PHYS 536

R. J. Wilkes

Session 16

High power transducers

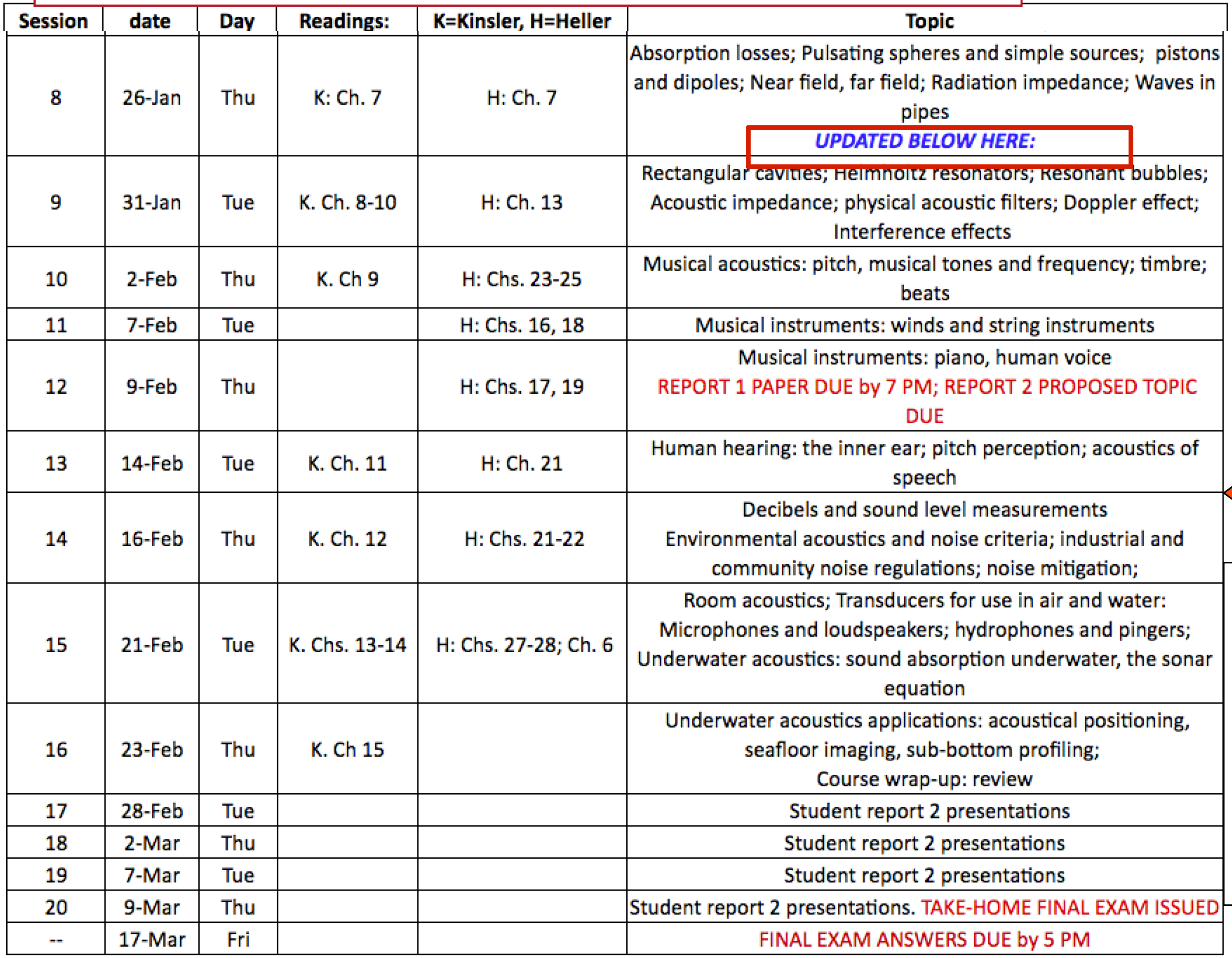
Underwater acoustics

Doppler shift

2/23/2023

Course syllabus and schedule

See : http://courses.washington.edu/phys536/syllabus.htm



Session	date	Day	Readings:	K=Kinsler, H=Heller	Topic
8	26-Jan	Thu	K: Ch. 7	H: Ch. 7	Absorption losses; Pulsating spheres and simple sources; pistons and dipoles; Near field, far field; Radiation impedance; Waves in pipes *UPDATED BELOW HERE:*
9	31-Jan	Tue	K. Ch. 8-10	H: Ch. 13	Rectangular cavities; Helmholtz resonators; Resonant bubbles; Acoustic impedance; physical acoustic filters; Doppler effect; Interference effects
10	2-Feb	Thu	K. Ch 9	H: Chs. 23-25	Musical acoustics: pitch, musical tones and frequency; timbre; beats
11	7-Feb	Tue		H: Chs. 16, 18	Musical instruments: winds and string instruments
12	9-Feb	Thu		H: Chs. 17, 19	Musical instruments: piano, human voice REPORT 1 PAPER DUE by 7 PM; REPORT 2 PROPOSED TOPIC DUE
13	14-Feb	Tue	K. Ch. 11	H: Ch. 21	Human hearing: the inner ear; pitch perception; acoustics of speech
14	16-Feb	Thu	K. Ch. 12	H: Chs. 21-22	Decibels and sound level measurements Environmental acoustics and noise criteria; industrial and community noise regulations; noise mitigation;
15	21-Feb	Tue	K. Chs. 13-14	H: Chs. 27-28; Ch. 6	Room acoustics; Transducers for use in air and water: Microphones and loudspeakers; hydrophones and pingers; Underwater acoustics: sound absorption underwater, the sonar equation
16	23-Feb	Thu	K. Ch 15		Underwater acoustics applications: acoustical positioning, seafloor imaging, sub-bottom profiling; Course wrap-up: review
17	28-Feb	Tue			Student report 2 presentations
18	2-Mar	Thu			Student report 2 presentations
19	7-Mar	Tue			Student report 2 presentations
20	9-Mar	Thu			Student report 2 presentations. TAKE-HOME FINAL EXAM ISSUED
--	17-Mar	Fri			FINAL EXAM ANSWERS DUE by 5 PM

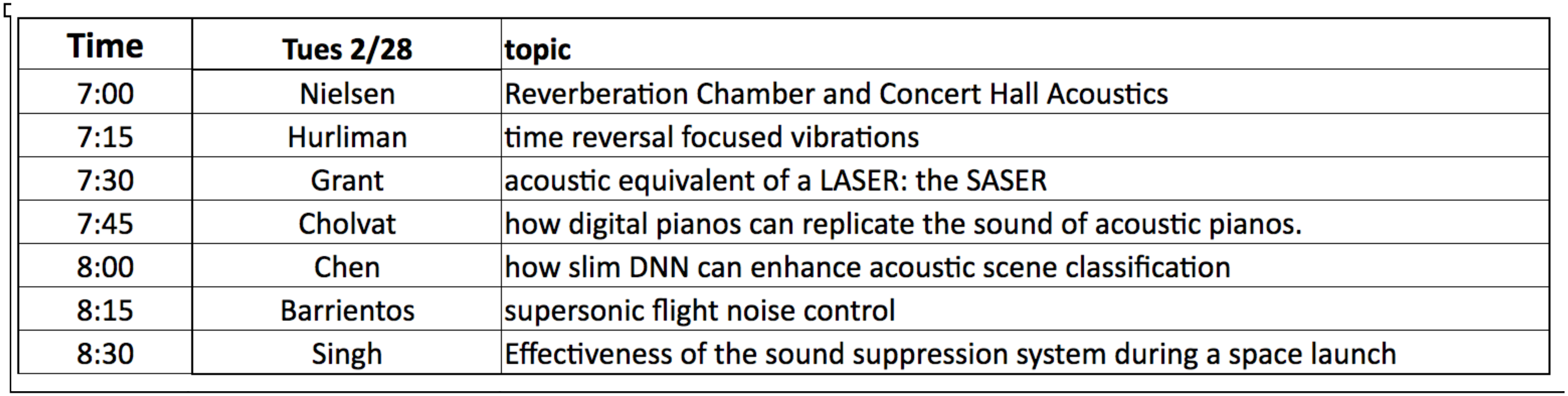
Tonight

Class is over after you turn in your take-home exam. No in-person final exam during finals week.

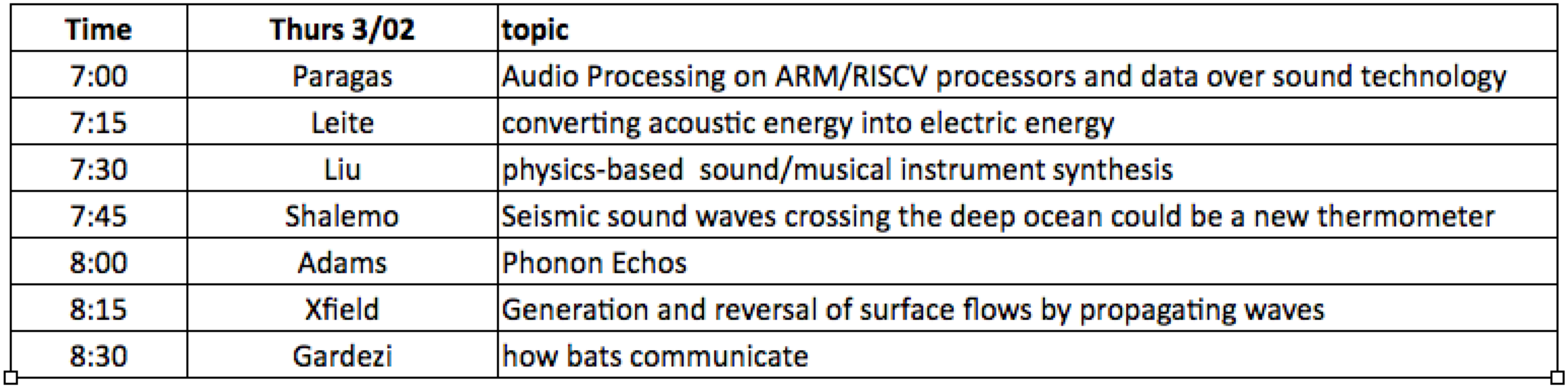
Presentations begin next session!

- Schedule has been posted (next slide) on the course website
  - Assignments were made randomly except for few who volunteered
- Turn in your (complete) draft slides on Tuesday 2/28 in Canvas
  - In fairness to those presenting in early time slots
  - You can tweak your slides until day of presentation, but do not add whole new sections
- BE SURE your talk is no longer than 15 minutes!
  - Practice talk to a friend (or the mirror) to check timing
  - Rule of thumb: should have no more than 15 slides for 15 min
    - Skip inessentials! Outline of talk, section title slides, etc
    - List your references on a final slide to be left on the screen when done
- On the day of your presentation:
  - Send me (wilkes@uw.edu) a file with your slides by 6 pm
  - TEST your audio to make sure your voice can be heard clearly

