Underwater Communications

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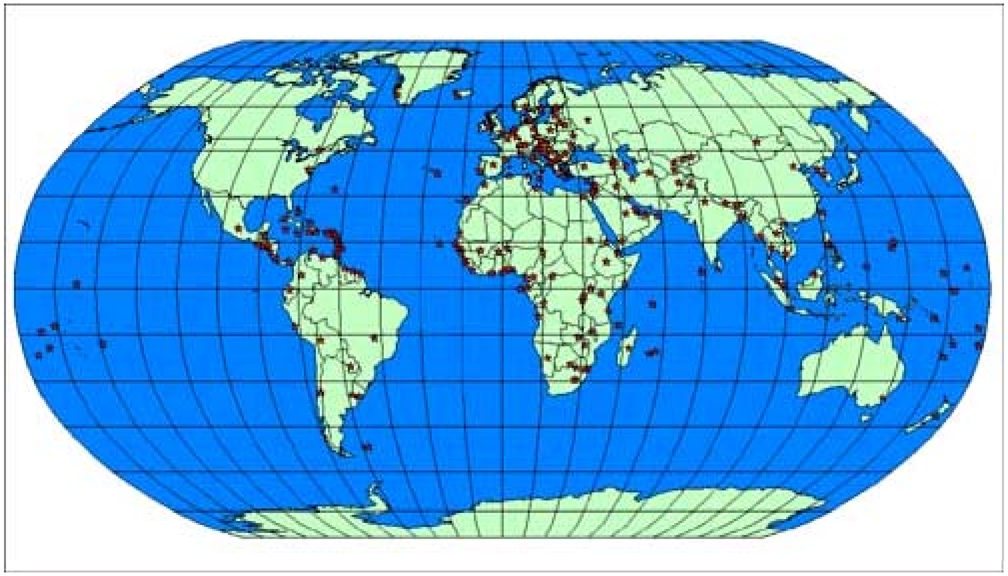
Background

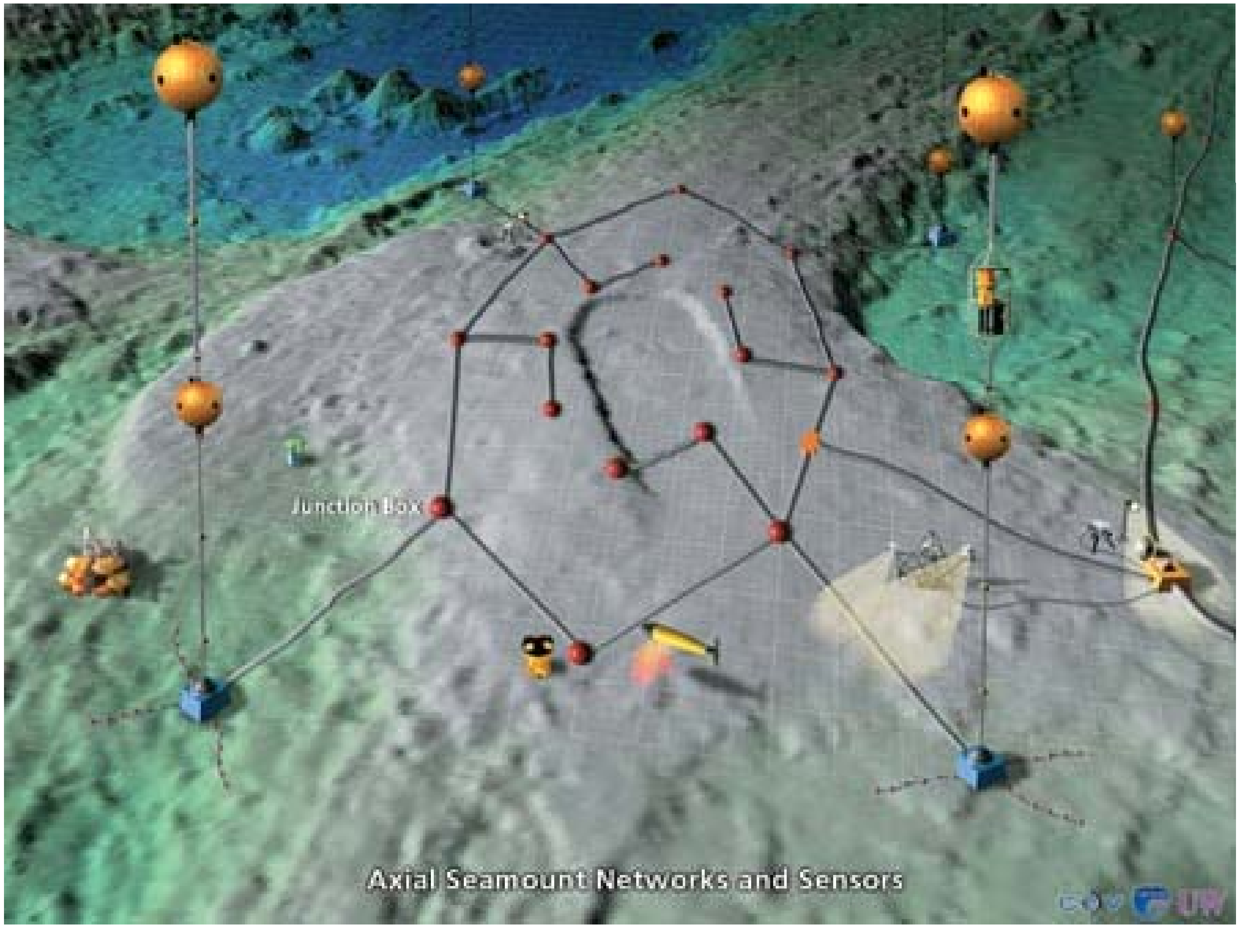
- BS in Electrical and Computer Engineering, Cornell university 2002
- MS in Electrical and Computer Engineering, Johns Hopkins 2005
- Hardware Engineer, JHUAPL 2002-2005
- PhD Candidate, MIT/WHOI Joint Program

Introduction and Motivation

- Ocean covers 70% of planet
- 11,000 meters at deepest point



Underwater Technology



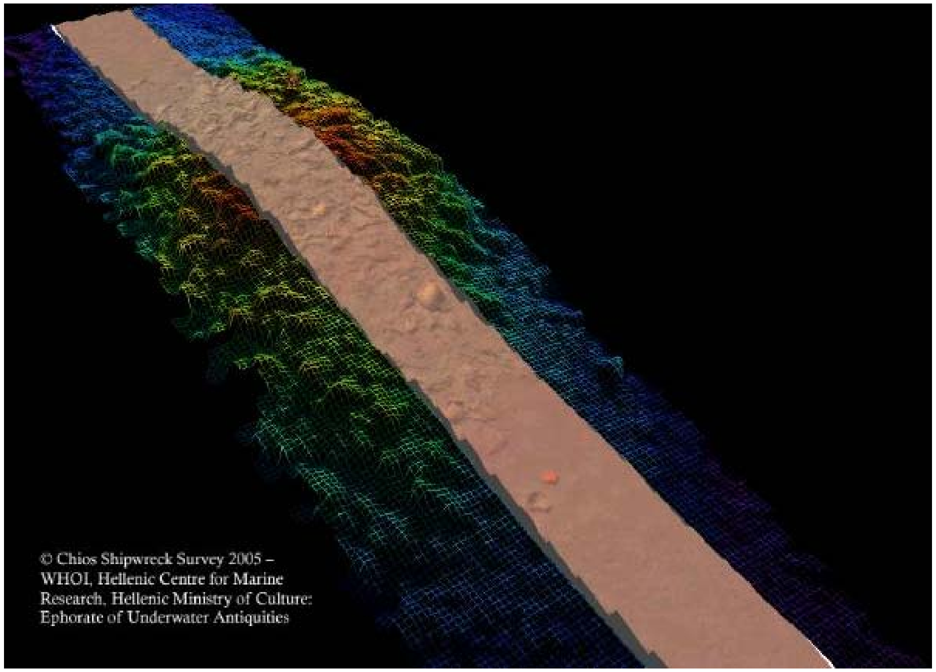
WHOI, 2006

Communication

- Sensor networks
- Autonomous underwater vehicles (AUV)
- Gliders
- Manned Vehicles

