sound velocity

Medvins formula:

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016D$$

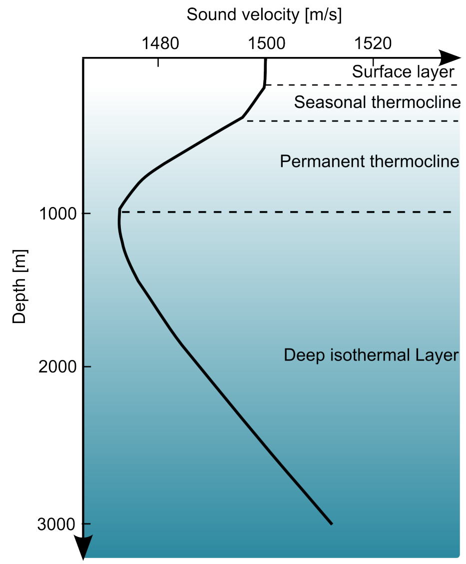
The sound velocity depends on 3 major parts:

- Temperature T in degrees Celsius
- Salinity S in parts per thousand
- Depth D in meters

The sound velocity contains information about the ocean environment.
Example: $T = 12.5\ ^\circ\mathrm{C}$, $S = 35\ \mathrm{ppt}$, $D = 100\ \mathrm{m}$ gives $c = 1500\ \mathrm{m/s}$

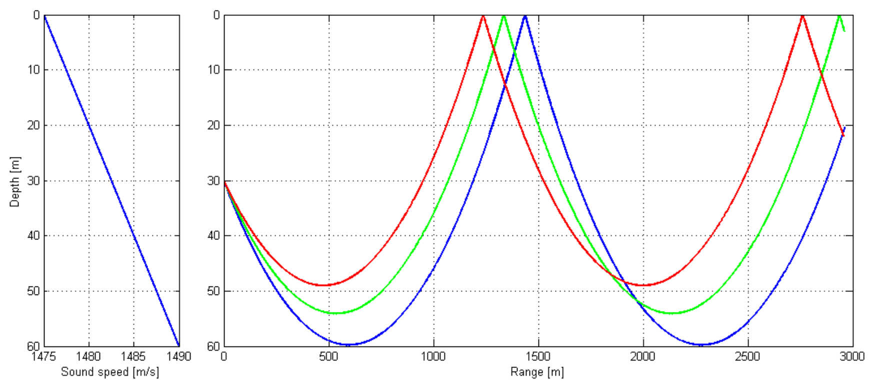
Deep sound velocity variation

- The surface layer
- The seasonal thermocline
- The permanent thermocline
- The deep isothermal layer



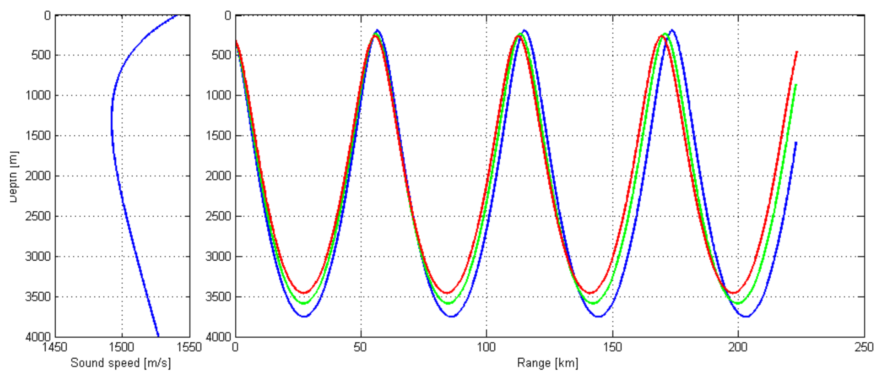
Sound refraction

- The sound will refract towards areas of slower speed
- SOUND IS LAZY



Underwater sound channel

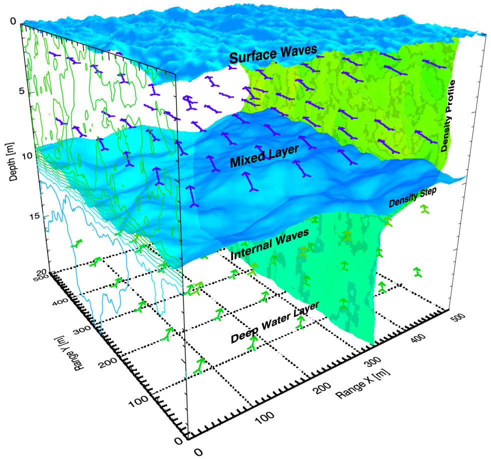
- waves are trapped in a guide
- The energy spreads in one dimension instead of two $I \sim 1/R$
- Much longer range
- *Acoustical Oceanography*: Map the effect of the medium on underwater acoustics



Coastal variability

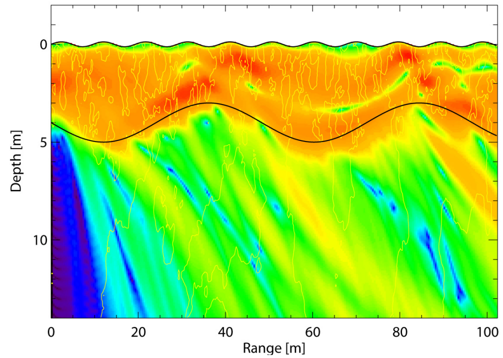
Factors that affect sound propagation:

- The sound velocity profile
- The sea surface
- Internal waves
- Turbulence
- Ocean current



Coastal variability

- The sound is trapped in a waveguide
- The boundaries of the waveguide changes the properties of the sound wave



Reflection: basic physics

- Characteristic impedance $Z_0 = \rho c$
  - ρ is the density $[\mathrm{kg/m^3}]$
  - c is the sound speed $[\mathrm{m/s}]$
- Reflection coefficient (normal incidence)

$$R(f) = \frac{Z - Z_0}{Z + Z_0}$$

- Transmission coefficient (normal incidence)

$$T(f) = \frac{2Z_0}{Z + Z_0}$$

The characteristic impedance is a material property

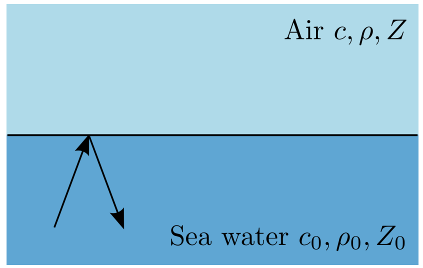
Material	Impedance
Air	415
Seawater	1.54×10^6
Clay	5.3×10^6
Sand	5.5×10^6
Sandstone	7.7×10^6
Granite	16×10^6
Steel	47×10^6