Presentation schedule: Next week

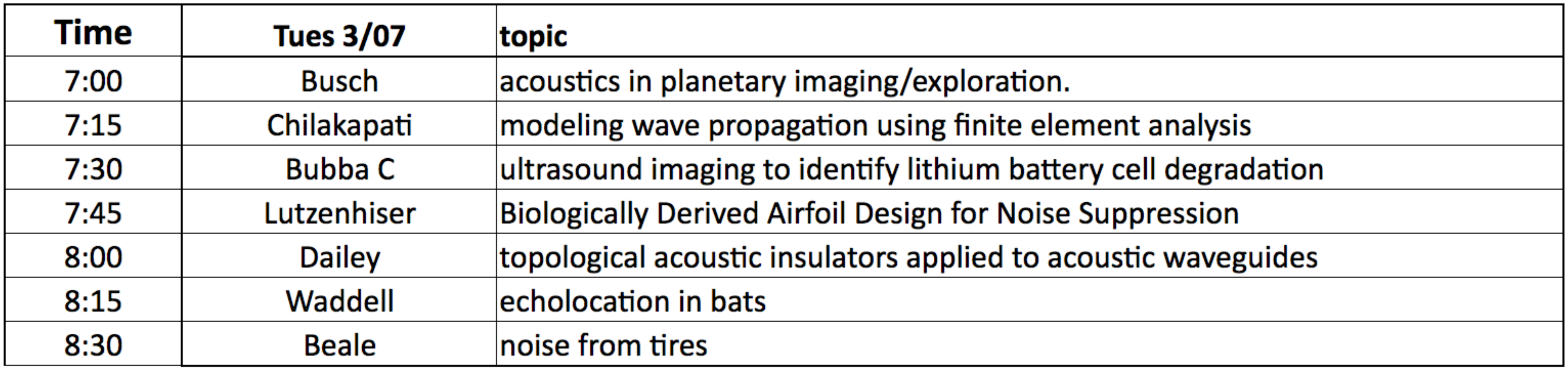


Time	Tues 2/28	topic
7:00	Nielsen	Reverberation Chamber and Concert Hall Acoustics
7:15	Hurliman	time reversal focused vibrations
7:30	Grant	acoustic equivalent of a LASER: the SASER
7:45	Cholvat	how digital pianos can replicate the sound of acoustic pianos.
8:00	Chen	how slim DNN can enhance acoustic scene classification
8:15	Barrientos	supersonic flight noise control
8:30	Singh	Effectiveness of the sound suppression system during a space launch

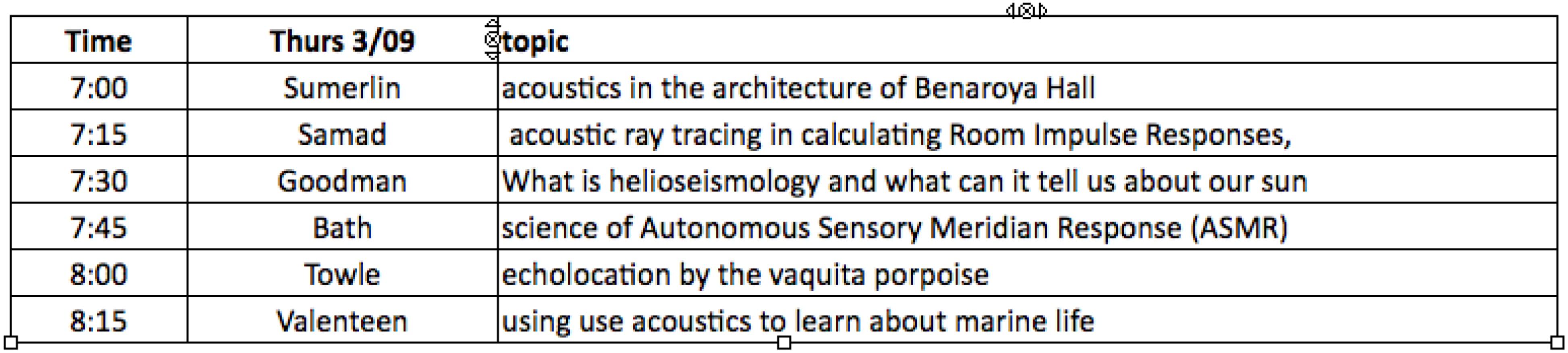


Time	Thurs 3/02	topic
7:00	Paragas	Audio Processing on ARM/RISCV processors and data over sound technology
7:15	Leite	converting acoustic energy into electric energy
7:30	Liu	physics-based sound/musical instrument synthesis
7:45	Shalemo	Seismic sound waves crossing the deep ocean could be a new thermometer
8:00	Adams	Phonon Echos
8:15	Xfield	Generation and reversal of surface flows by propagating waves
8:30	Gardezi	how bats communicate

Following week



Time	Tues 3/07	topic
7:00	Busch	acoustics in planetary imaging/exploration.
7:15	Chilakapati	modeling wave propagation using finite element analysis
7:30	Bubba C	ultrasound imaging to identify lithium battery cell degradation
7:45	Lutzenhiser	Biologically Derived Airfoil Design for Noise Suppression
8:00	Dailey	topological acoustic insulators applied to acoustic waveguides
8:15	Waddell	echolocation in bats
8:30	Beale	noise from tires

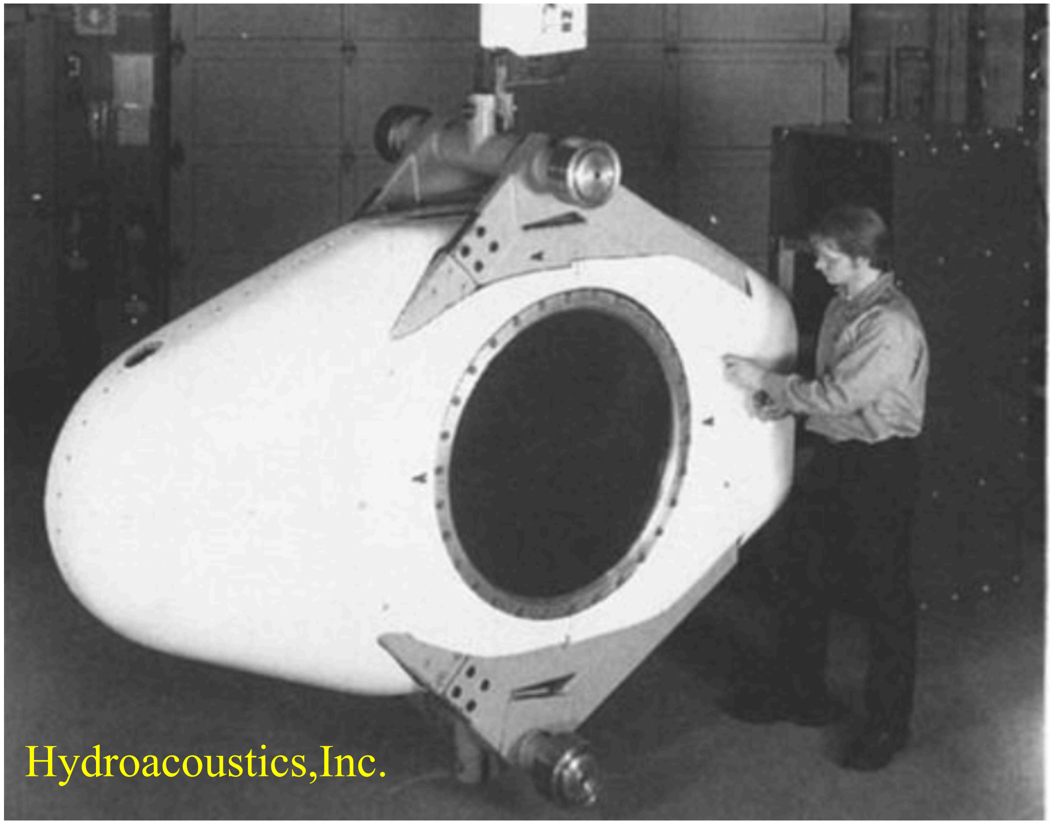


Time	Thurs 3/09	topic
7:00	Sumerlin	acoustics in the architecture of Benaroya Hall
7:15	Samad	acoustic ray tracing in calculating Room Impulse Responses,
7:30	Goodman	What is helioseismology and what can it tell us about our sun
7:45	Bath	science of Autonomous Sensory Meridian Response (ASMR)
8:00	Towle	echolocation by the vaquita porpoise
8:15	Valenteen	using use acoustics to learn about marine life

High power underwater transducers

Example: MassaSonic TR-1075, 600 W up to a 30% duty cycle, 200 Watts max for continuous operation

- Circular piston's 7" diameter is $\lambda/2$ at 4 KHz.
- Typically assembled into arrays to achieve desired beam pattern and source SPL.



··· and here's a really big one:

Acoustic source used in the Acoustic Thermometry of Ocean Climate (ATOC) Project (UW APL). The smooth fiberglass housing covers most of the components. One of two exposed circular radiating faces is shown.

W. Munk et al, J. Acoust. Soc\. of America ***96****, 2330 (1994)*

Underwater acoustics

- Propagation of sound in the ocean is of great interest to many mammals (and other classes of animals)
  - We'll focus on acoustics of seawater
  - Jumping ahead for a quick intro before our guest speakers
- Speed of sound in water
  - Freshwater c depends on T and P
  - Seawater adds another factor: salinity
  - Formulas for c
    - Historic example: Wilson formula (JASA 32:641, 1960): coefficients for a polynomial fit with standard deviation 0.22 m/sec.
    - Simplified formula (Medwin, JASA 58:1318, 1975)
      - T = deg C, z=depth in m, S=salinity in ppt (0/00)

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

Underwater acoustics

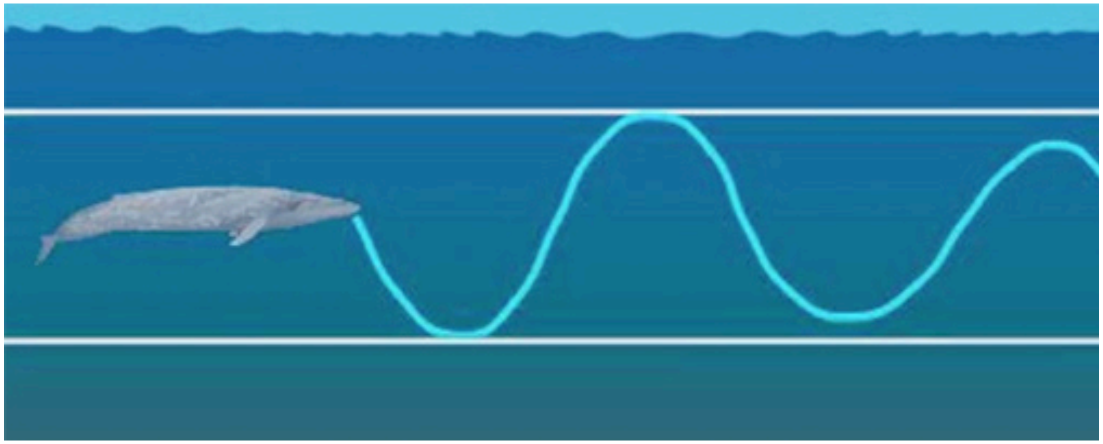
- Famous feature of ocean sound speed vs depth:
  - Reversing slope at ~1 km

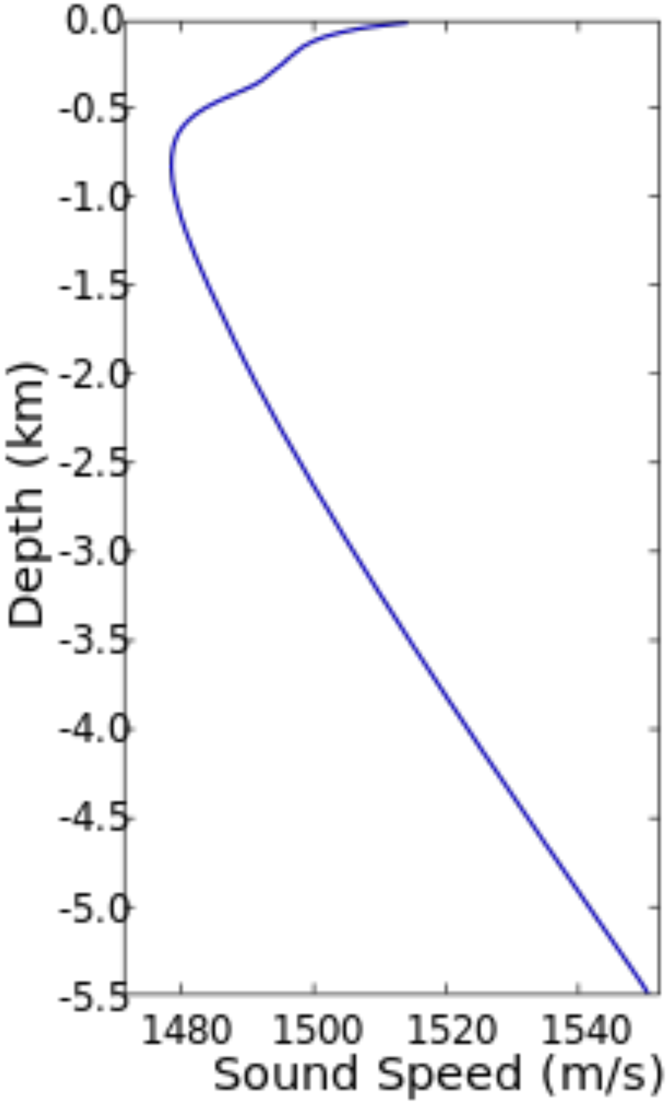
Recall: sound rays refract when c changes