Current Applications

- Science
  - Geological / bathymetric surveys
  - Underwater archeology
  - Ocean current measurement
  - Deep ocean exploration
- Government
  - Fish population management
  - Costal inspection
- Industry
  - Oil field discovery maintenance

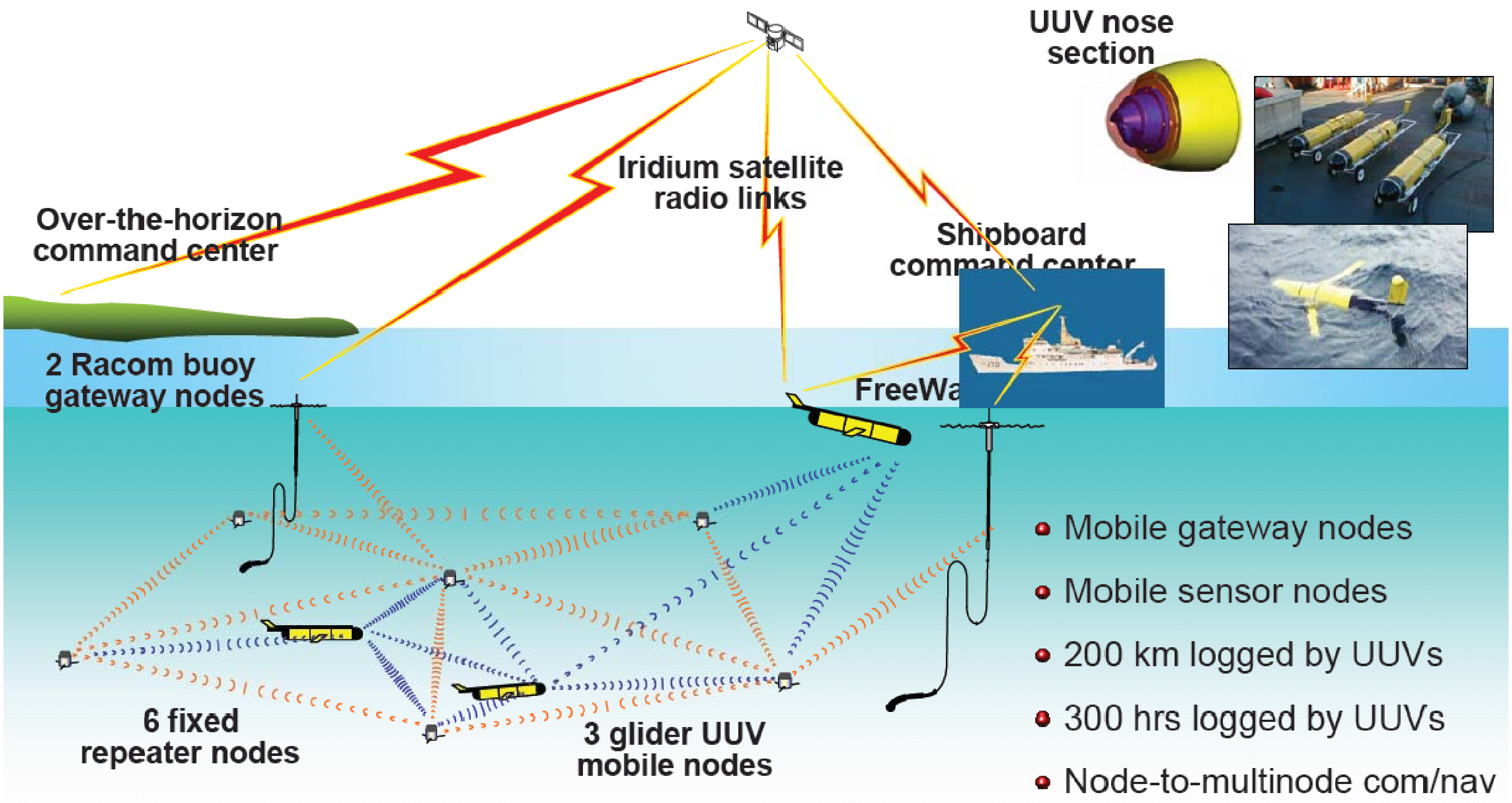


WHOI, 2005

Applications planned / in development

- Ocean observation system
  - Costal observation
- Military
  - Submarine communications (covert)
  - Ship inspection
- Networking
  - Mobile sensor networks (DARPA)
- Vehicle deployment
  - Multiple vehicles deployed simultaneously
  - Resource sharing among vehicles

Example Communication System



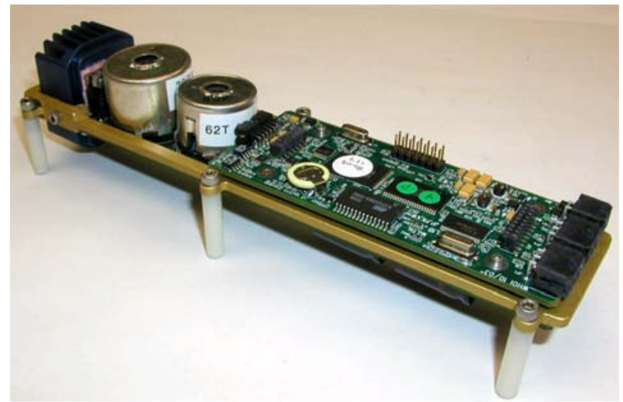
PLUSnet/Seaweb

Technology for communication

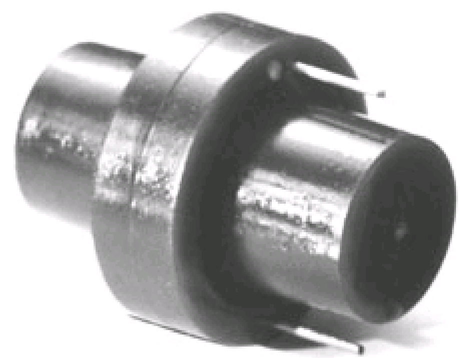
- RF (~1m range)
  - Absorbed by seawater
- Laser (~100m range)
  - Hard to aim/control
  - High attenuation except for blue/green
- Ultra Low Frequency (~100 km)
  - Massive antennas (miles long)
  - Very narrowband (~50 Hz)
  - Not practical outside of navy
- Cable
  - Expensive/hard to deploy maintain
  - Impractical for mobile work sites

Acoustics is the solution

- Fairly low power
  - ~10-100W Tx
  - ~100 mW Rx
- Well studied
  - Cold war military funding
- Compact
  - Small amount of hardware needed
- Current Best Solution



WHOI Micromodem



- Acoustic wave is compression wave traveling through water medium

Wave Equation for Pressure

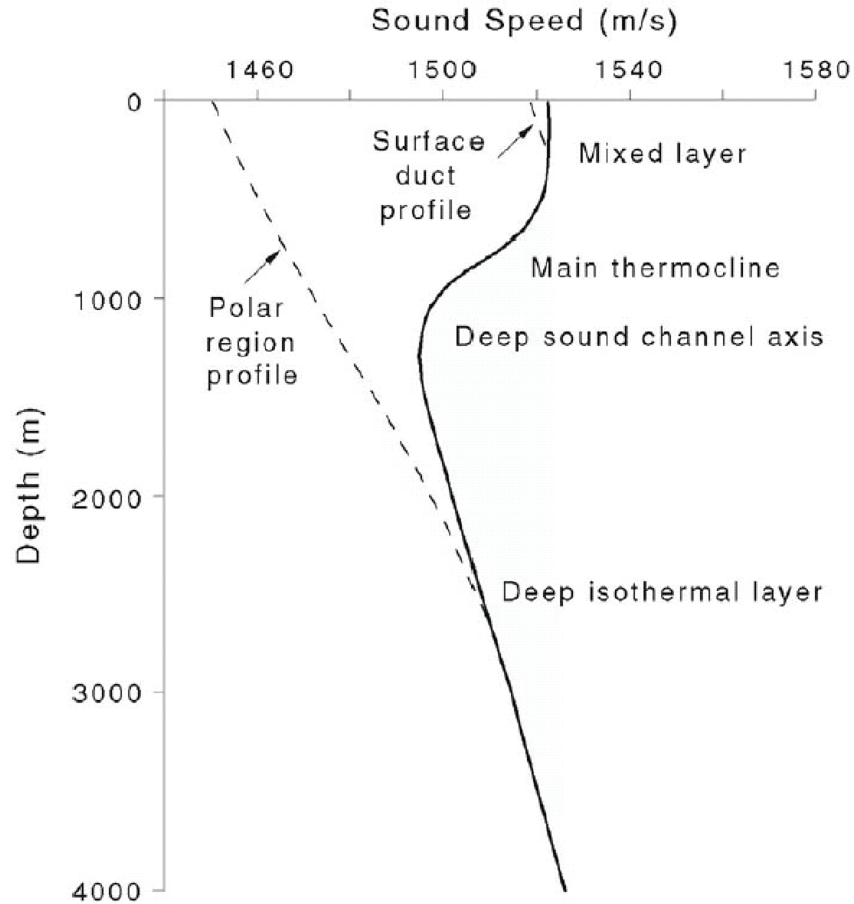
$$\rho \nabla \cdot \left(\frac{1}{\rho} \nabla p \right) - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0 \,,$$