Reflection: the sea surface

- The sea surface (sea-air interface)
- Air: $Z = 415$
- Seawater: $Z_0 = 1.54 \times 10^6$
- Reflection coefficient

$$R = \frac{Z - Z_0}{Z + Z_0} \approx -1$$

- The sea surface is a perfect reflector

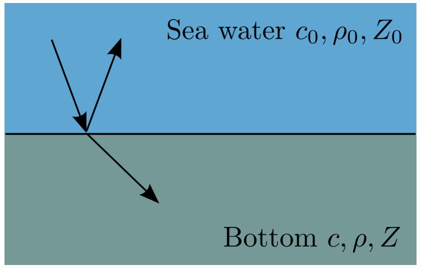


Reflection: the sea floor (or bottom)

- The sea floor (sea-bottom interface)
- Sand: $Z = 5.5 \times 10^6$
- Seawater: $Z_0 = 1.54 \times 10^6$
- Reflection coefficient

$$R = \frac{Z - Z_0}{Z + Z_0} \approx 0.56$$

- Sandy seafloors partially reflects, partially transmits
- Estimated reflection coefficient can be used in classification of bottom type



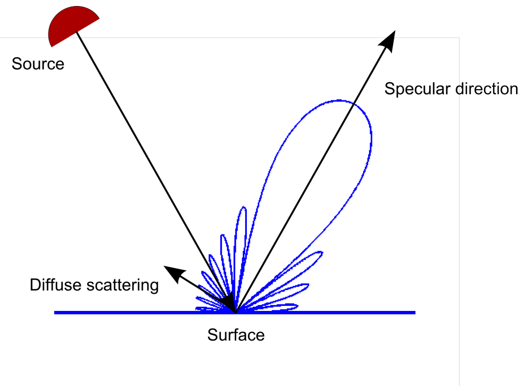
Scattering - smooth surfaces

Scattering from rough surfaces

- The sea surface
- The seafloor

Other scattering sources

- Volume scattering from fluctuations
- Scattering from marine life



A smooth surface gives mainly specular reflection

Scattering - rough surfaces

Scattering from rough surfaces

- The sea surface
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Other scattering sources

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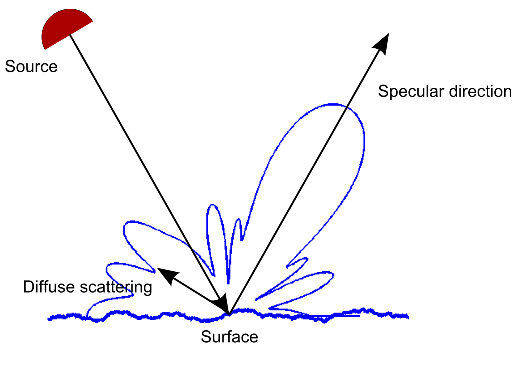
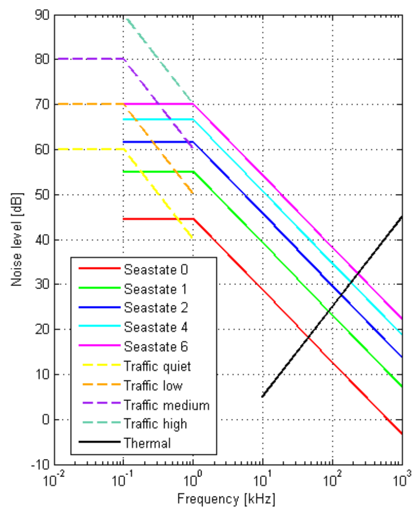


A rough surface gives specular reflection and diffuse scattering

Ambient Noise

The ocean is a noisy environment

- Hydrodynamic
  - Tides, ocean current, storms, wind, surface waves, rain
- Seismic
  - Movement of the earth (earthquakes)
- Biological
  - Produced by marine life
- Man made
  - Shipping, industry



Marine Life and Acoustics

- Dolphins and whales use acoustics for echolocation and communication.
- Whale songs are in the frequency between 12 Hz and a few kHz.
- Dolphins use a series of high frequency clicks in the range from 50 to 200 kHz for echolocation.

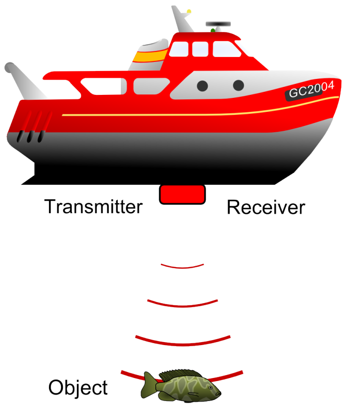
From wikipedia.org. Courtesy of NASA.

From wikipedia.org. Author Zorankovacevic.

Outline

Active sonar

- Transmits a signal
- The signal propagates towards the object of interest
- The signal is reflected by the target
- The signal is recorded by a receiver



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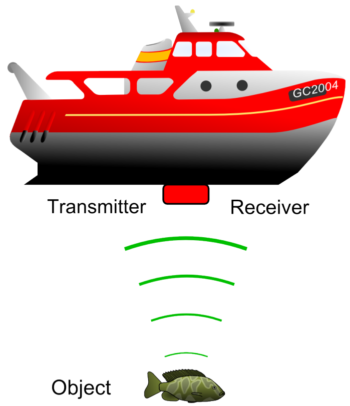
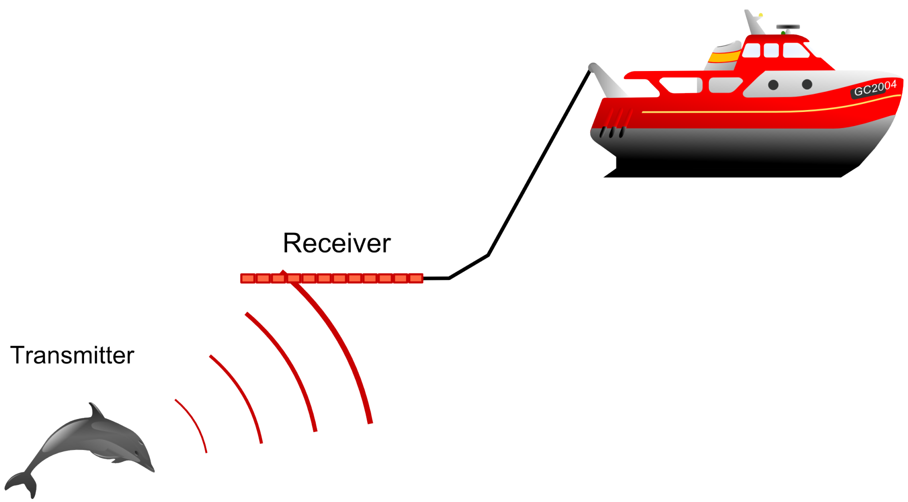