  - Produces a trap for sound rays:

Deep Sound Channel

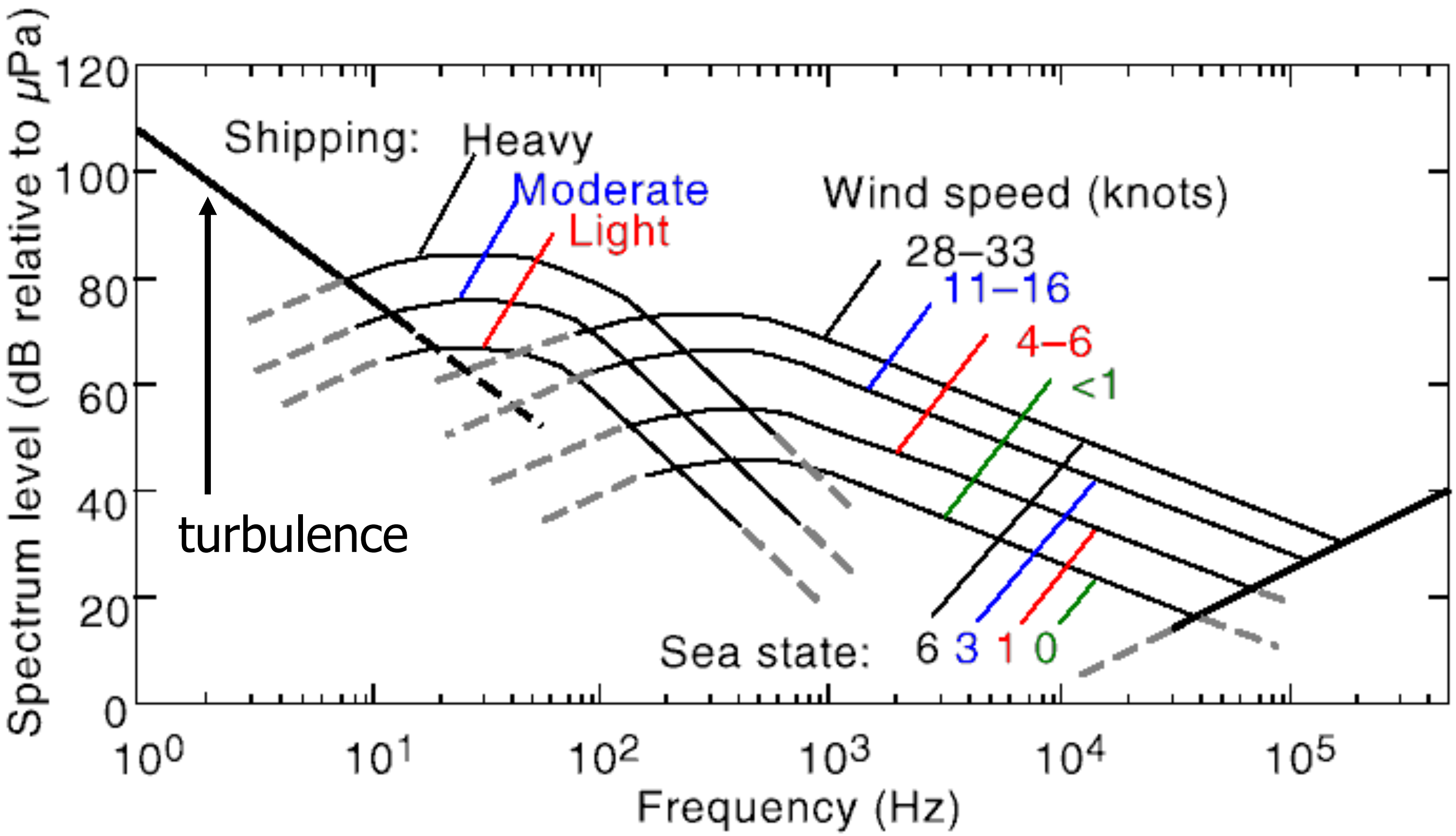
  - Acts like a waveguide for sound
  - Sound can travel great distances
  - Surface observers can't hear sounds produced in the channel





Underwater acoustics

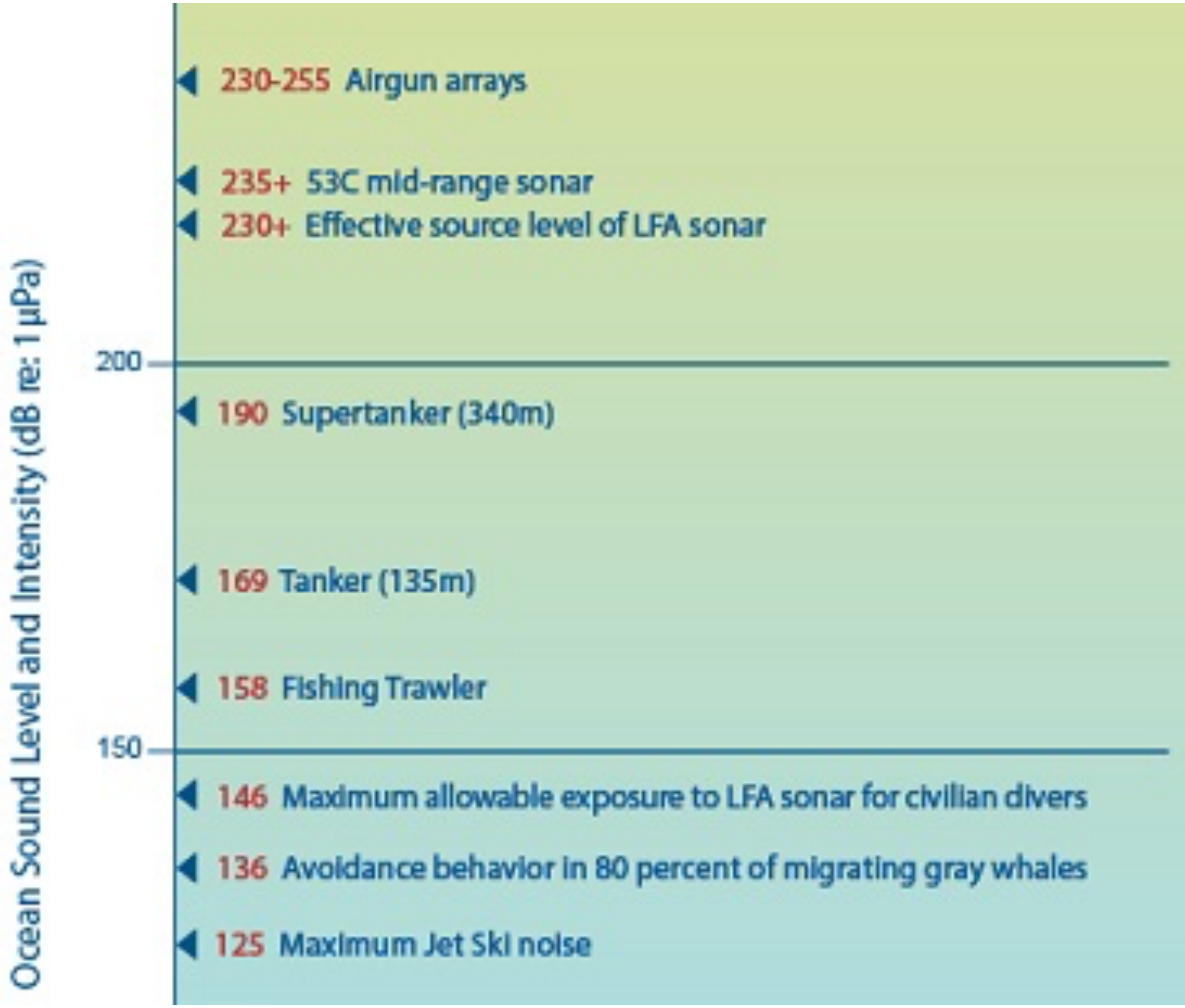
- Background noise underwater
  - Shipping noise has increased greatly since 1983!



Average deep-water ambient noise spectra
© 1983 by McGraw-Hill

Underwater acoustics

- Major noise pollution sources
  - Broadband dB re 1 microPa



Sound absorption underwater

- Loss of intensity in water is related to shear and bulk viscosity
  - Shear viscosity: due to relative motion between water layers
    - Usually less important than bulk viscosity
  - Bulk viscosity: due to molecular effects during a sound wave cycle
    - Relaxation time = characteristic time τ for molecular effect
      - Small effects unless $\tau \sim T = 1/f$
      - Main culprits are $MgSO_4$ and boric acid $B(OH)_3$
- Loss rate depends on temperature, seawater pressure and salinity
  - SPL in a plane wave decreases as

$$\frac{dp}{dx} \approx -\alpha_{\exp} p \rightarrow p(x) = p_0 \exp(-\alpha_{\exp} x) \rightarrow \ln\left(\frac{p}{p_0}\right) = -\alpha_{\exp} x$$

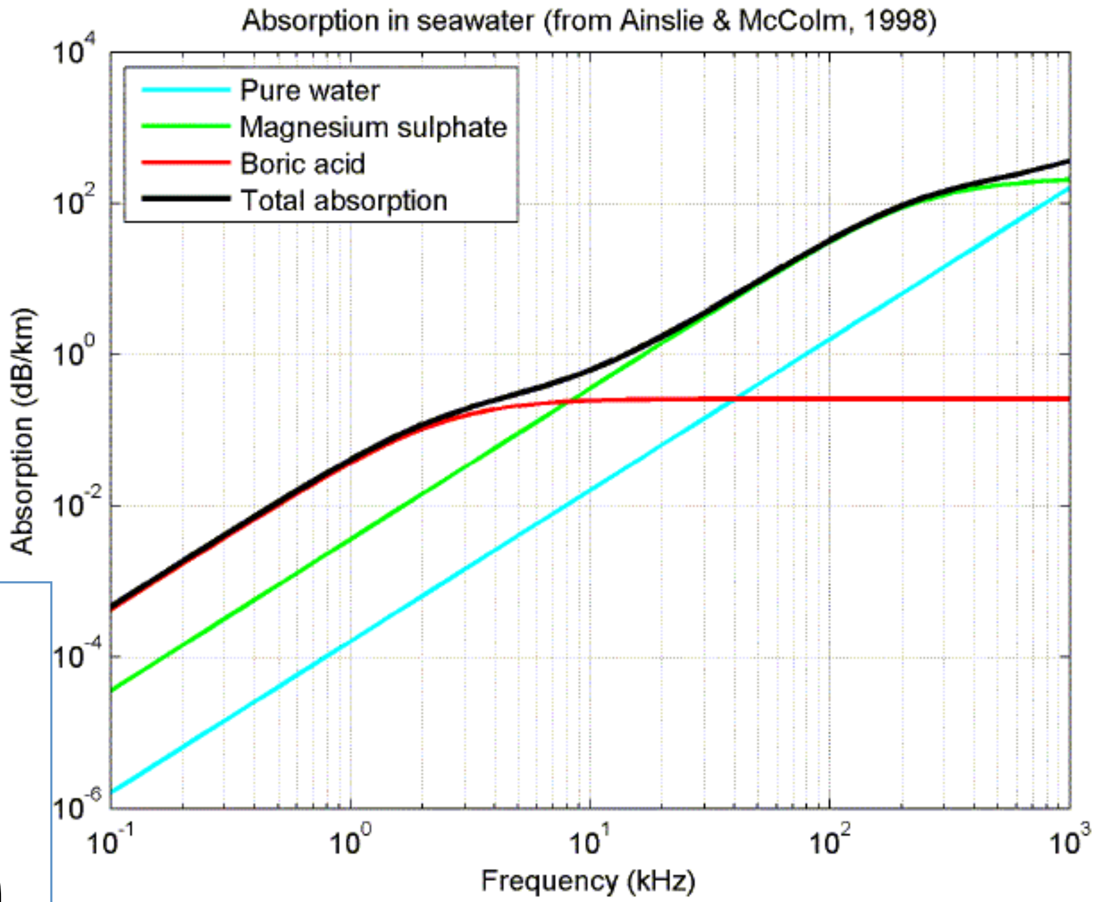
$$\alpha_{\exp} = \text{exponential attenuation } \textit{rate}$$

$$\text{dB } \textit{loss} = -20\log_{10}\left(\frac{p}{p_0}\right) = \alpha_{\exp} x \left[20\log_{10}(e)\right] = 8.66\alpha_{\exp} x$$

$$\text{Attenuation } \textit{coefficient } \alpha = (\text{dB loss}/x) \rightarrow \text{dB loss} = \alpha x$$