Wave Equation for Particle Velocity

$$\frac{1}{\rho} \nabla \left(\rho c^2 \, \nabla \cdot \mathbf{v} \right) - \frac{\partial^2 \mathbf{v}}{\partial t^2} = \mathbf{0} \,.$$

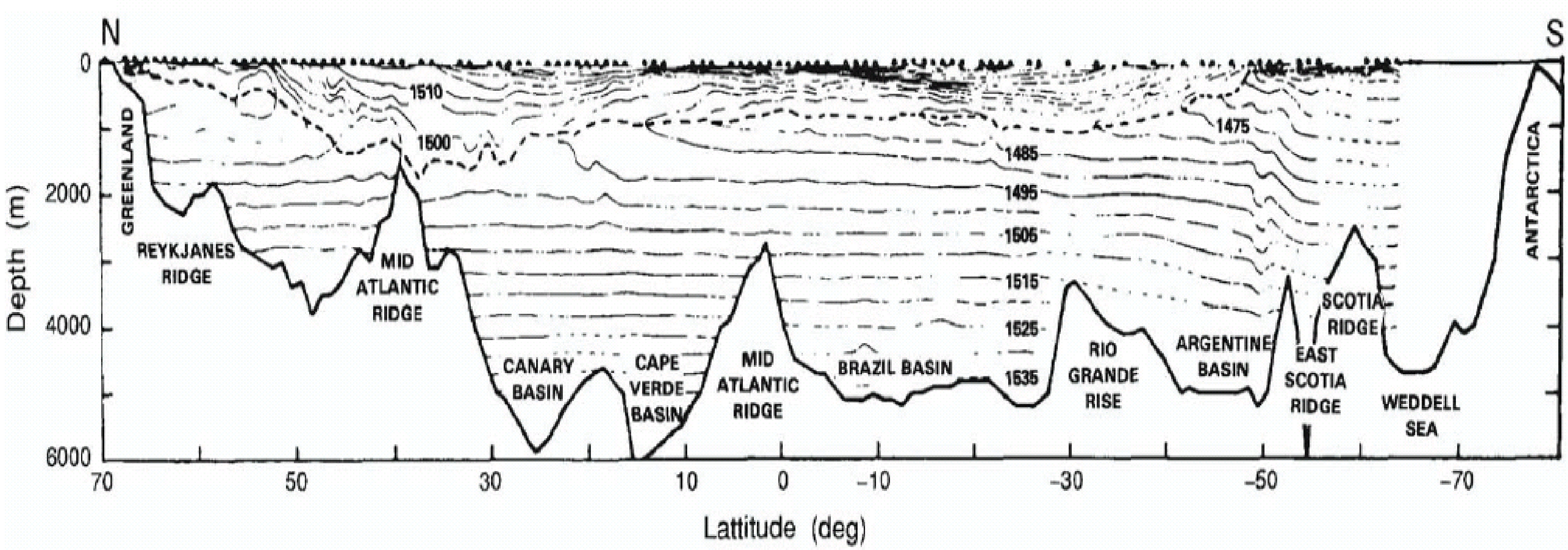
Sound Profile

- Speed of sound ~ 1500 m/s
- Deep water profile



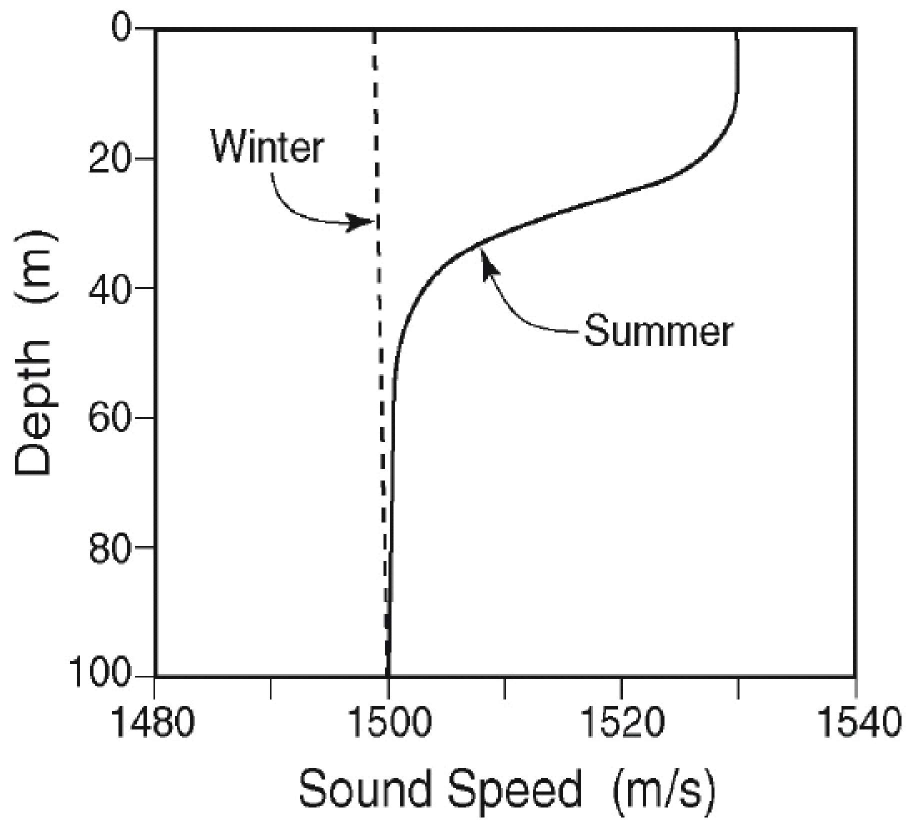
Schmidt, *Computational Ocean Acoustics*