Passive sonar

- Passive sonar only records signals

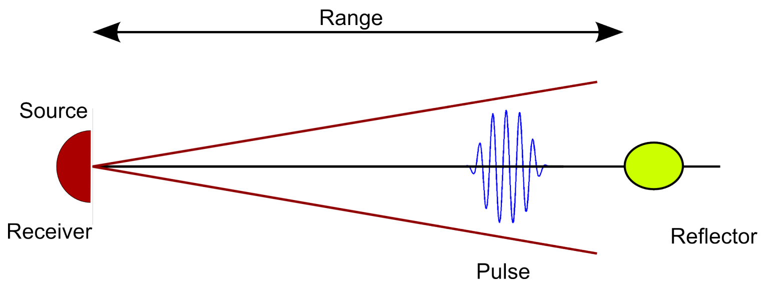


Range Estimation

- Estimation of time delay (or two way travel time) τ
- Relate time delay to range

$$R = \frac{c\tau}{2}$$

- Sound velocity must be known



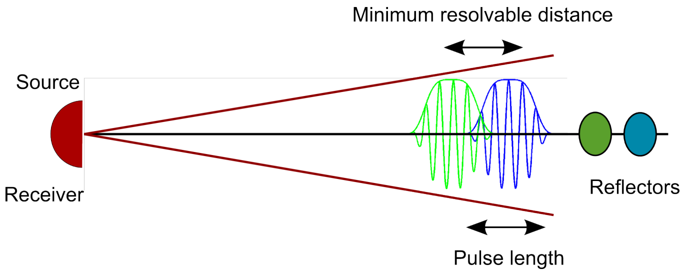
Range Resolution

- The minimum distance two echoes can be seperated
- Related to the pulse length T_p for *non-coded* pulses

$$\delta R = \frac{cT_p}{2}$$

- Related to bandwidth B for *coded* pulses

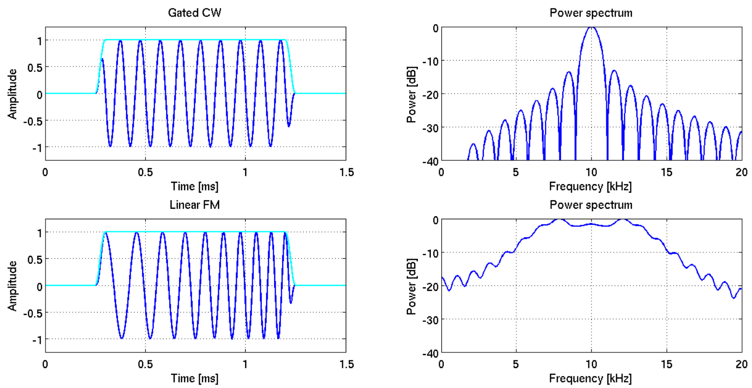
$$\delta R = \frac{c}{2B}$$



Pulse forms 1 - active sonar

Different pulse forms for different applications

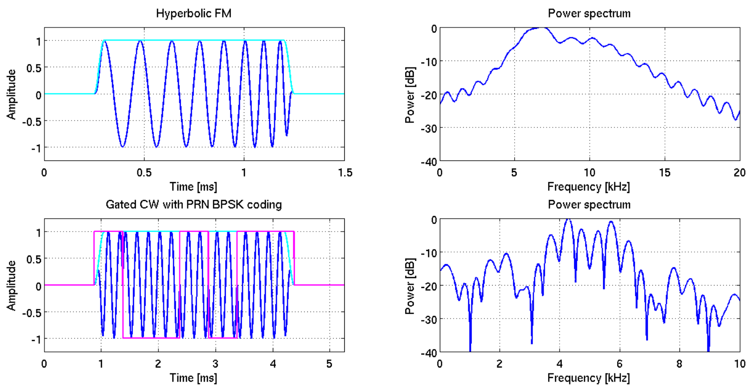
- Gated Continuous Wave (CW)
  Simple and good Doppler sensitivity but does not have high BT
- Linear Frequency Modulated (LFM) (or chirp)
  Long range and high resolution but cannot handle Doppler



Pulse forms 2 - active sonar

Different pulse forms for different applications

- Hyperbolic Frequency Modulated (HFM) pulses
  Long range and high resolution and Doppler resistive
- Pseudo Random Noise (PRN) BPSK Coded CW
  High resolution and good Doppler sensitivity but low efficiency

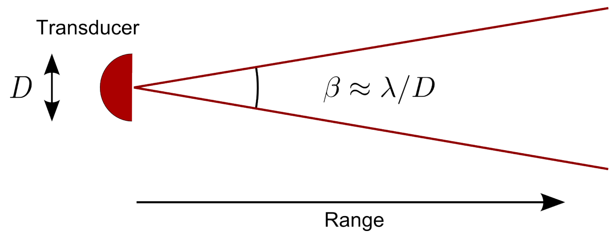


Directivity

- Transducers (or antennas or loudspeakers) are directive
- The beamwidth (or field of view) of a disc of size D is

$$\beta \approx \frac{\lambda}{D}$$

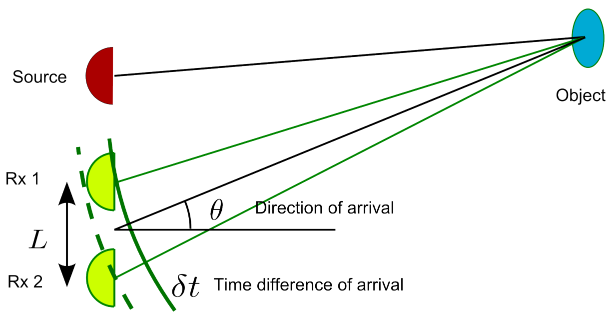
- The beamwidth is frequency dependent. Higher frequency gives narrower beam.