Sound absorption underwater

- Attenuation coefficients for relevant components of seawater
  - Frequency dependent



For plane → spherical waves, replace

$$x \to (R - R_0), \quad p_0 \to p_0 R_0 / R$$

$$p = p_0 (R_0 / R) \exp\left[-\alpha_{\exp} (R - R_0)\right]$$

$$\text{Transmission loss TL} = -20 \log_{10}\left(\frac{p}{p_0}\right)$$

$$TL = 20 \log_{10}\left(\frac{R}{R_0}\right) + \alpha (R - R_0), \ dB$$

→ (spherical spreading) + (absorption)

distance R where loss *rate* $\left(\frac{d}{dR}\right)$ due to absorption term exceeds rate due to spreading $R_t = \dfrac{8.68}{\alpha}$

Sonar equation

- Sonar equation gives intensity vs distance, after all quantities are made dimensionless by ratios with reference values:

  SPL = SL – TL

  SPL = dB at distance R = 10 log$(P/P_{ref})^2$ dB re P_{ref}

  SL=source level= 10 log$(P_0/P_{ref})^2$ dB re P_{ref}

  TL =transmission loss (as discussed previously)P

  Here dB = "underwater dB" → P=rms sound pressure, with P_{ref} = 1 μPa

  - This is the sonar equation for passive sonar (1-way, only receiving) where the signal is ~ mono-frequency tone (narrow bandwidth source)
  - SL can be obtained from power output of source:

Total power from source over spherical surface is

$$\Pi = \langle I \rangle R^2 \int d\Omega = 4\pi p_0^2 \left(\frac{R_0^2}{\rho\, c} \right)$$

R_0 = spherical source reference radius (1 m is conventional)

p_0 = sound p at source; usually dB are taken re 1μPa

ρ = water density (1026 kg/m^3 for seawater), c = sound speed

so SL = 10 log Π + 171 dB re 1μPa

Sonar equation

- Receivers with wider bandwidth have to take into account ambient noise spectra:

Noise Spectrum Level NSL = noise spectral density (dB re 1 μPa per Hz)

Sound source spectrum: $\mathrm{SSL} = 10\log_{10}\left(\frac{s \cdot 1Hz}{I_{REF}}\right)$

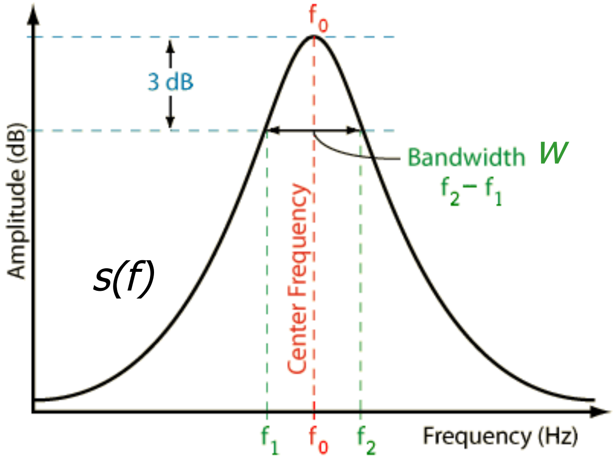
$s(f) =$ source spectral *density* at frequency f (intensity per Hz)

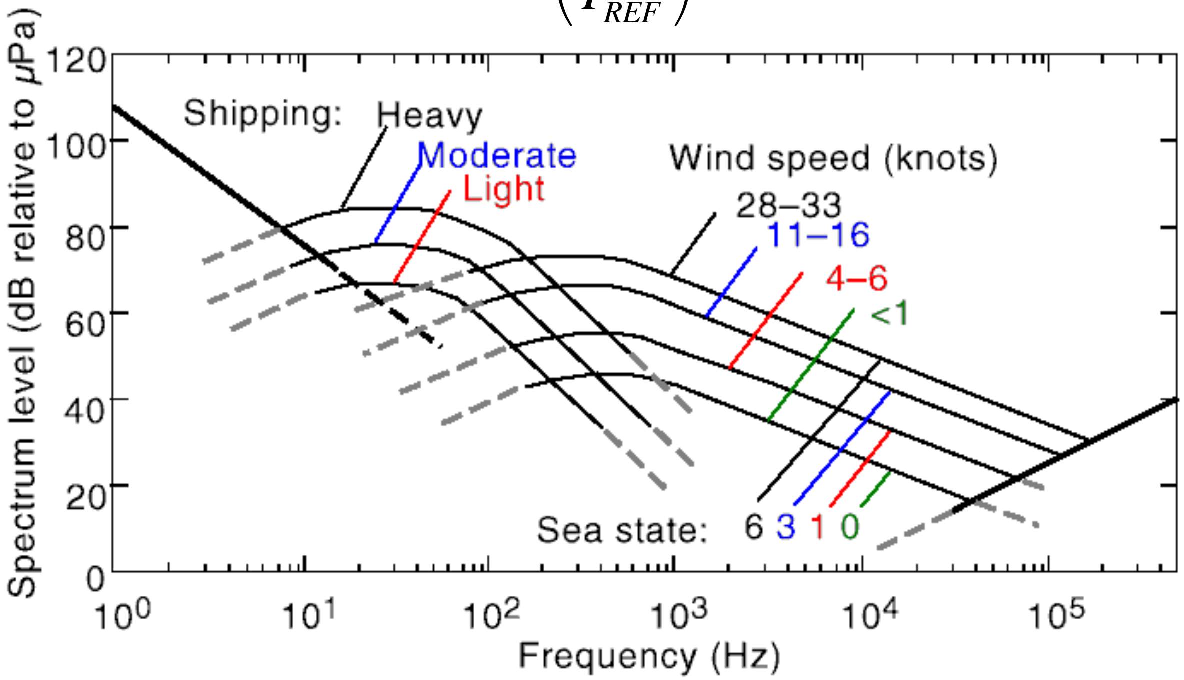
for $s(f) \sim$ const over bandwidth (w, Hz), $\mathrm{SL} = 10\log\left(\frac{s \cdot w}{I_{REF}}\right)$,

Detected noise level

$$DNL = NSL + (10\log w) - DI$$

$DI =$ directivity index





From lecture 9

Defining source characteristics

- Directivity *D* : how concentrated is a source's angular distribution, relative to simple isotropic source?

Angular variation of $P(\theta,\phi) = H(\theta) = \left|\frac{2J_1(v)}{v}\right|$, with $v = ka\sin\theta$

Intensity $\approx H^2 \rightarrow$ Directivity $D = \frac{I_{AXIAL}(r)}{I_{SIMPLE}(r)}$:

intensity of given source / that of simple (spherical pattern) source

$$\frac{I_{AXIAL}(r)}{I_{SIMPLE}(r)} = \frac{P^2_{AXIAL}(r)}{P^2_{SIMPLE}(r)} \rightarrow D = \frac{4\pi}{\left\langle H^2(\theta)\right\rangle_\Omega} ,$$

where $\left\langle H^2(\theta)\right\rangle_\Omega$ = average over solid angle Ω

  - **Directivity index:** ***DI = 10 log D***

Sonar equation

- Taking into account noise, the sonar equation becomes

SNR (dB) = SL -TL – DNL

SNR = signal to noise ratio, SPL/DNL

SPL = dB level at given location = $10 \log(P/P_{ref})^2$ dB re P_{ref}

(SL=source level, TL =transmission loss, DNL=detected noise level)

- For active sonar (looking for reflected signals), must add

TS = target strength factor:

- ability of object to reflect sound
- linear measure: backscattering cross section σ_{bs} has units m^2
  - measured as a ratio of sound intensities or pressures ($I \propto p^2$)

→ SNR (dB) = SL -TL – DNL – TS

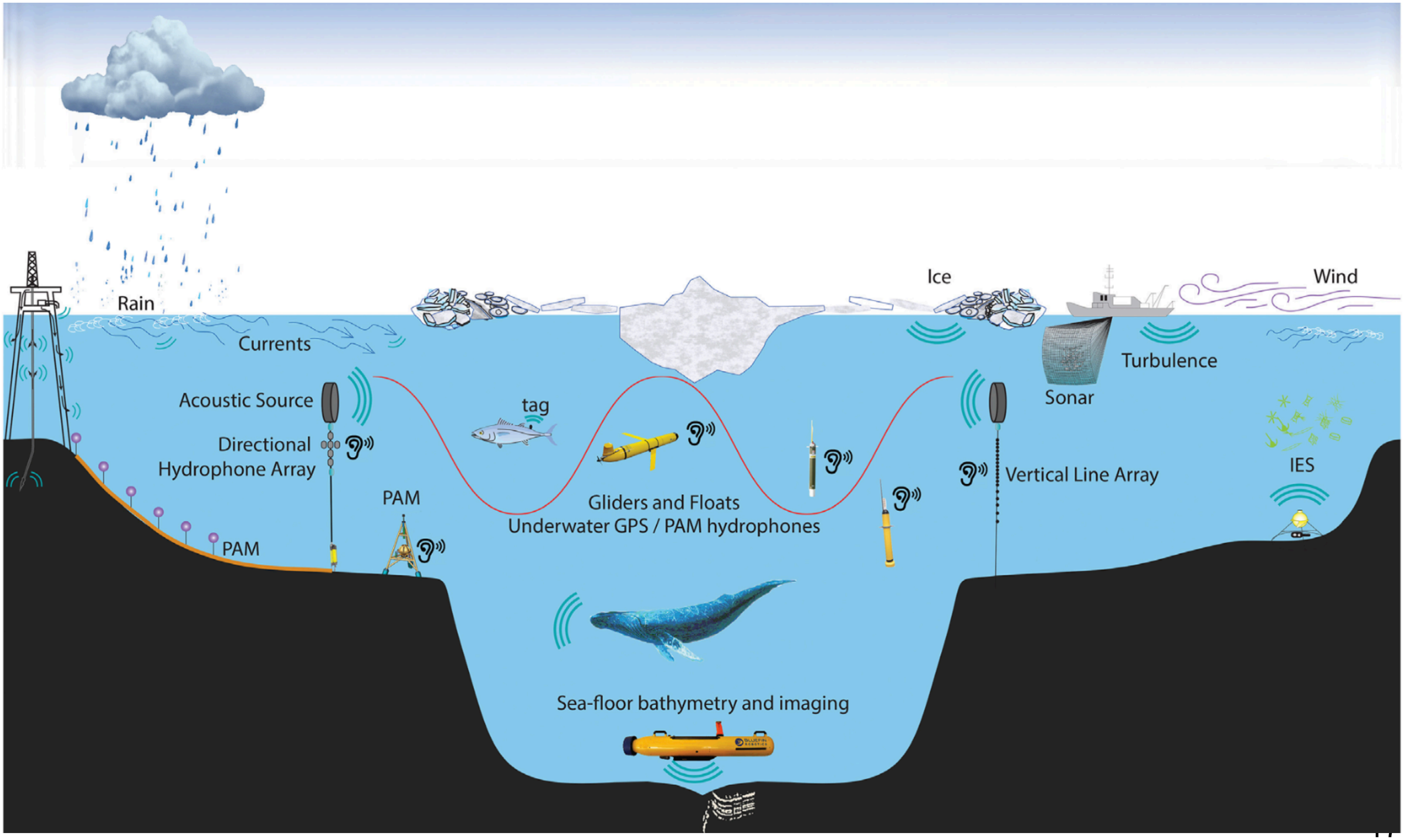
effective acoustic size (cross section) of target (e.g. fish, plankton, or submarine) is

$\sigma_{bs} = I_{refl} / I_{inc}$ → TS = 10log(I refl) – 10 log(I inc)

Example: juvenile walleye pollock has $TS = 20\log($Length, cm $-$ 66 dB

Active and passive ocean acoustic applications

- Observations: surface rainfall, sea ice, wind turbulence; surveys of organisms, bathymetry, seafloor mapping, subsurface profiling



Example of contributions of acoustic surveys

Soundscape recorded in the winter/spring of 2009 in the central region of the Bering Sea Shelf. Each point on the image represents the ratio of sound pressure level between 2 and 20 kHz at a specific point in time.