Global Ocean Profile



Schmidt, *Computational Ocean Acoustics*

Shallow water profile



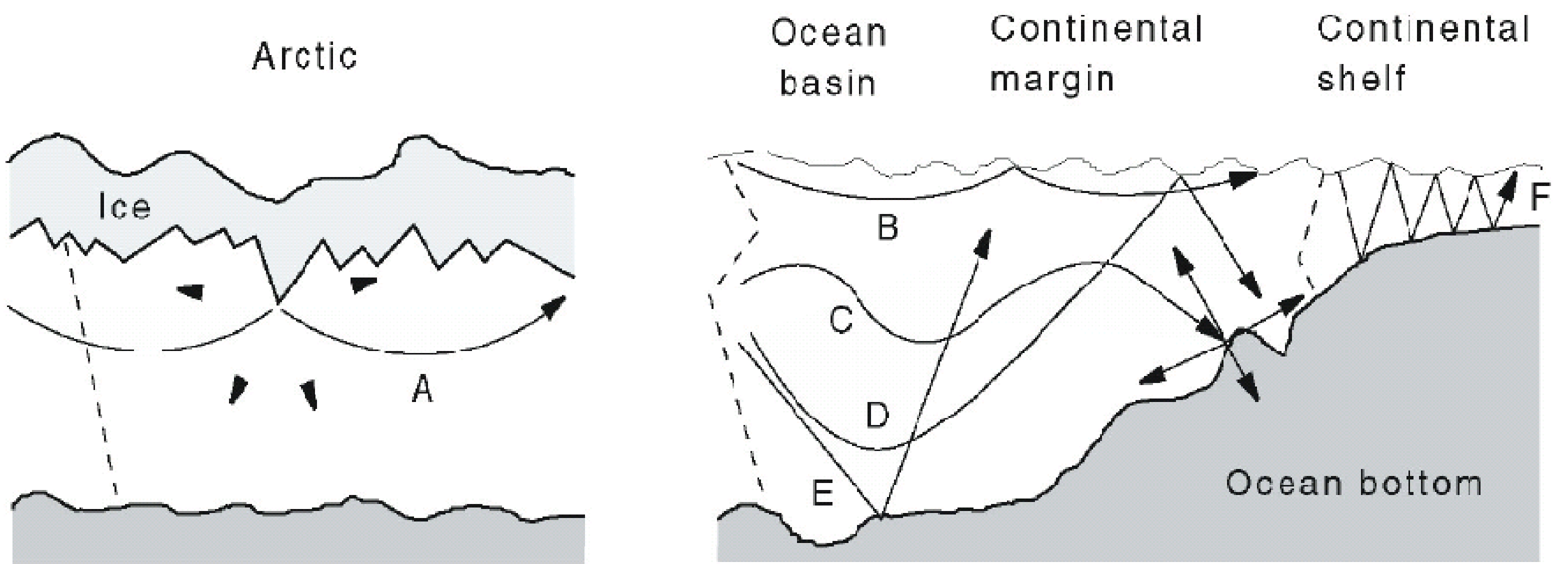
Schmidt, *Computational Ocean Acoustics*

Speed of Sound Implications

- Vertical sound speed profile impacts
  - the characteristics of the impulse response
  - the amount and importance of surface scattering
  - the amount of bottom interaction and loss
  - the location and level of shadow zones

- Horizontal Speed of Sound impacts
  - Nonlinearities in channel response

Propagation Paths

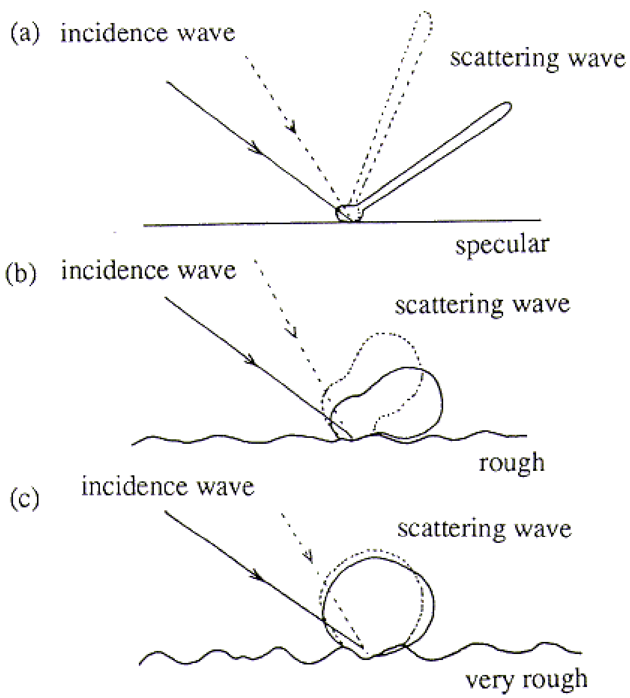


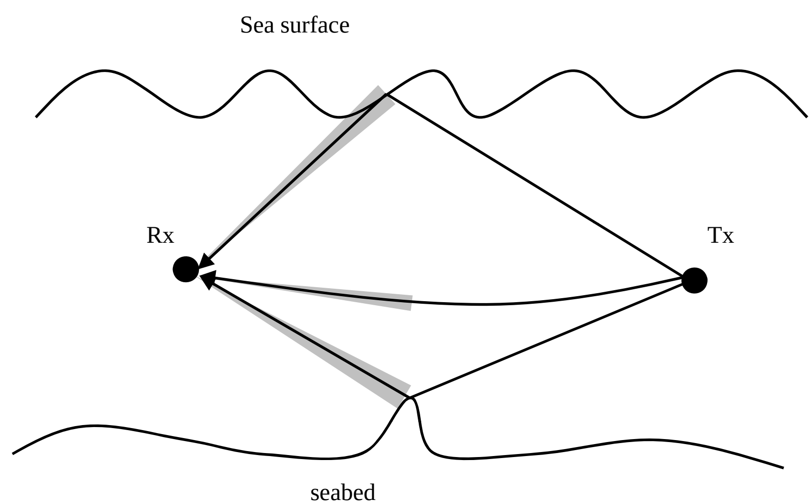
A. Arctic
B. Surface duct
C. Deep sound channel
D. Convergence zone
E. Bottom bounce
F. Shallow water