Bearing estimation - arbitrary Rx positions

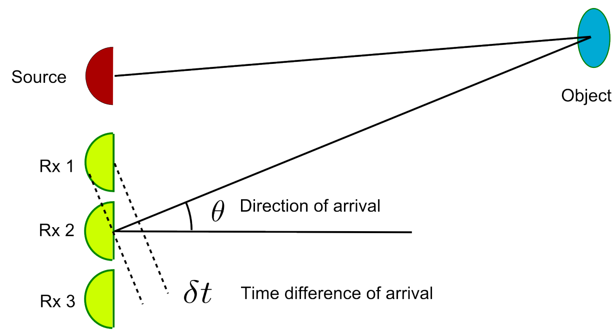
- Direction of arrival can be calculated from the time difference of arrival

$$\theta = \sin^{-1}\left\{\frac{c\delta t}{L}\right\}$$



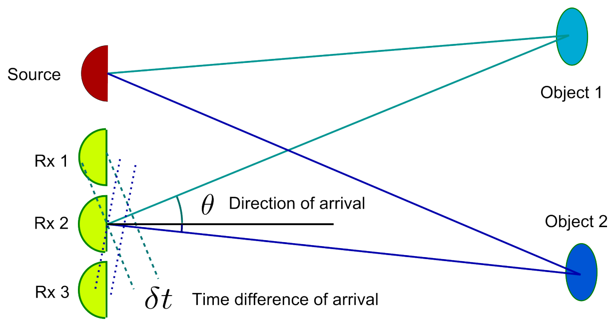
Bearing estimation - array sensor

- By delaying the data from each element in an array, the array can be steered (electronically)



Bearing estimation - array sensor

- Direction of arrival from several reflectors can be estimated by using several receivers.



Imaging sonar / beamforming

- Echo location is estimation of range and bearing of an echo (or target)
- Imaging sonar is to produce an image by estimating the echo strength (target strength) in every direction and range

Algorithm

```
for all directions
   for all ranges
      estimate echo strenght in each pixel
   end
end
```


Beamforming defined

Beamforming

Processing algorithm that focus the array's signal capturing ability in a particular direction

- Beamforming is spatio-temporal filtering
- Beamforming turns recorded time series into images (from time to space)
- Beamforming can be applied to all types of multi-receiver sonars: active, passive, towed array, bistatic, multistatic, synthetic aperture

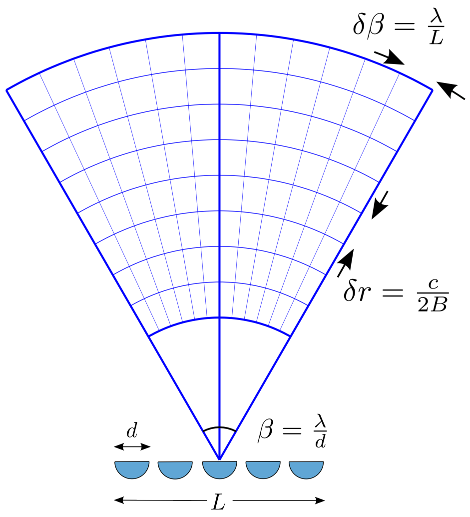
Beamforming algorithm in time domain

Algorithm

```
for all directions
   for all ranges
      for all receivers
         Calculate the time delay
         Interpolate the received time series
         Apply appropriate amplitude factor
      end
      sum over receivers and store in result(x,y)
   end
end
```

Imaging sonar resolution

- Range resolution given by pulse length (actually bandwidth)
- Azimuth resolution given by array length measured in wavelengths
- Field of view is given by element length measured in wavelengths

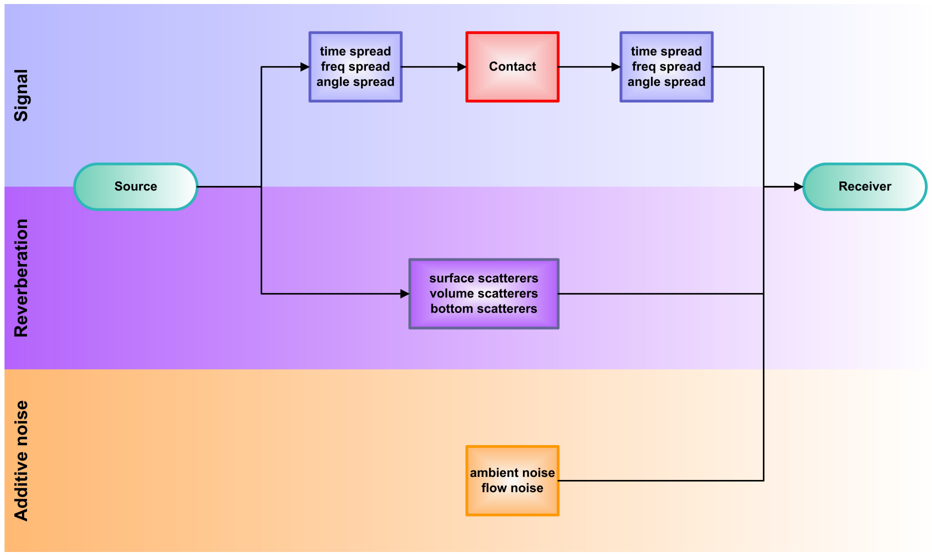


Array signal processing in imaging is the primary topic in INF 5410

Imaging: Performance measures

- **Detail resolution**
  Geometrical resolution - minimum resolvable distance
- **Contrast resolution**
  Value resolution, echogenicity, accuracy
- **Temporal resolution**
  Number of independent images per unit time
- **Dynamic range**
  Resolvability of small targets in the presence of large targets
- **Sensitivity**
  Detection ability of low level targets

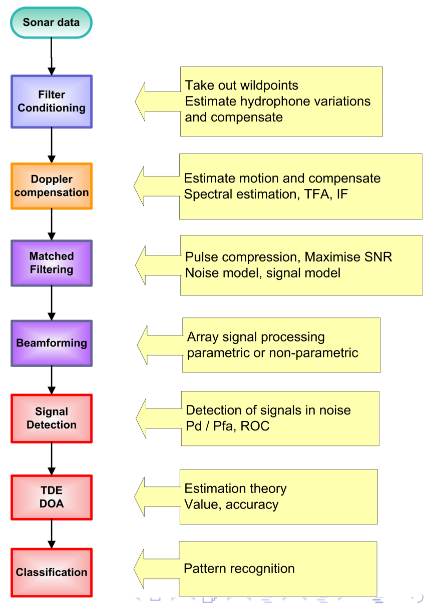
Sonar signal model



Active sonar processing

The basic active sonar processing consists of

- Preprocessing
- Pulse compression (range)
- Beamforming (azimuth)
- Detection
- Parameter estimation - position
- Classification



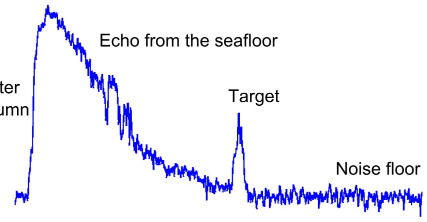
The sonar equation

The sonar equation is an equation for energy conservation for evaluation of the sonar system performace.