B. Howe, et al, Front. Mar. Sci., 26 July 2019
Sec. Ocean Observation

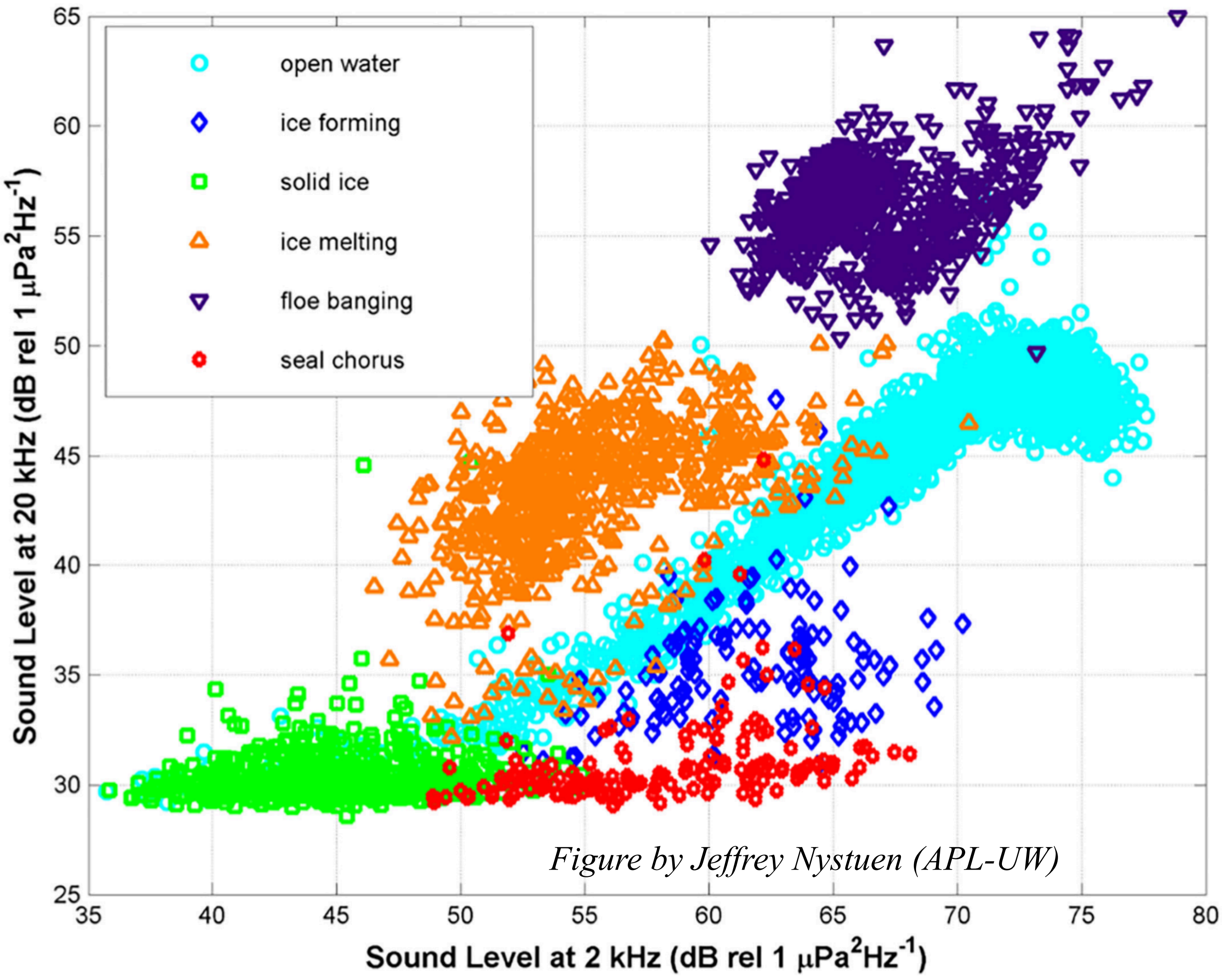
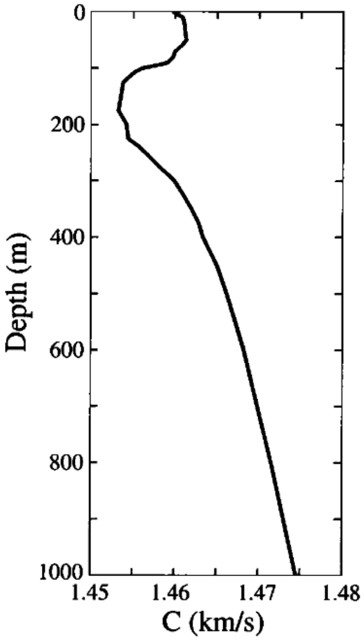


Figure by Jeffrey Nystuen (APL-UW)

Acoustic Thermometry of Ocean Climate (ATOC*)

ATOC = collaboration of UW-APL, UC-Scripps Institution of Oceanography, U. Michigan and MIT, 1996—



- Undersea sound speed temperature dependence is well studied

  → Estimate grand average ocean temperature T_{AVG} by measuring transit time $\Delta t = t_{RECEIVED} - t_{PING}$ over very long baselines

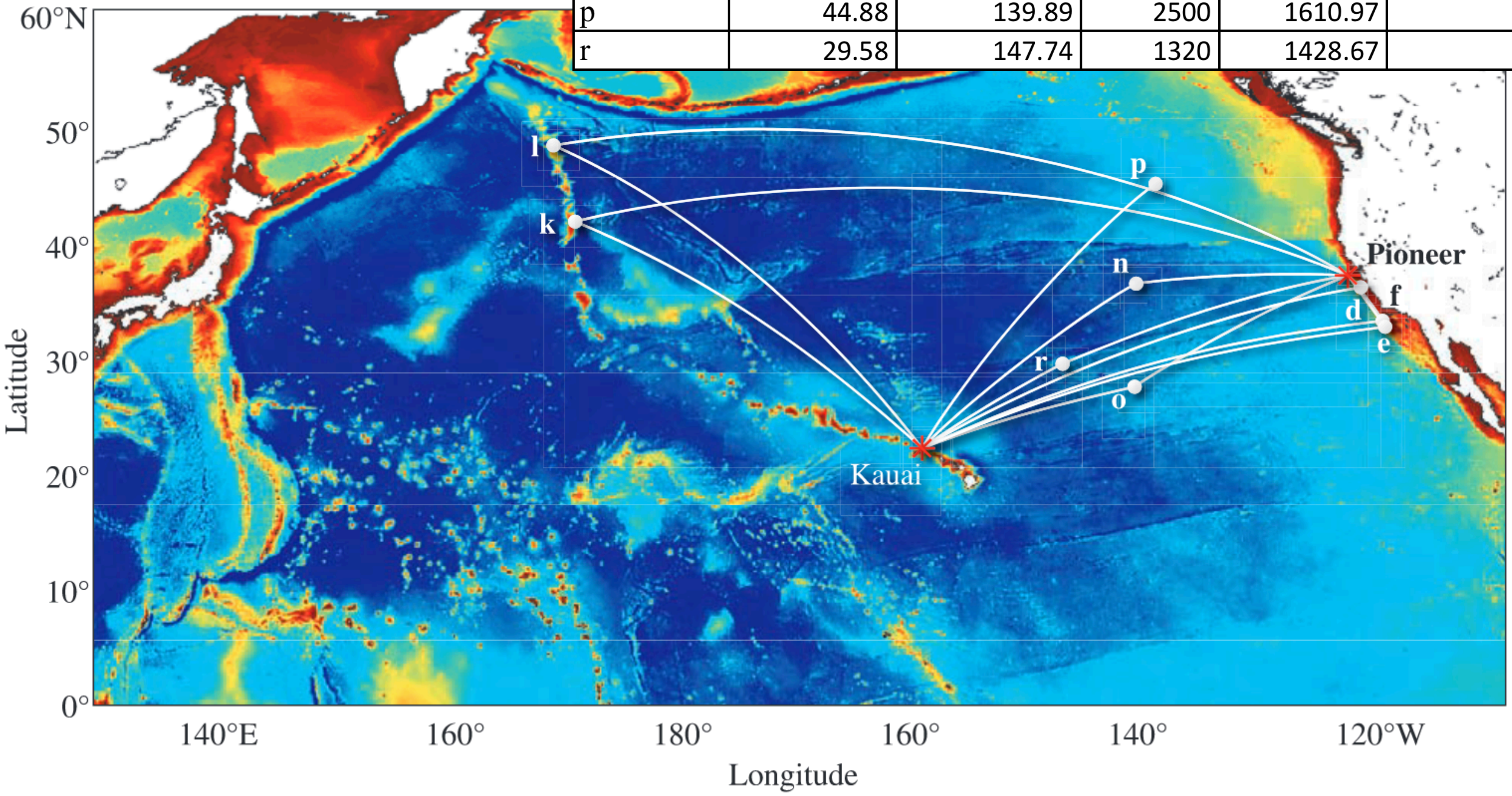
  - GPS permits time synch between all locations to 10 microsec level
  - Effectively integrates over an enormous array of ray paths
- ATOC Goal: Settle objections to global warming hypothesis based on possible inconsistency/inaccuracy of individual temperature measurements
- Feasibility test, 1994: R/V CORY CHOUEST deployed a vertical array of 10 HLF-4 pingers with ~ 4m spacing
  - Up to 5 sources were energized for each hour-long transmission.
  - The center of the source array was placed at a depth of 175 m.
- Sources transmitted broadband signals centered at 75 Hz to receivers distributed throughout the North Pacific from 1996 through 1999

* See R. Spindel, et al, *A decade of acoustic thermometry in the North Pacific Ocean*, J. Geophysical Res., **114**, C07021 (2009)

ATOC array

Source and receiver sites

Site	Latitude (°N)	Longitude (°E)	Depth (m)	Range (km) to Pioneer	Range (km) to Kauai
Sources					
Pioneer	37.34	123.45	939		
Kauai	22.35	159.57	811		
Receivers					
d	36.30	122.39	1359	149.02	3897.56
f	33.38	120.62	1100	3999.97	
k	42.01	170.98	1000	5511.01	3499.87
l	48.60	169.19	1000	5451.52	
n	36.43	141.53	2500	1613.01	2337.99
o	27.59	141.61	2500	2016.10	1901.62
p	44.88	139.89	2500	1610.97	
r	29.58	147.74	1320	1428.67	