Schmidt, *Computational Ocean Acoustics*

Multipath

- Micro-multipath due to rough surfaces
- Macro-multipath due to environment



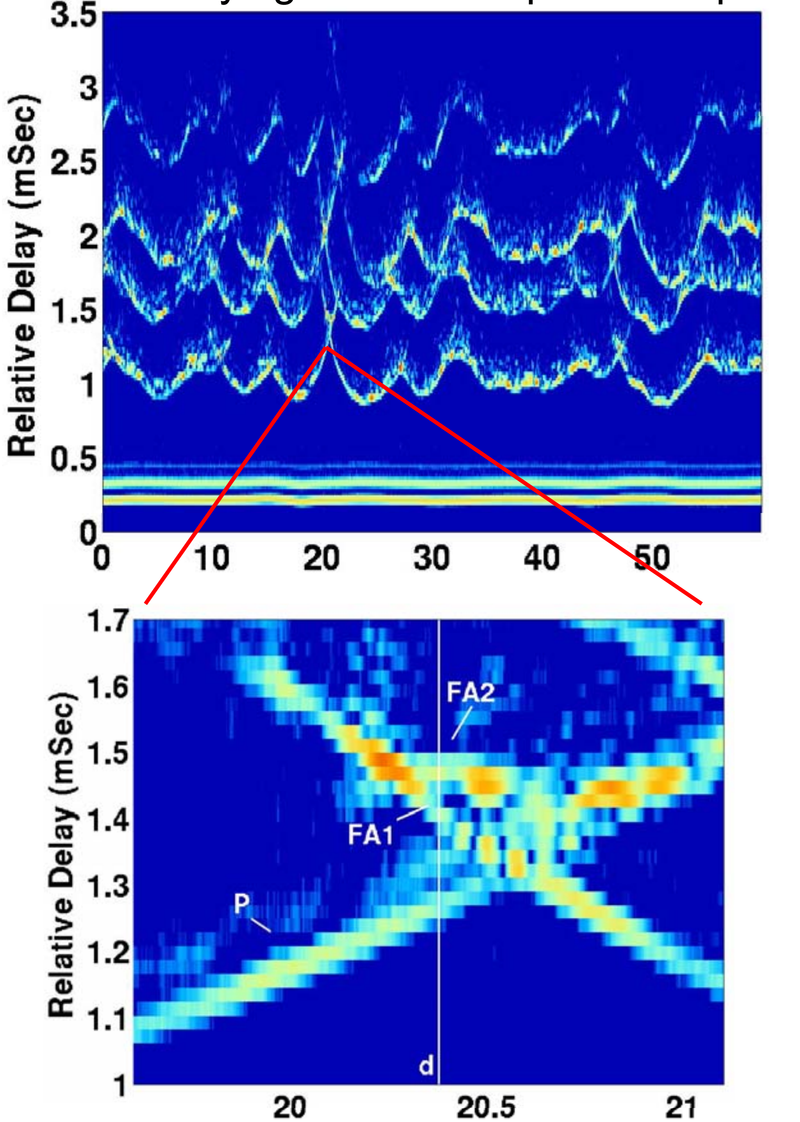


Time varying channel

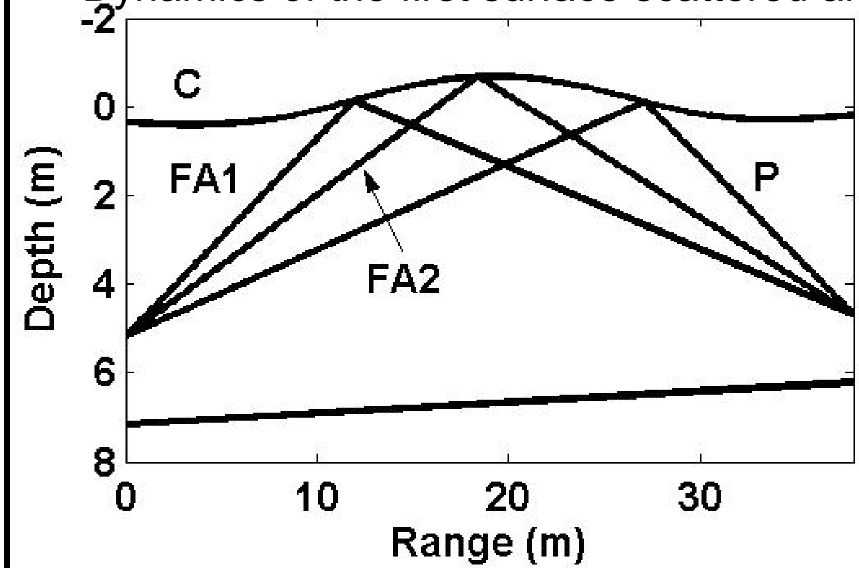
- Time variation is due to:
  - Platform motion
  - Internal waves
  - Surface waves
- Effects of time variability
  - Doppler Shift $$f_d = f_c \frac{u}{c}$$
  - Time dilation/compression of the received signal
- Channel coherence times often << 1 second.
- Channel quality can vary in < 1 second.

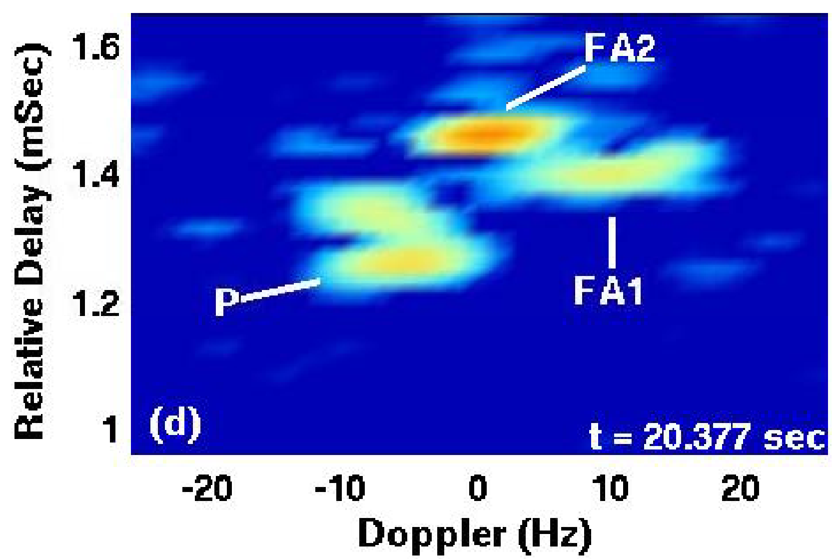
Acoustic Focusing by Surface Waves

Time-Varying Channel Impulse Response



Dynamics of the first surface scattered arrival



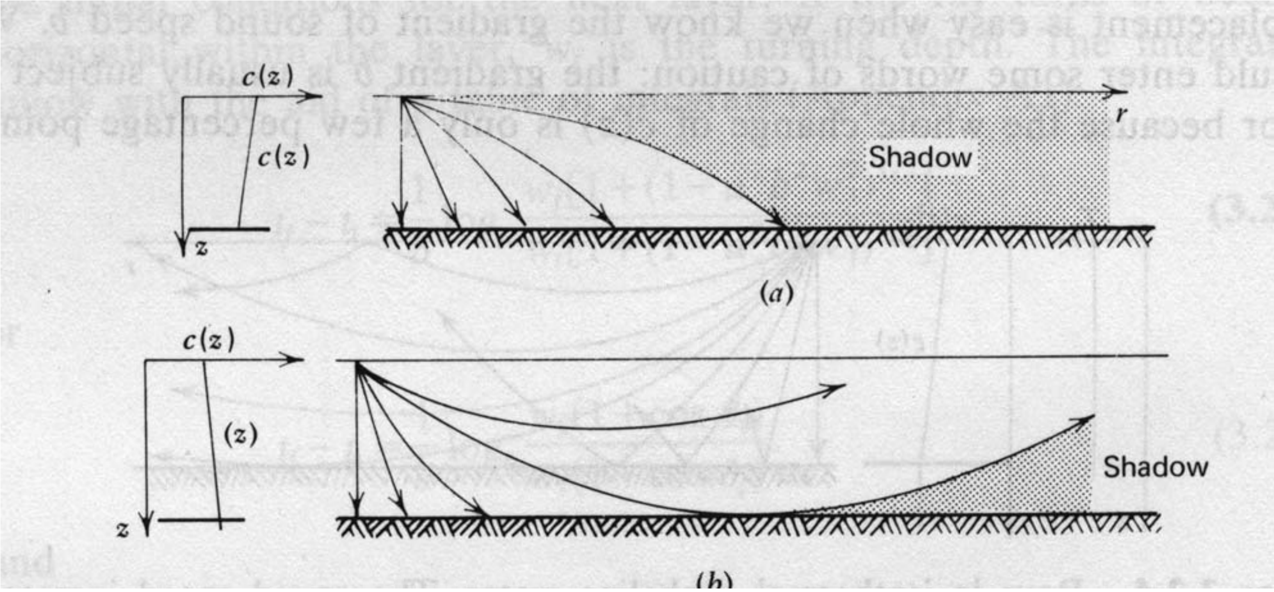


Preisig, 2006

Multipath and Time Variability Implications

- Channel tracking and quality prediction is vital
  - Equalizer necessary and beefy
- Coding and interleaving
- In networks, message routing