- In its simplest form: Signal $-$ Noise $+$ Gain $>$ Threshold
- More detailed (for active sonar):

$$SL - 2TL + TS - NL + DI + PG > RT$$

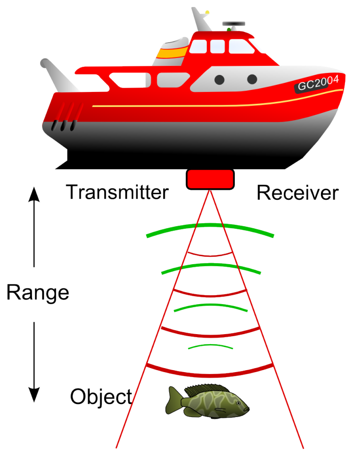
- *SL* is source level
- *TL* is transmission loss
- *TS* is target strenght
- *NL* is noise level
- *DI* is directivity index
- *PG* is processing gain
- *RT* is reception threshold



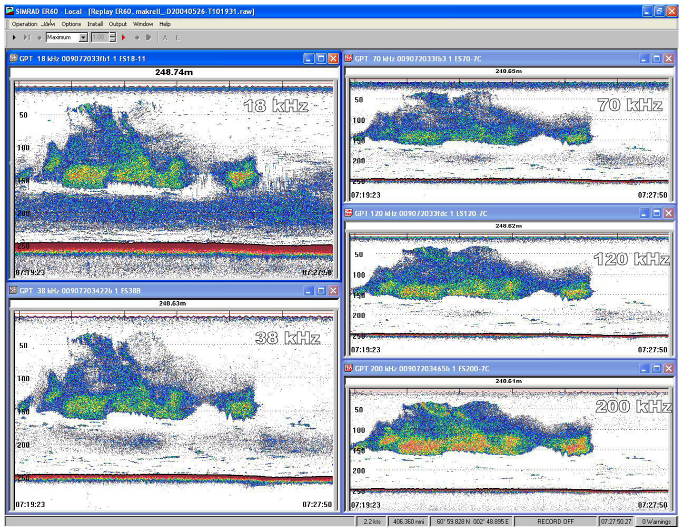
Outline

Echosounders

- The echosounder is oriented vertically
- The target strength is estimated in every range (depth)
- The ship moves forward to make a 2D map of fish density
- The target strength is related to fish size (biomass)
- Different frequencies can be used for species characterisation



Stock abundance and species characterisation



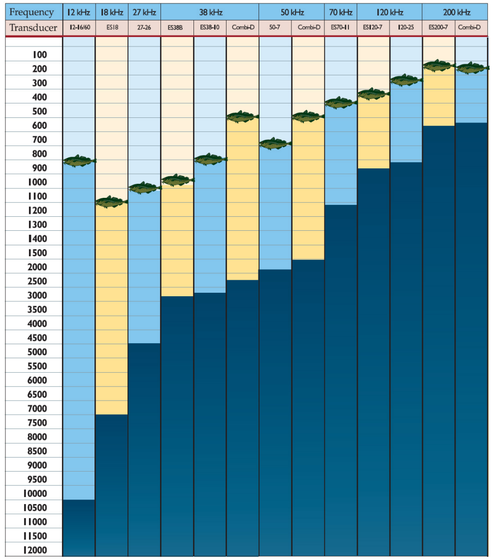
From www.simrad.com. Courtesy of Kongsberg Maritime

Fish detection range

- Modern echosounders can detect a single fish at 1000 m range.
- Some fish have a swimbladder (air filled) which gives extra large target strength

From www.simrad.com.

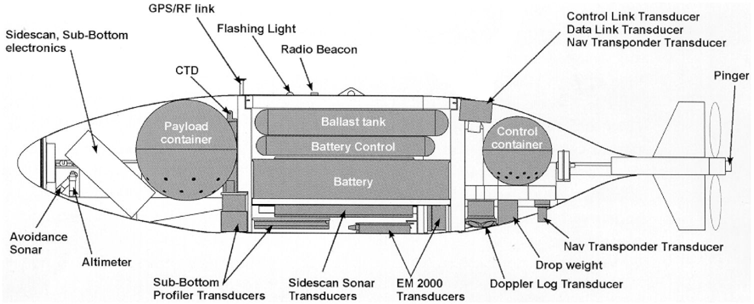
Courtesy of Kongsberg Maritime



The HUGIN autonomous underwater vehicle

The HUGIN autonomous underwater vehicle

- Free swimming underwater vehicle
- Preprogrammed (semi-autonomous)
- Used primarily to map and image the seafloor
- Runs up to 60 hours, typically in 4 knots (2 m/s)
- Maximum depth: 1000, 3000, 4500 m

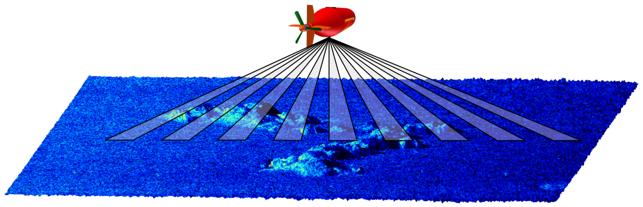


Acoustic sensors on HUGIN

- Multibeam echosounder
- Imaging sonar
- Altimeter
- Anti collision sonar
- Doppler velocity logger
- Subbottom profiler
- Acoustic communications

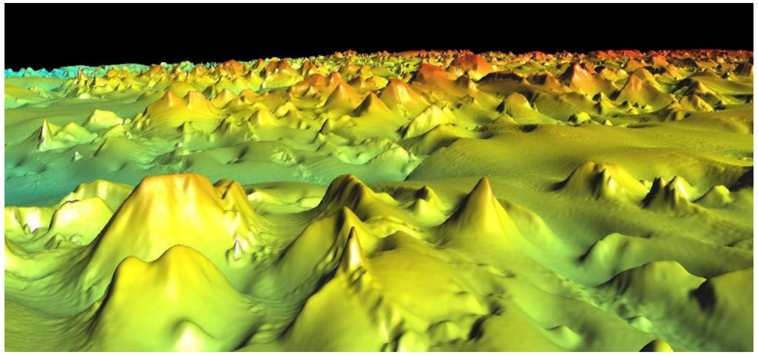
Multibeam echosounders

- Multibeam echosounders maps the seafloor by estimating the range in different direction
- The map resolution is determined by the 2D beamwidth and the range resolution



MBE Example 1

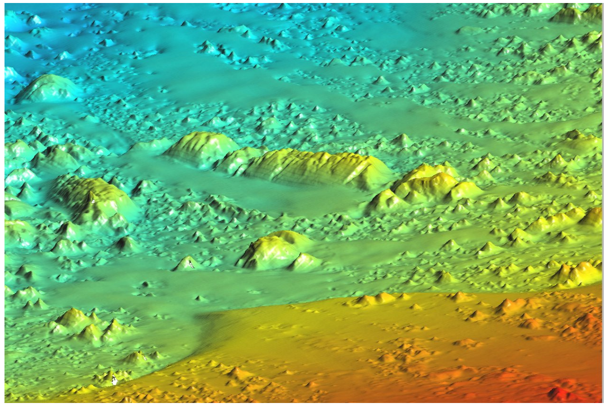
- Data collected by HUGIN AUV
- Maps from the Ormen Lange field
- The peaks are 50 m high



Courtesy of Geoconsult / Norsk Hydro.