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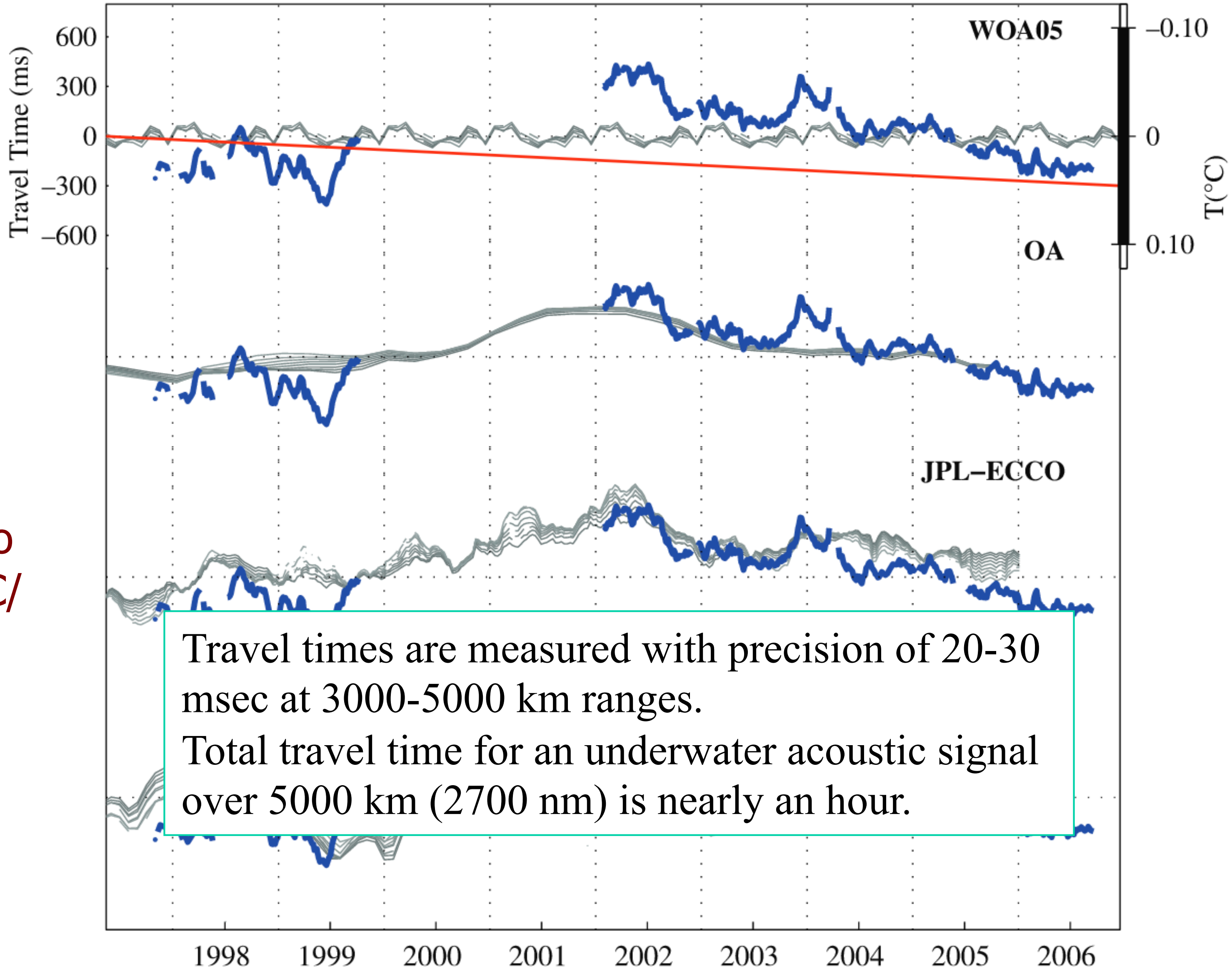
ATOC results

Measured travel times from Kauai to site f (blue)

Travel time trend (red) corresponds to a warming of 5 m°C/a on the sound channel axis

Gray: simulation results

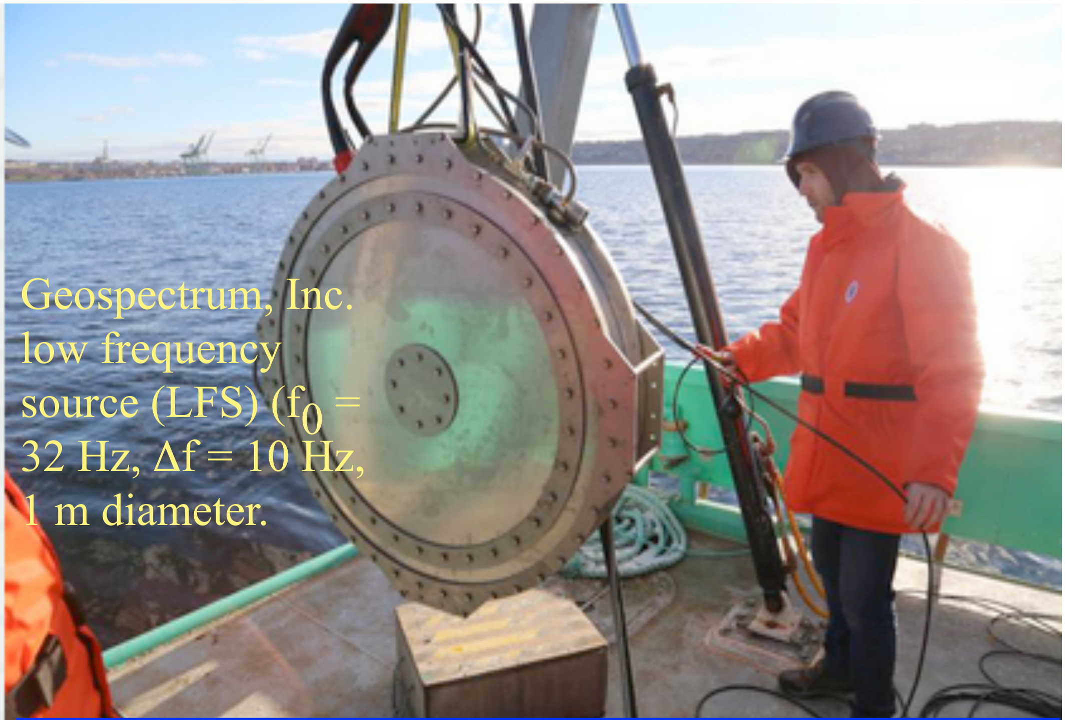


Travel times are measured with precision of 20-30 msec at 3000-5000 km ranges.
Total travel time for an underwater acoustic signal over 5000 km (2700 nm) is nearly an hour.

Another application of high power transducers

- CAATEX (Coordinated Arctic Acoustic Thermometry Experiment, US-Norway collaboration) observed water temperature in the Arctic Ocean 2019--2020 and compared to similar measurements from experiments in the 1990’s.
- Moorings with acoustic and oceanographic instruments on a steel cable reaching from just below the ocean surface down to the sea floor were deployed across the Arctic Ocean.

https://www.nersc.no/



Geospectrum, Inc. low frequency source (LFS) (f_0 = 32 Hz, Δf = 10 Hz, 1 m diameter.

floatation buoy designed to keep the source mooring as vertical as possible

Sample of CAATEX results

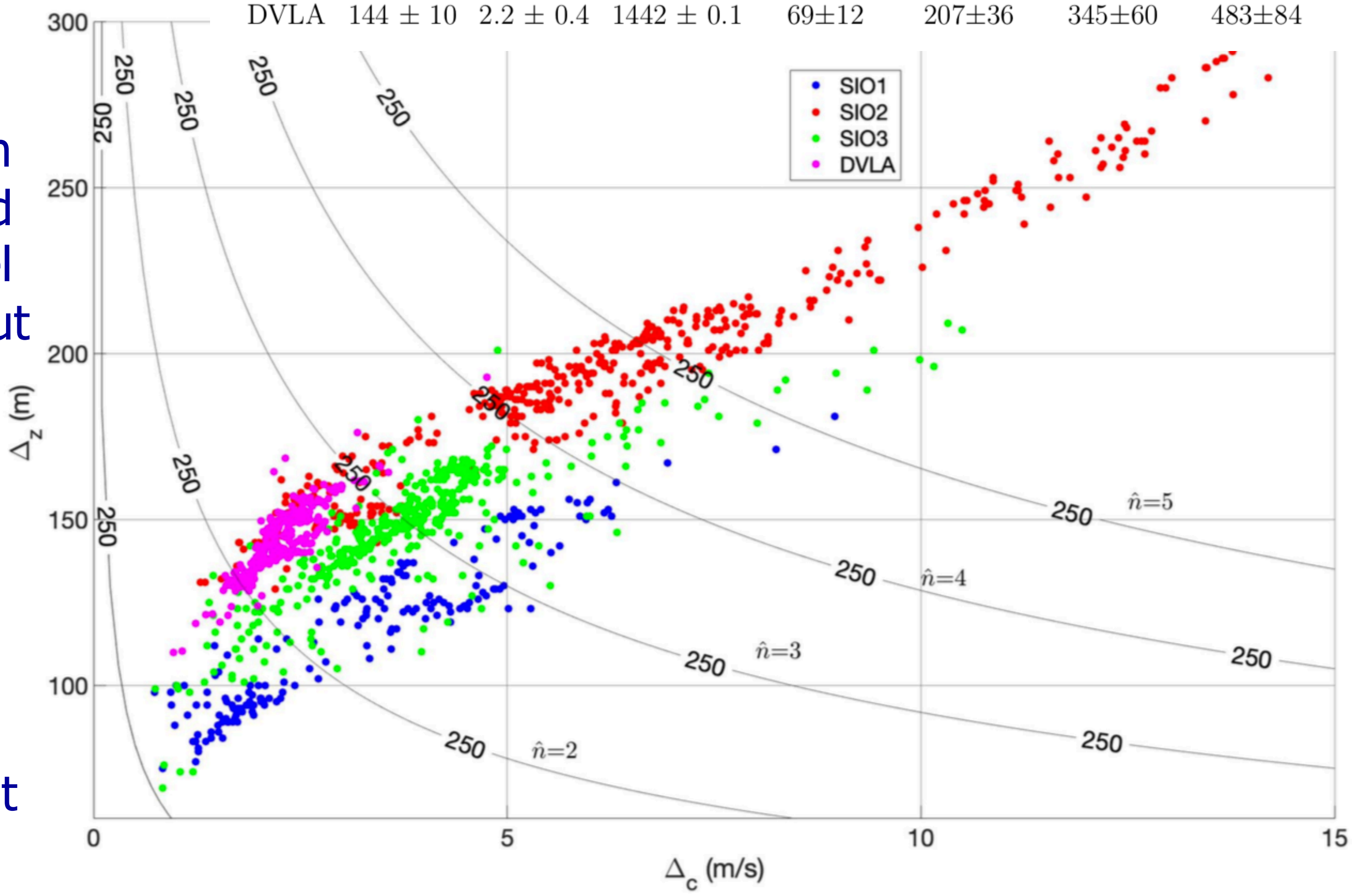
	δz (m)	δc (m/s)	c_a (m/s)	f_c [1] (Hz), n=1	f_c (Hz), n=2	f_c (Hz), n=3	f_c (Hz), n=4
SIO 1	103 ± 34	2.7 ± 1.8	1441 ± 0.6	119±96	357±288	595±480	833±672
SIO 2	203 ± 31	7 ± 3.2	1442 ± 0.4	32±15	96±45	160±75	224±105
SIO 3	147 ± 23	3.9 ± 2.0	1442 ± 0.6	58±29	174±87	290±145	406±203
DVLA	144 ± 10	2.2 ± 0.4	1442 ± 0.1	69±12	207±36	345±60	483±84

Beaufort duct (BD): subsurface sound channel in the Western Arctic Ocean

Sound waves trapped in this duct can travel long distances without losing energy due to sea ice and surface waves interactions.