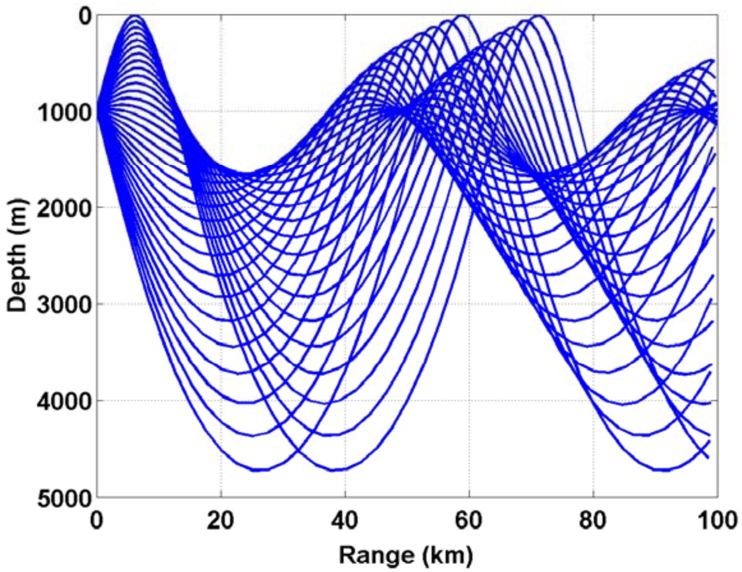
Shadow Zones

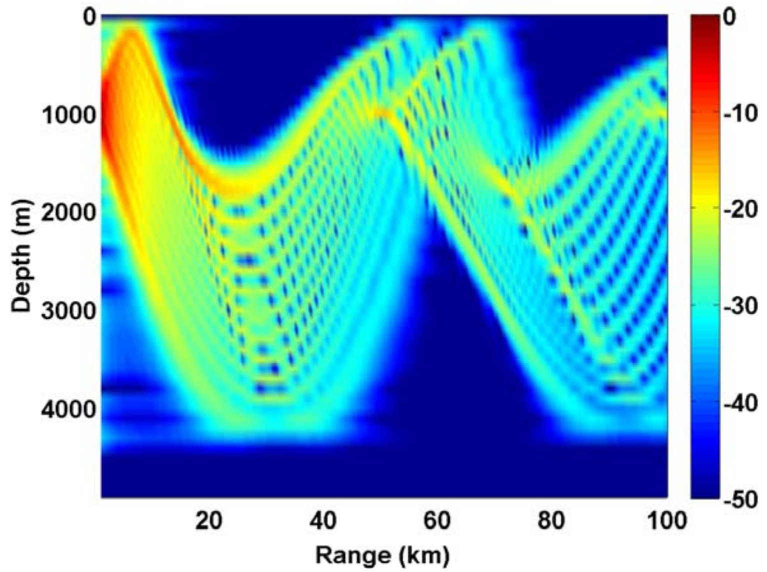


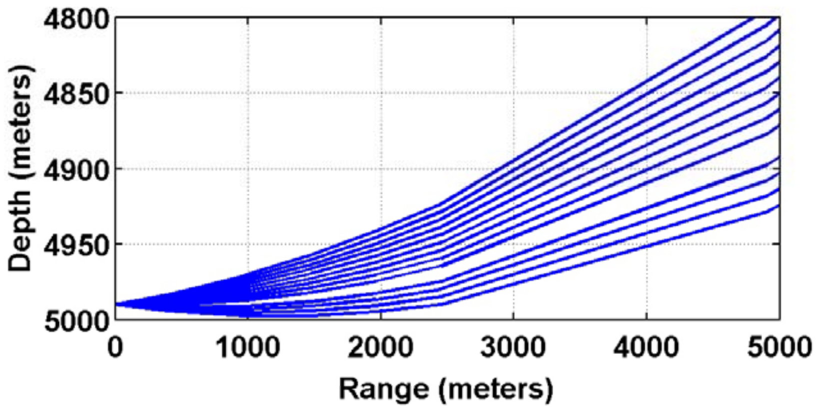
Clay and Medwin, "Acoustical Oceanography"

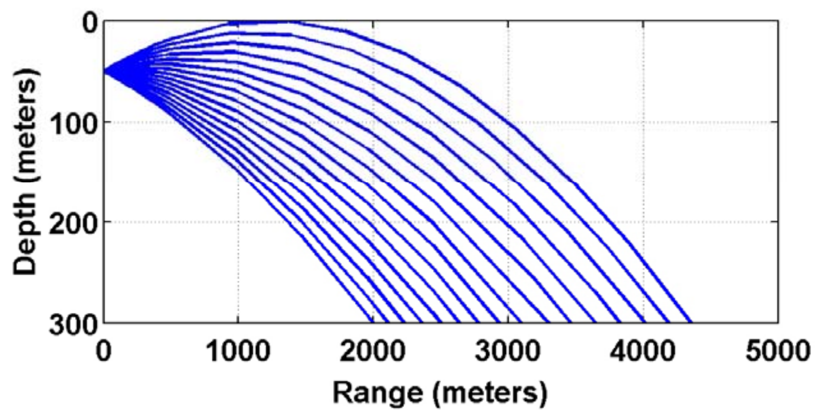
- **Sometimes there is no direct path (unscattered) propagation between two points. All paths are either surface or bottom reflected or there are no paths.**
- **Problem with communications between two bottom mounted instruments in upwardly refracting environment (cold weather shallow water, deep water).**
- **Problem with communications between two points close to the surface in a downwardly refracting environment (warm weather shallow water and deep water).**

Shadow Zone Examples (Deep Water)









Figures from J. Preisig

Ambient Noise

- Ambient noise
  - Passing ships, storms, breaking waves, seismic events
  - p.s.d. decays as 20dB/decade ->$N(f)= 10^{10} f^{-2}$ Watts/Hz re 1μPa
- Primary natural sources
  - bubbles, rain, and biologic sources such as snapping shrimp
- Bubbles
  - Can cause communications channel to disappear
  - Can increase surface scattering losses (up to 10dB per bounce)
  - Attenuation in bubble cloud can be 20dB/meter
  - Freq dependent attenuation (peak near 30kHz)
  - Can persist for minutes
  - Cause sound (noise)

Noise

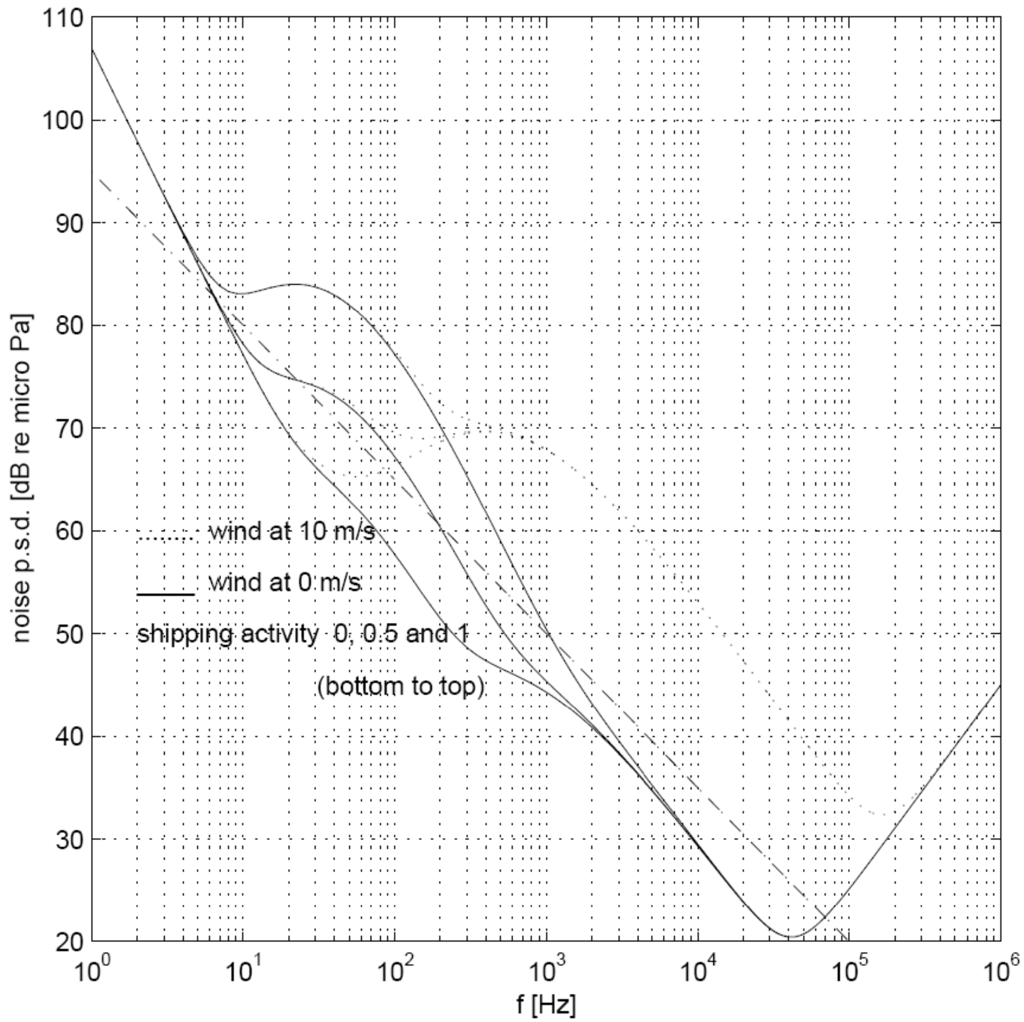
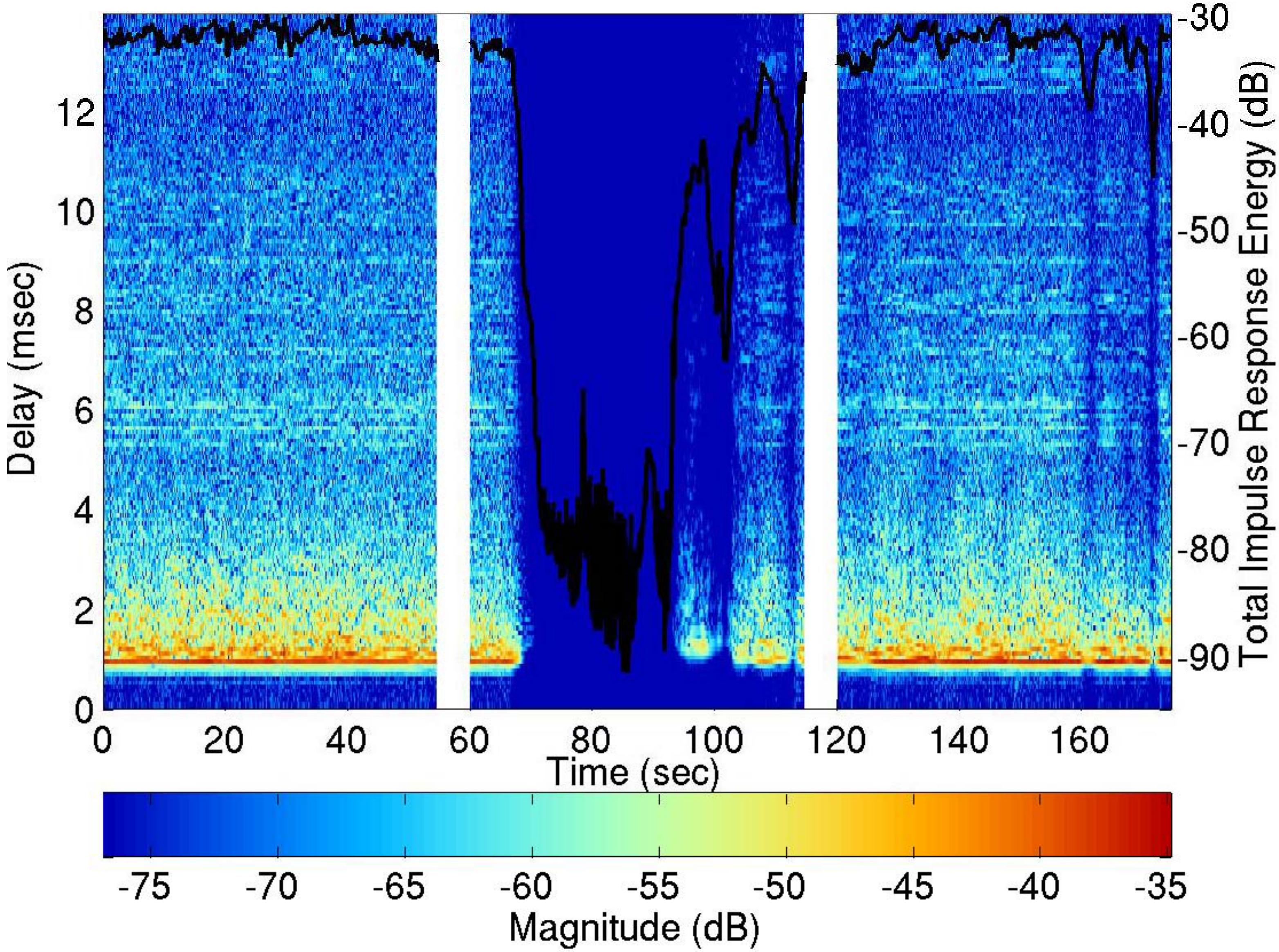