MBE Example 2

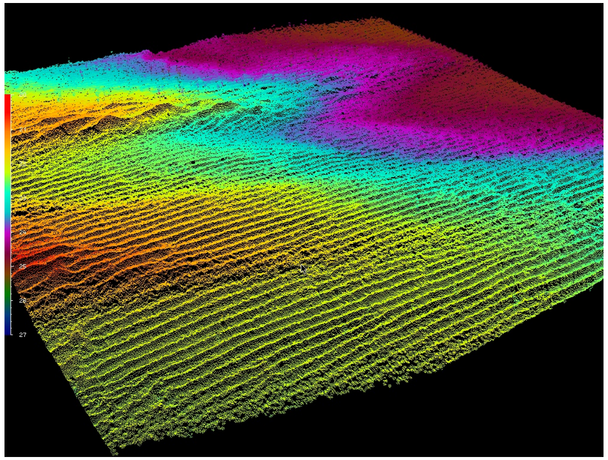
- Data collected by HUGIN AUV
- Maps from the Ormen Lange field
- The ridge is 900 m long and 50 m high.



Courtesy of Geoconsult / Norsk Hydro.

MBE Example 3

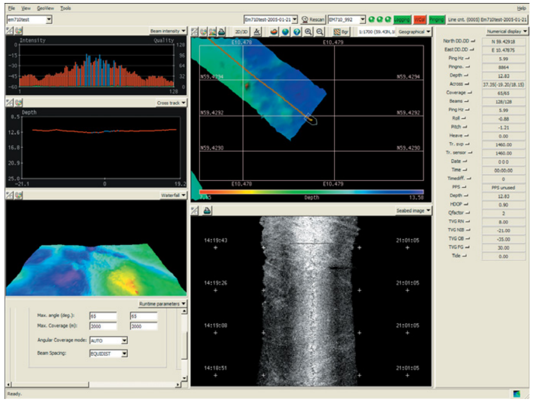
- Data collected by HUGIN AUV
- Example area with large sand ripples



Courtesy of Kongsberg Maritime / FFI.

MBE Example 3

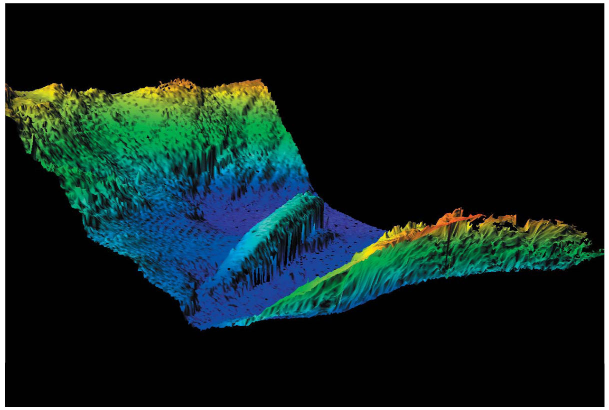
- Hull mounted MBE
- 70 - 100 kHz
- Magic T (Mills cross) layout



From www.simrad.com. Courtesy of Kongsberg Maritime

MBE Example 4

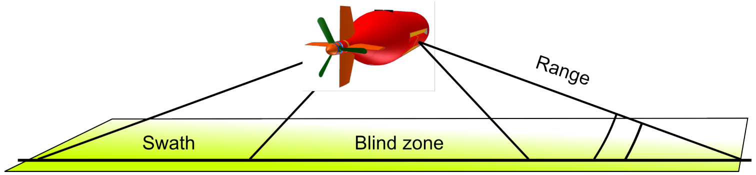
- Hull mounted MBE
- 70 - 100 kHz
- Colour coded seafloor depth



From www.simrad.com. Courtesy of Kongsberg Maritime

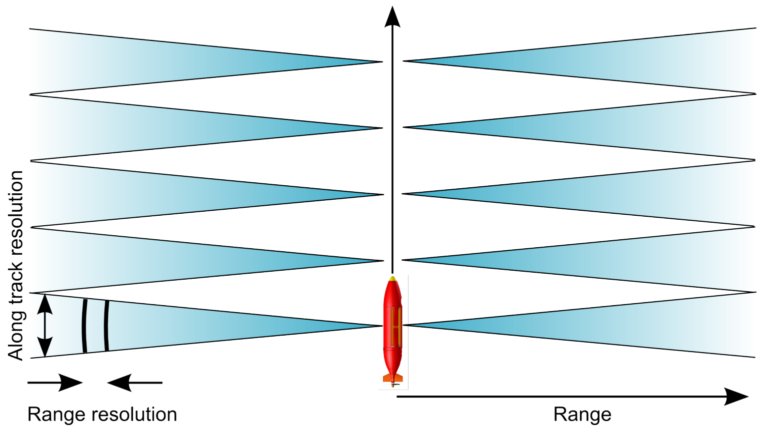
Sidescan sonar

- Sidescan sonar: sidelooking sonar to image the seafloor
- Typical platform: towfish, hull mounted, AUV
- An image is created by moving and stacking range lines
- Typically frequency 100 kHz - 500 kHz
- Typical range 100 - 500 m



Sidescan sonar area coverage

- Range resolution is given by the pulse length (or bandwidth)
- Along-track resolution is range dependent