The BD has been slowly strengthening across the entire western basin due to increasing ocean heat content in warm halocline water

B. Howe, et al, Front. Mar. Sci., 26 July 2019
Sec. Ocean Observation



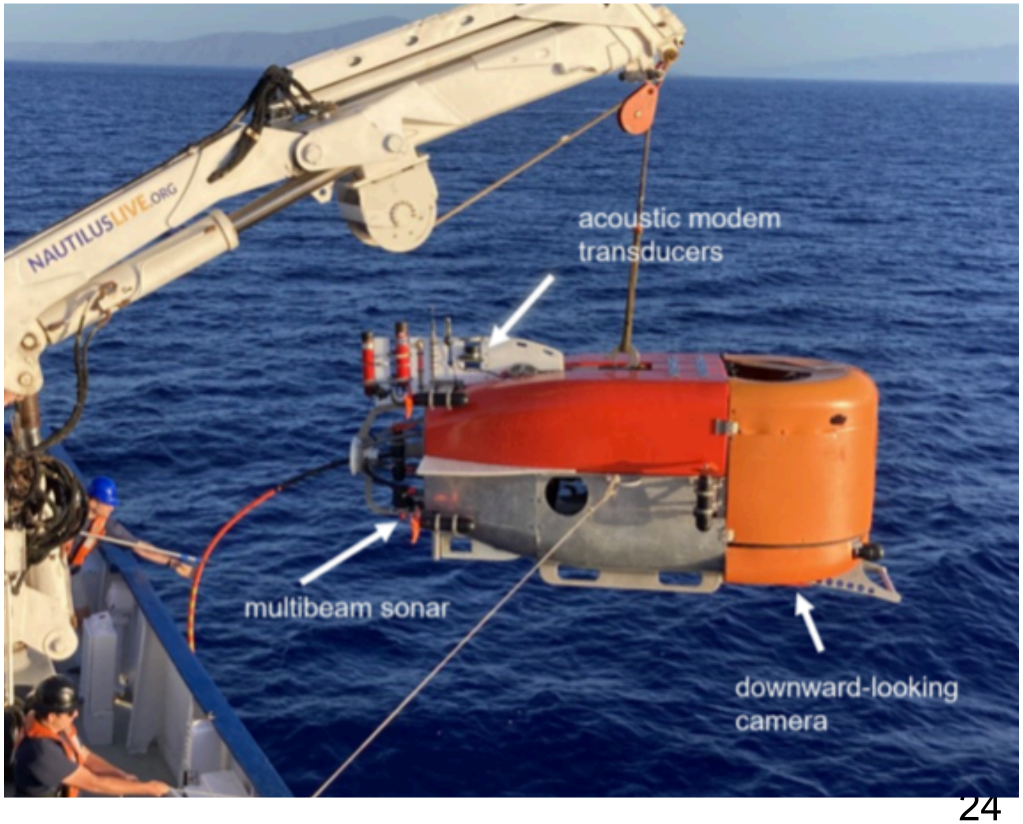
δz (duct width) vs δc (width of sound spectrum) in the BD at CAATEX moorings between September 2016 and August 2017, and between September 2019 and October 2020. Cutoff frequency fc = 250 Hz lines are shown with black lines for each of the first 5 harmonics.

Acoustical modems: undersea data/communications

- AUVs (autonomous underwater vehicles) = unmanned vehicles with various sensors
  - Can stay much longer at depth than human diver or manned UV
  - Earlier generations depended upon data-transfer tether cable
  - Now acoustic modems can be used → free-flying AUVs
  - Common application: high resolution seafloor mapping

NUI: Nereid Under Ice AUV (Woods Hole):
Deployment at seea, showing 10 kHz and 3.5 kHz acoustic modems, downward-looking camera, and the Norbit multibeam sonar.

NUI normally uses a fiber optic data tether. Can travel up to 40 kilometers from ship laterally underwater, and to 5000 m depths



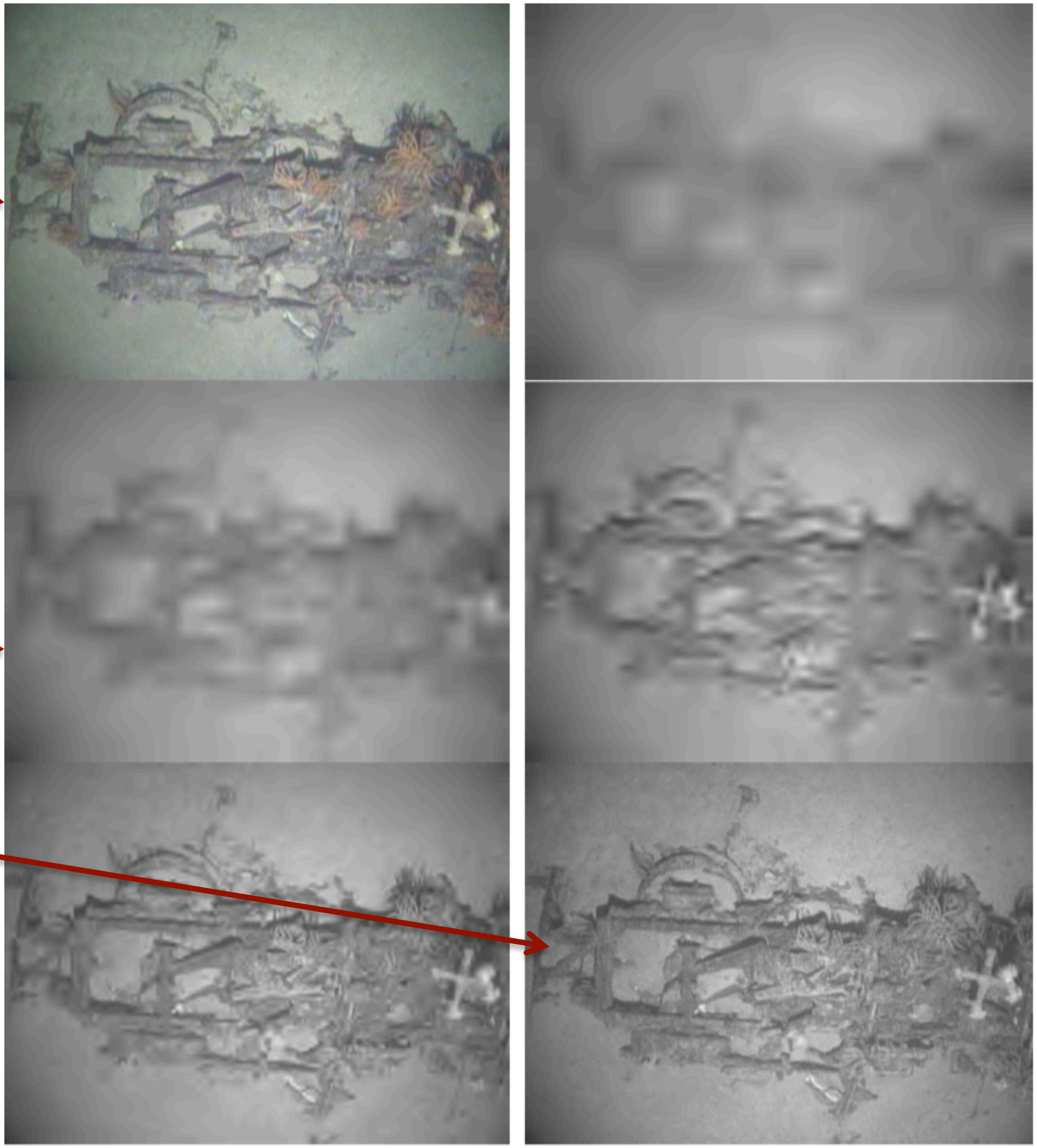
Acoustic data link results

Camera image of car wrecks dumped on ocean bottom (500 m)

Successive re-scans build up hi-res sonar image despite limited data rate:

Merging data from 1, 2, 3, 4, 16 scans (taking 40 seconds) makes resolution approach camera image

2022 IEEE/OES Autonomous Underwater Vehicles Symposium (AUV), Laura Lindzey (UW APL) et al

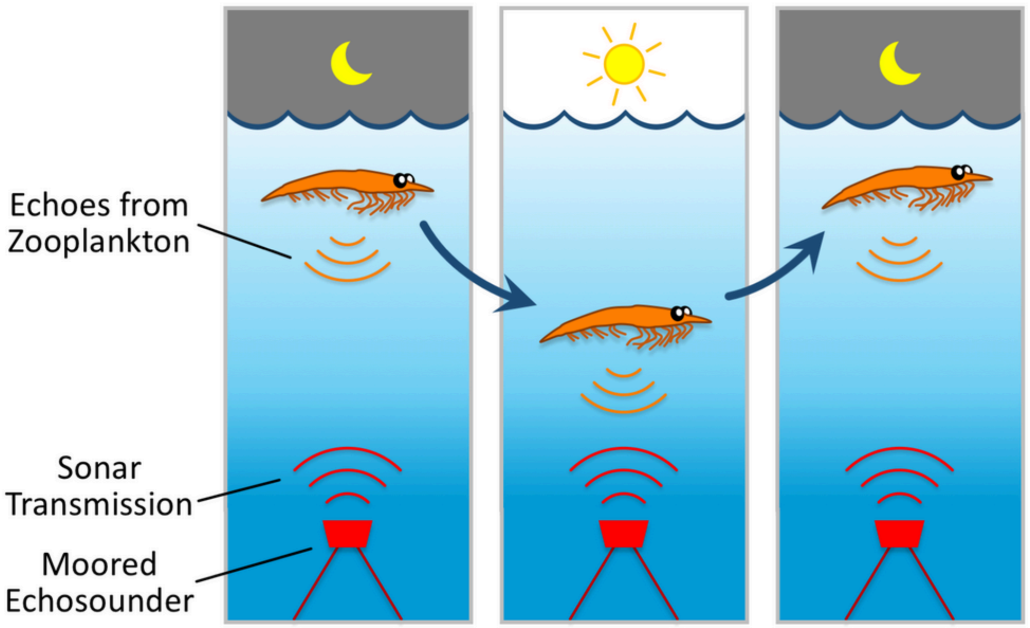


Acoustic echo analysis for biology surveys

- Sonar echograms using allow identification of species, population surveys from surface ships or AUVs
  - Acoustic wave scattering models based on physics or heuristics
  - Apply adaptive sampling and AI pattern recognition
- Example: studies of Diel vertical migration (DVM, diurnal vertical migration)
  - pattern of daily movement in the ocean and in lakes by organisms such as crustaceans (copepods), squid, and ray-finned fishes (trout).

- Organisms move up to the uppermost layer of the sea at night and return to the bottom of the daylight zone in the oceans or lakes during the day

- Important in deep-sea food webs and biologically driven sequestration of carbon