Figure from:

Stojanovic, WUWNeT'06

Bubble Cloud Attenuation



Figures from J. Preisig

Bandwidth

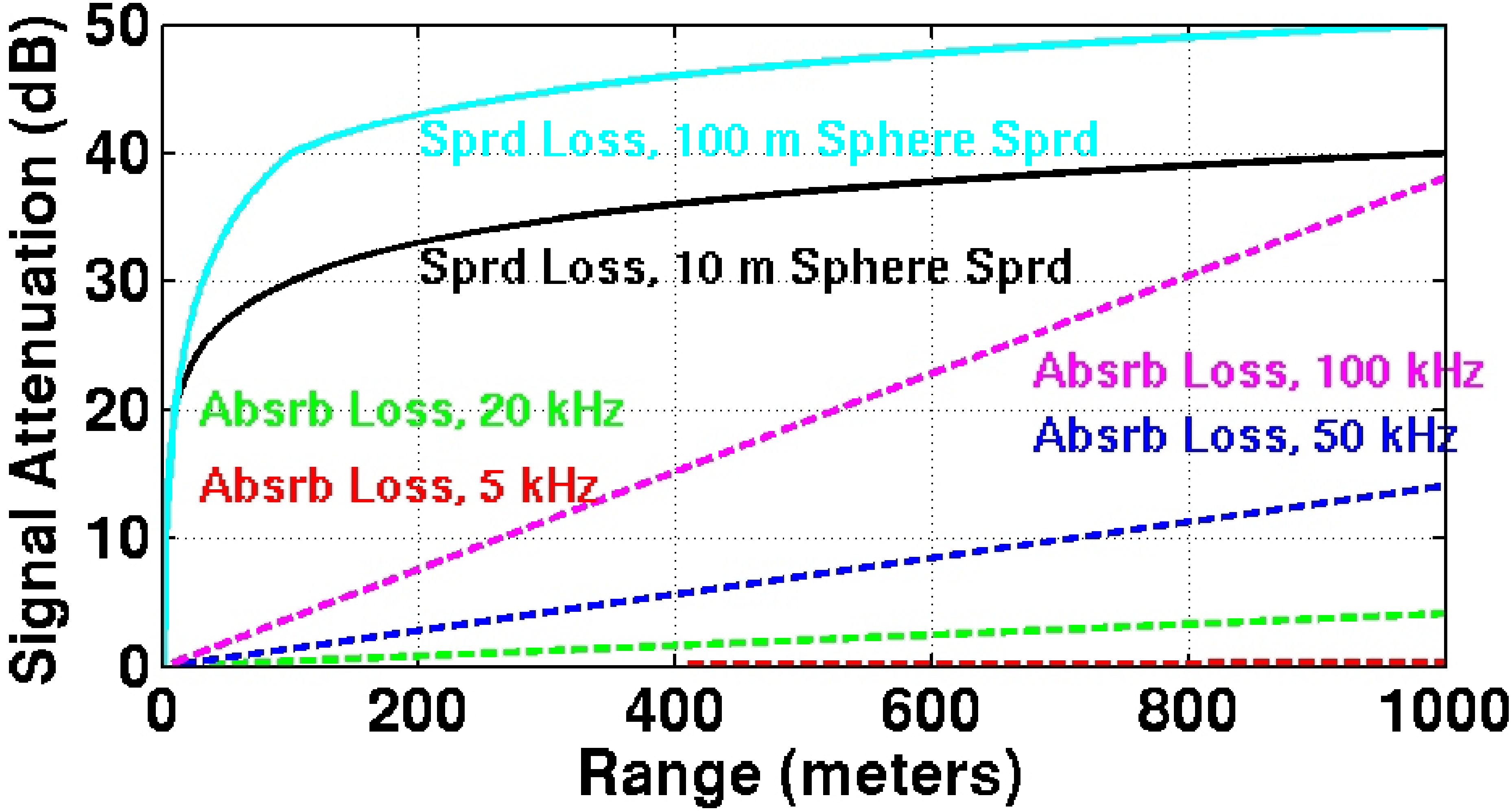
- Center frequency typically around 10-30kHz
- Typical Bandwidth ~ 5-15kHz
- Channel is inherently band-limited
  - Modulation essential for high rate communications

Path loss and Absorption

- Path Loss
  - Spherical Spreading ~ r^{-1}
  - Cylindrical Spreading ~ $r^{-0.5}$
- Absorption ~ $\alpha(f)^{-r}$
  - Thorp's formula (for sea water):

$$10\log\alpha(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 0.000275\,f^2 + 0.003 \quad \text{(dB/km)}$$