Sidescan sonar example

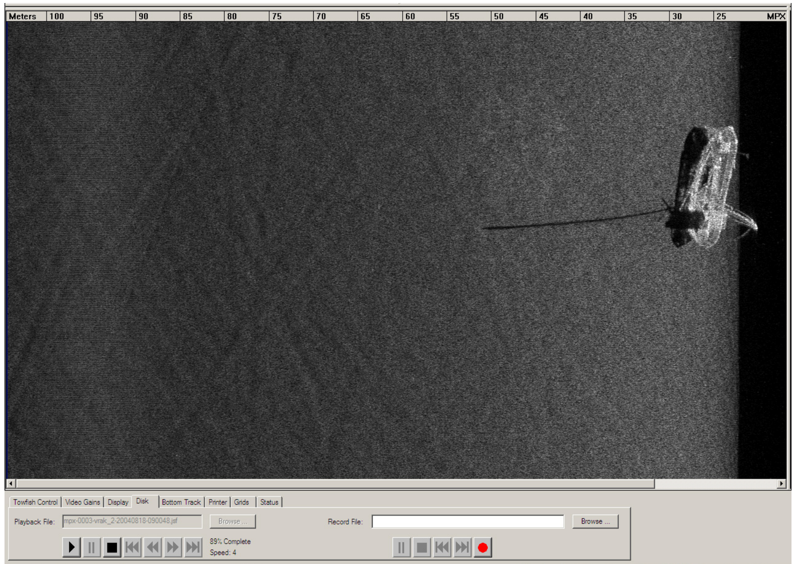
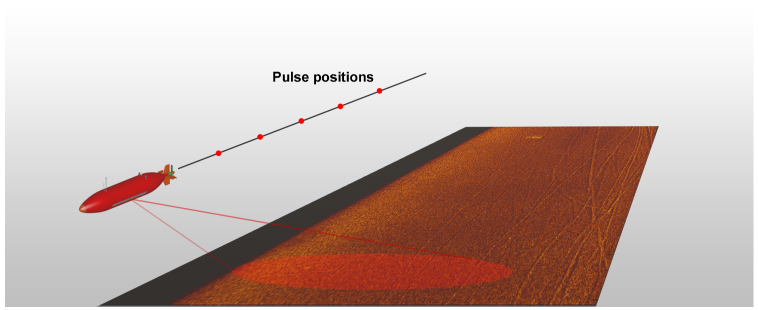


Image collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI

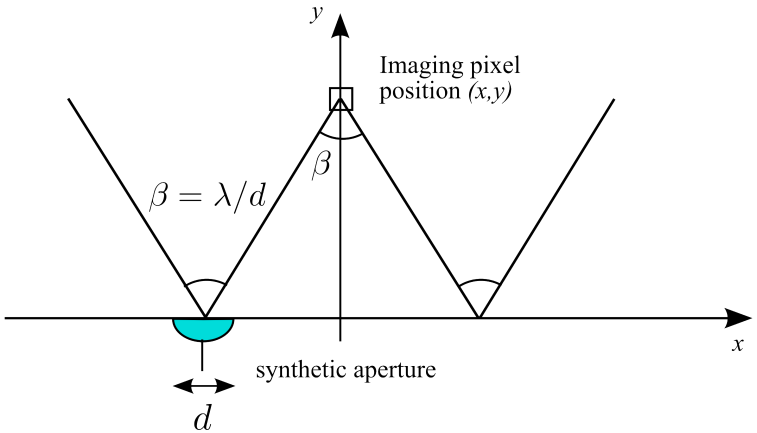
Synthetic aperture sonar principle

- Collect succesive pulses in a large synthetic array (aperture)
- Increase the azimuth (or along-track) resolution
- Requires accurate navigation - within a fraction of a wavelength
- Very similar to Synthetic Aperture Radar (SAR)



Synthetic aperture sonar principle

- The length of the synthetic aperture increases with range
- Along-track resolution becomes independent of range
- Along-track resolution becomes independent of frequency



Sidelooking Example - very high resolution (SAS)