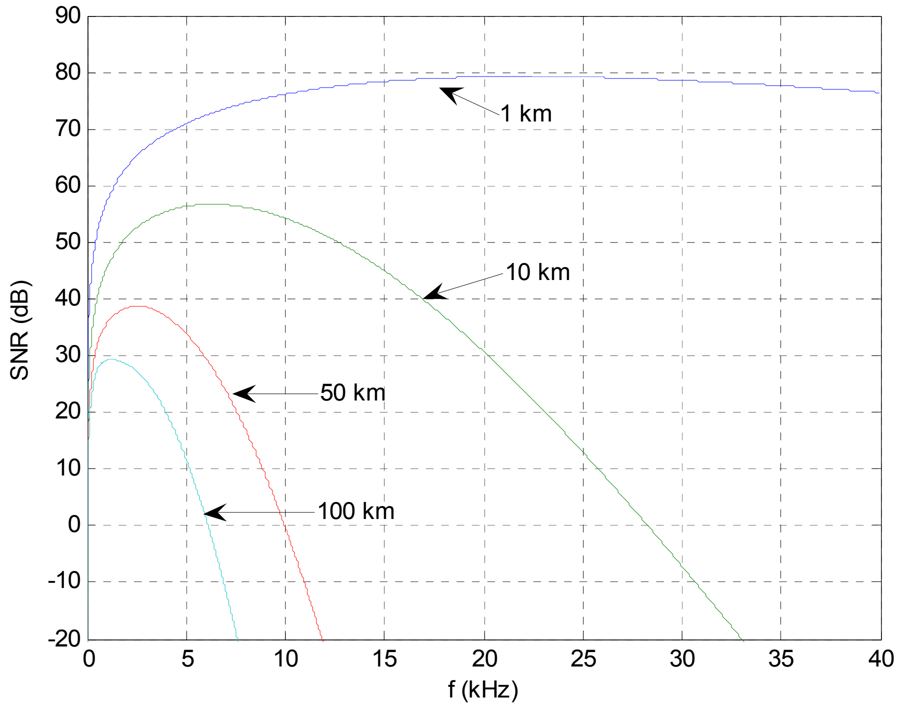
Short Range Attenuation



Figures from J. Preisig

Long Range Bandwidth

$$SNR(f) = 171 + 10\log(P) - r\,\alpha(f) - 20\log(h/2) - 10\log(r - h/2) - 10\log\left(\int_{f-df/2}^{f+df/2} N(f)\,df\right) \text{ dB}$$

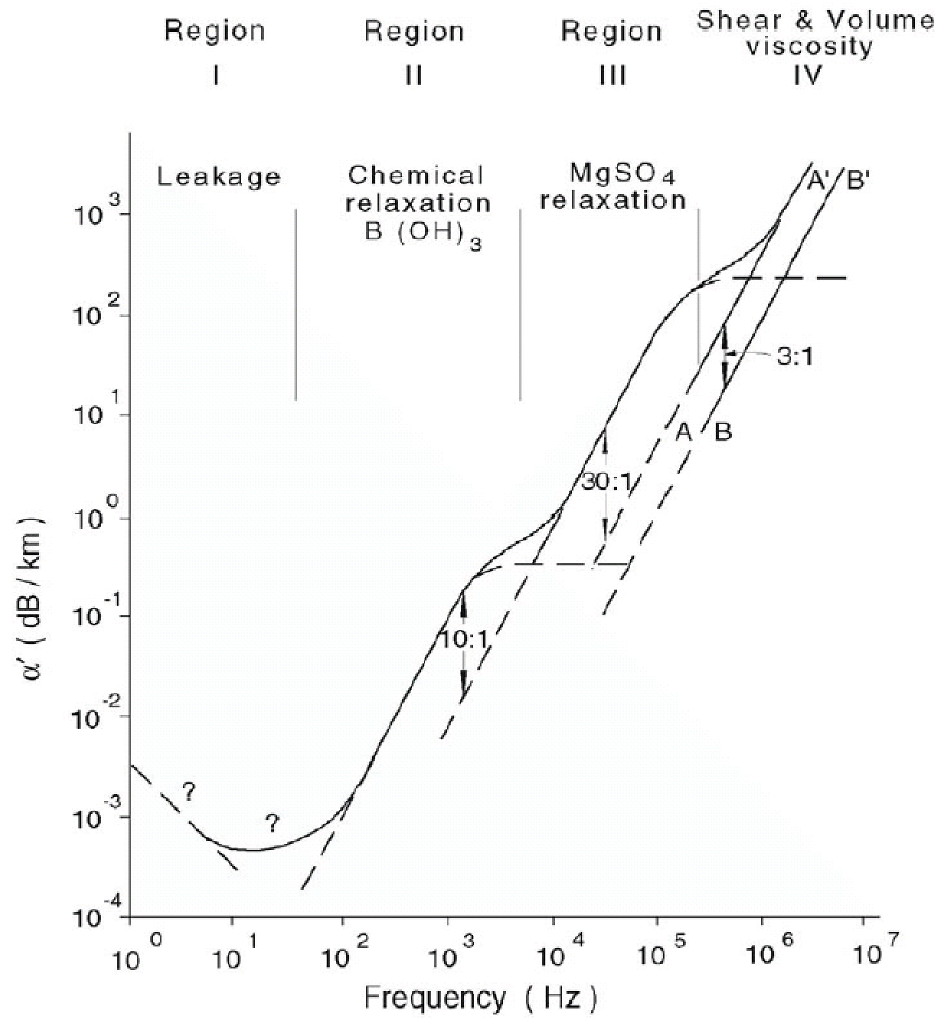


Source: 20 Watts

h = 500 m

Figure courtesy of Costas Pelekanakis

Attenuation of Sound in Seawater



Schmidt, *Computational Ocean Acoustics*

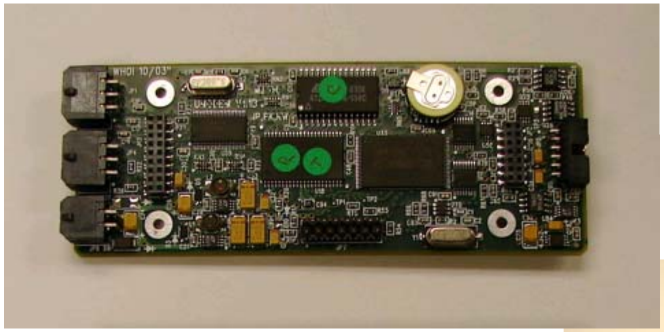
Bandwidth Implications

- Modulation frequency must be kept low
- System inherently wide-band
- Frequency curtain effect
  - Form of covert communications
  - Might help with network routing

Latency and Power

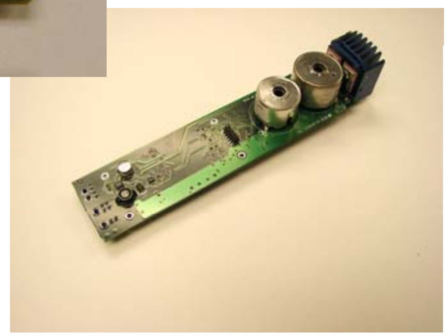
- Propagation of sound slower than light
  - Feedback might take several second
  - Channel changing faster than feedback
- Most underwater nodes battery powered
  - Communications Tx power (~10-100W)
  - Retransmissions costly

Example Hardware

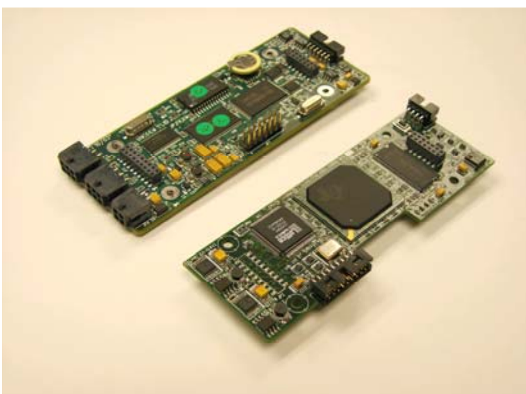


WHOI Micromodem

Power Amp



Micromodem in action



Daughter Card / Co-processor

Micromodem Specifications

DSP	Texas Instruments TMS320C5416 100MHz low-power fixed point processor
Transmit Power	10 Watts Typical match to single omni-directional ceramic transducer.
Receive Power	80 milliwatts While detecting or decoding an low rate FSK packet.
Data Rate	80-5400 bps 5 packet types supported. Data rates higher than 80bps FSK require additional co-processor card to be received.

Conclusions

- Communicating in the ocean is difficult
  - Time varying channel
  - Inconsistent noise
  - Shadow zones
  - Bubbles
  - Latency

- Many questions still left to be answered
  - Communications is not well researched
  - Many opportunities for advances

Acknowledgements

- I would like to thank the following people for helping me with this presentation:
  - Jim Preisig
  - Costas Pelekanakis
  - Henrik Schmidt
  - Milica Stojanovic
  - WHOI Acoustic team

My Research

- Coding for the underwater channel