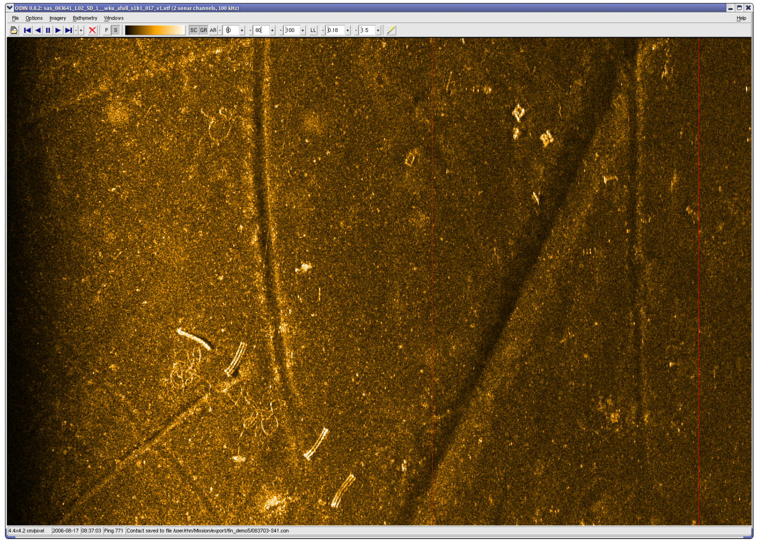


Image collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI

Resolution matters

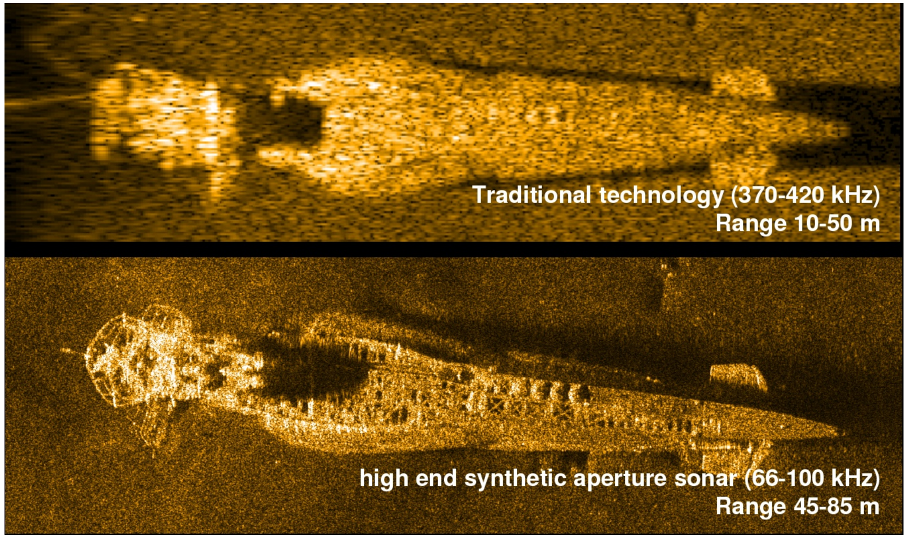


Image collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI

Example: Fishing boat

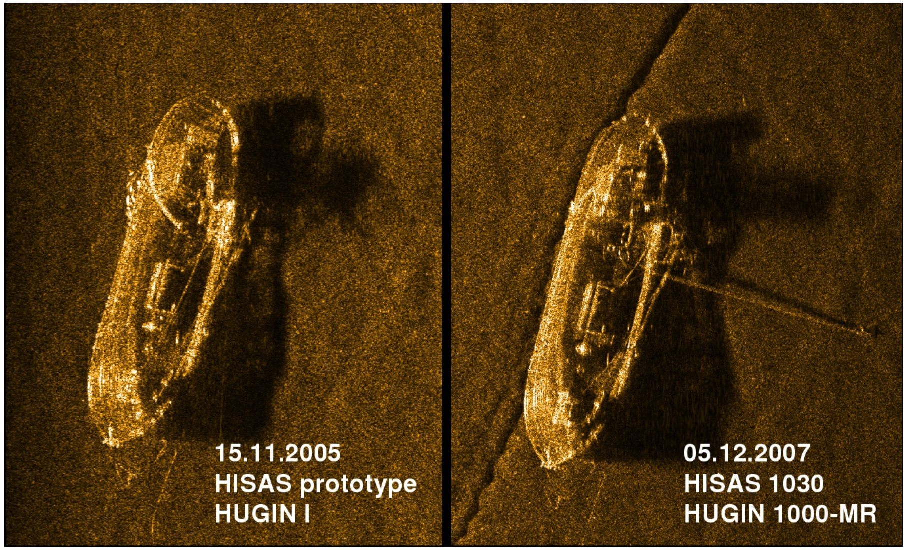
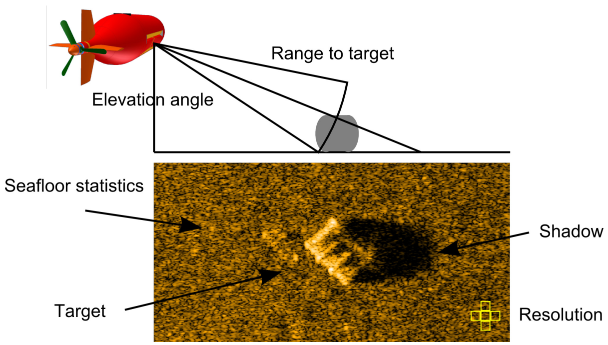


Image collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI

Properties in a sonar image

- Geometry: Range and elevation
- Resolution
- Random variability - speckle
- Signal to noise
- Object highlight and shadow



Example large scene with small objects

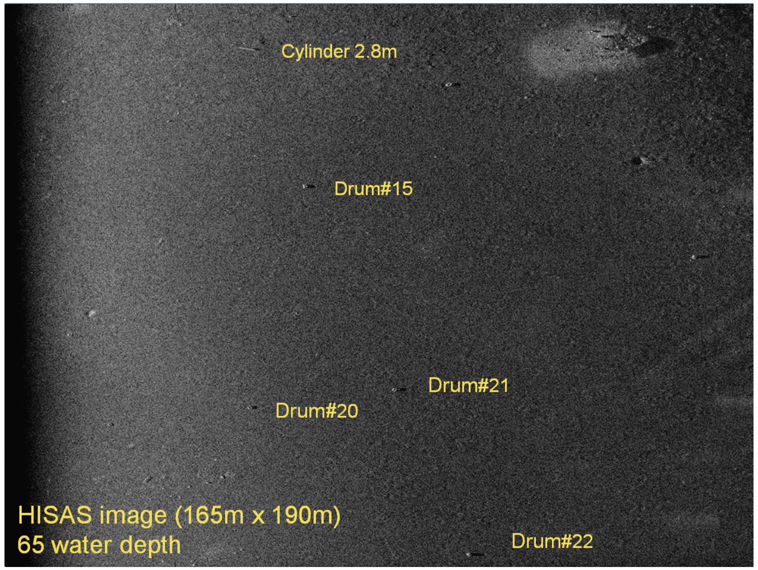


Image collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI

Comparison of sonar image with optical image

- Sonar range: 112 m
- Optical range: 4.5 m

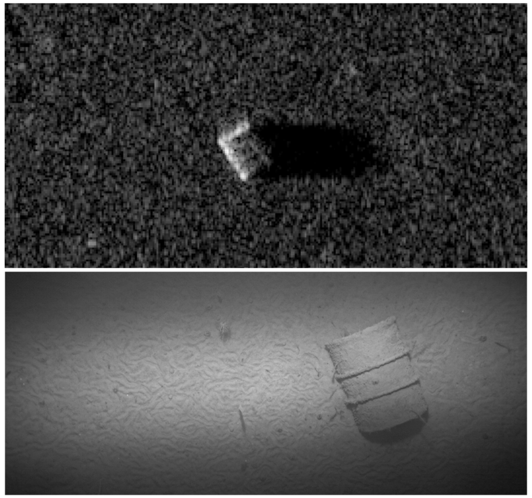


Image collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI

Comparison of sonar image with optical image

- Sonar range: 73 m
- Optical range: 5 m

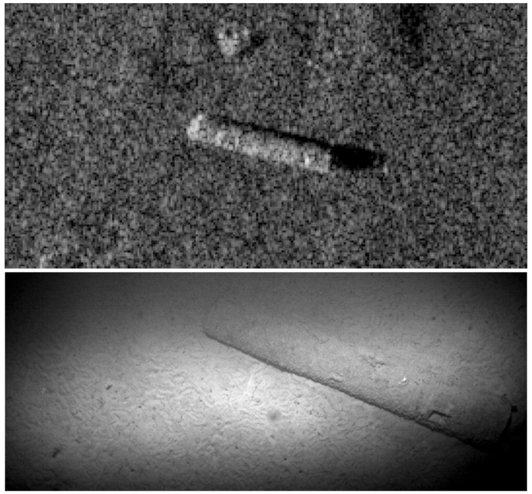


Image collected by HUGIN AUV. Courtesy of Kongsberg Maritime / FFI

Outline

Summary

- Acoustics is the only long ranging information carrier under water
- Sound velocity variations cause refraction of acoustic waves
- The ocean is lossy: higher frequencies have shorter range
- SONAR is used for
  - positioning
  - velocity estimation
  - characterisation
- Applications:
  - Fish finding
  - Imaging of the seafloor
  - Mapping of the seafloor
  - Military

På Norsk

Engelsk	**Norsk**
beam	stråle
beamwidth	strålebredde
range	avstand
bearing	retning
echosounder	ekkolodd
sidescan sonar	sidesøkende sonar
multibeam echosounder	multistråle ekkolodd