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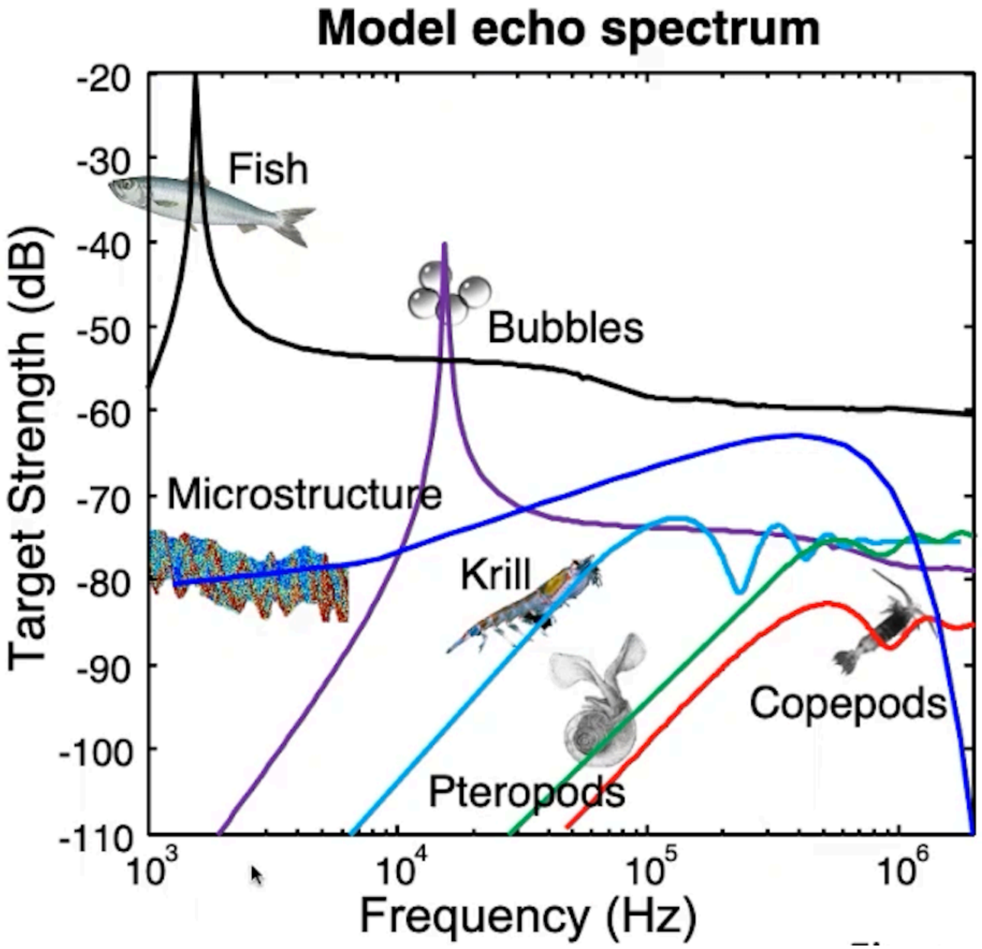
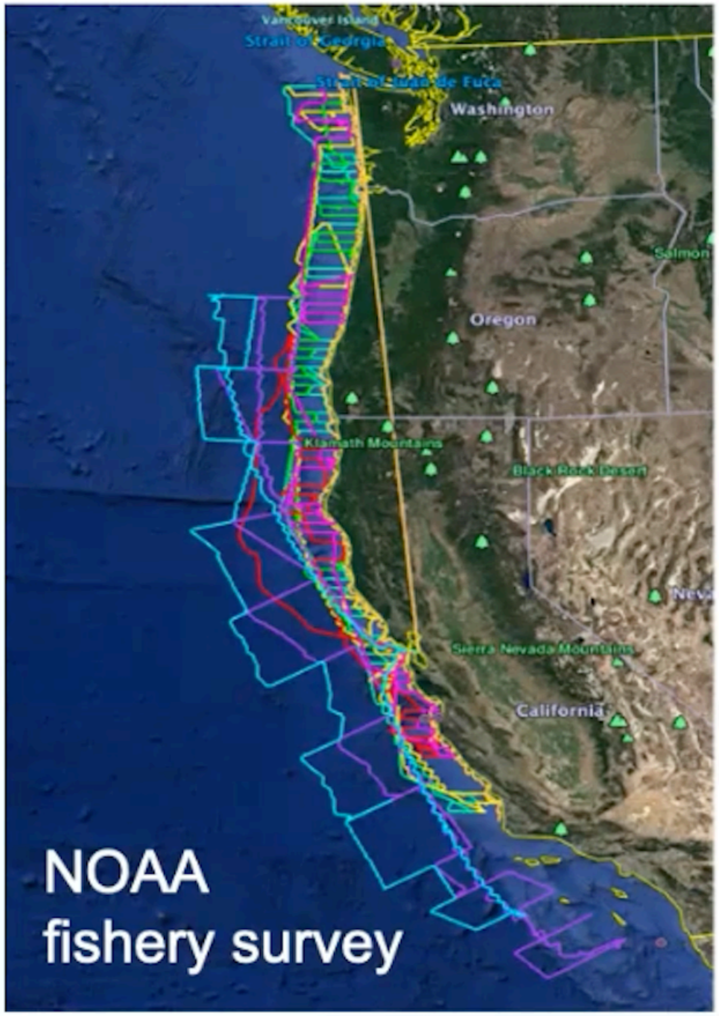
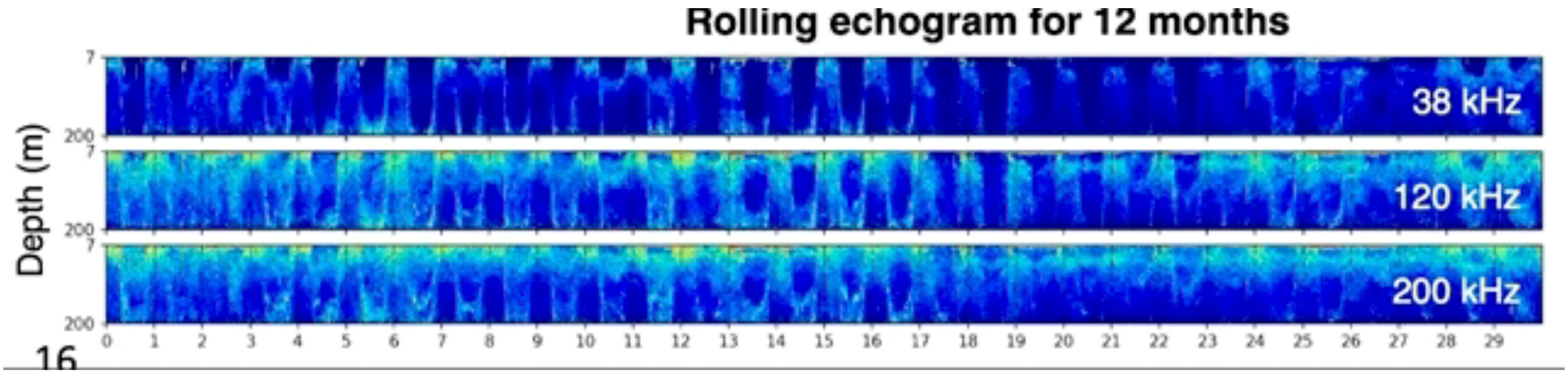
Echogram applications to fisheries studies


Model echo spectrum


NOAA fishery survey

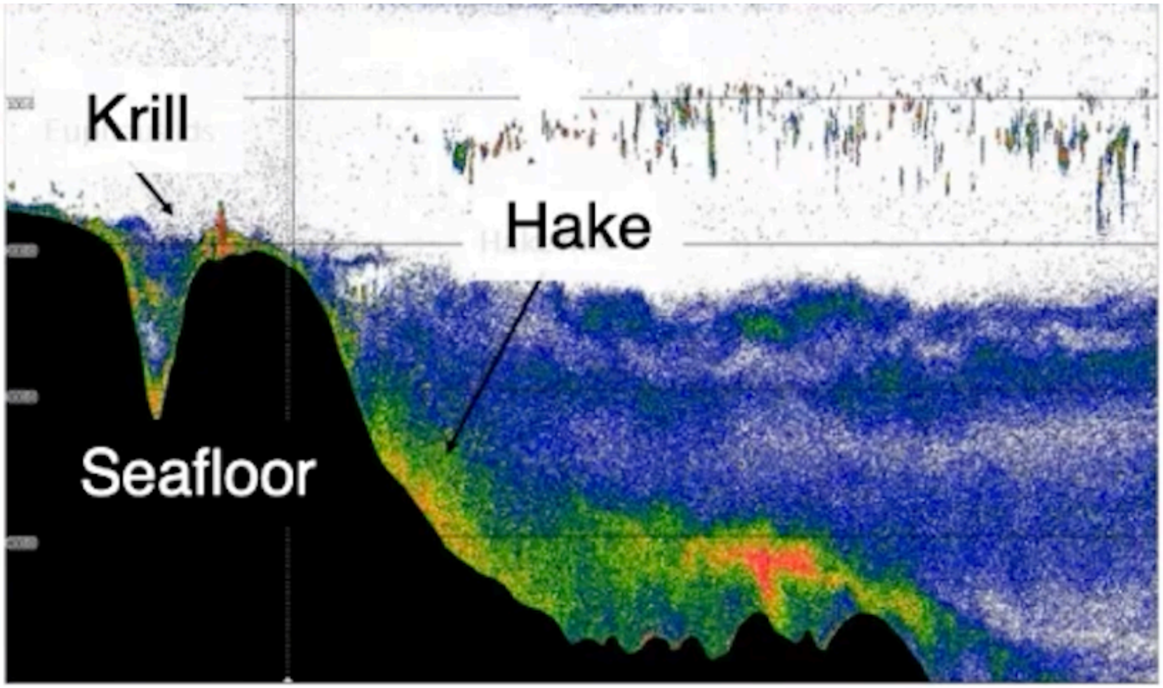
Examples of echograms



Rolling echogram for 12 months

Echoes can identify biomass

Understanding Echoes,
Wu-Jung Lee, UW-APL,
ASA Denver, 2022

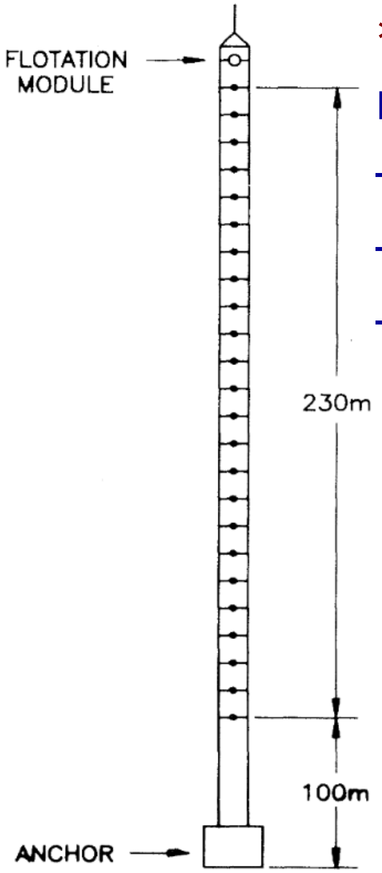


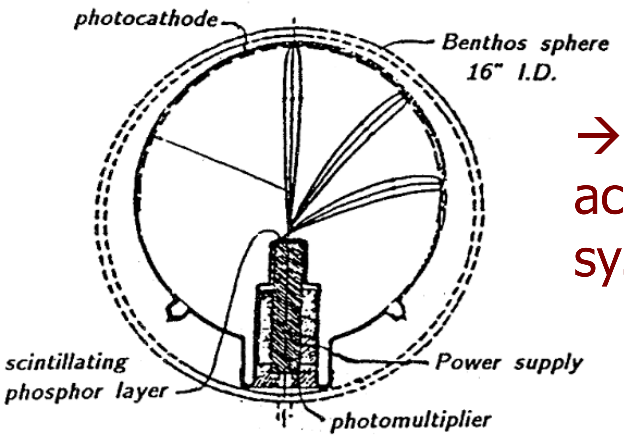
Acoustical positioning – personal experience

- DUMAND* (Hawaii):
  - development 1976—85, construction 1985—94
  - Acknowledged source of basic techniques for all existing water Cherenkov** astrophysical neutrino detectors

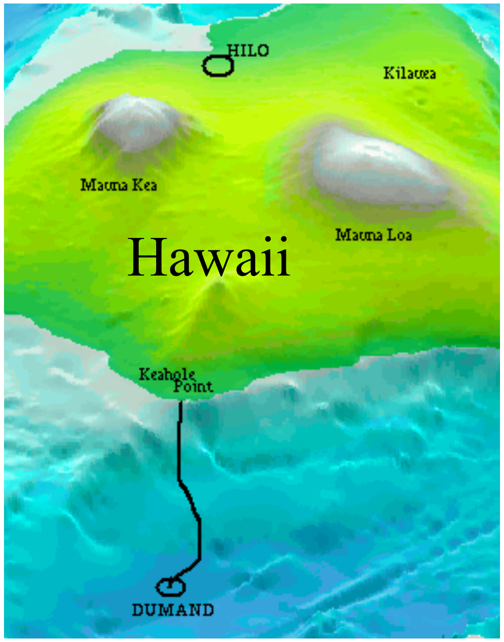
** Neutrinos interact in water, produce charged particles → Cherenkov radiation detected by phototubes

  - 4800 m depth, 30 km off Kona, Hawaii
  - “Strings” of photomultiplier tubes (PMTs) anchored at bottom
  - Must know position of each PMT vs time to a few cm





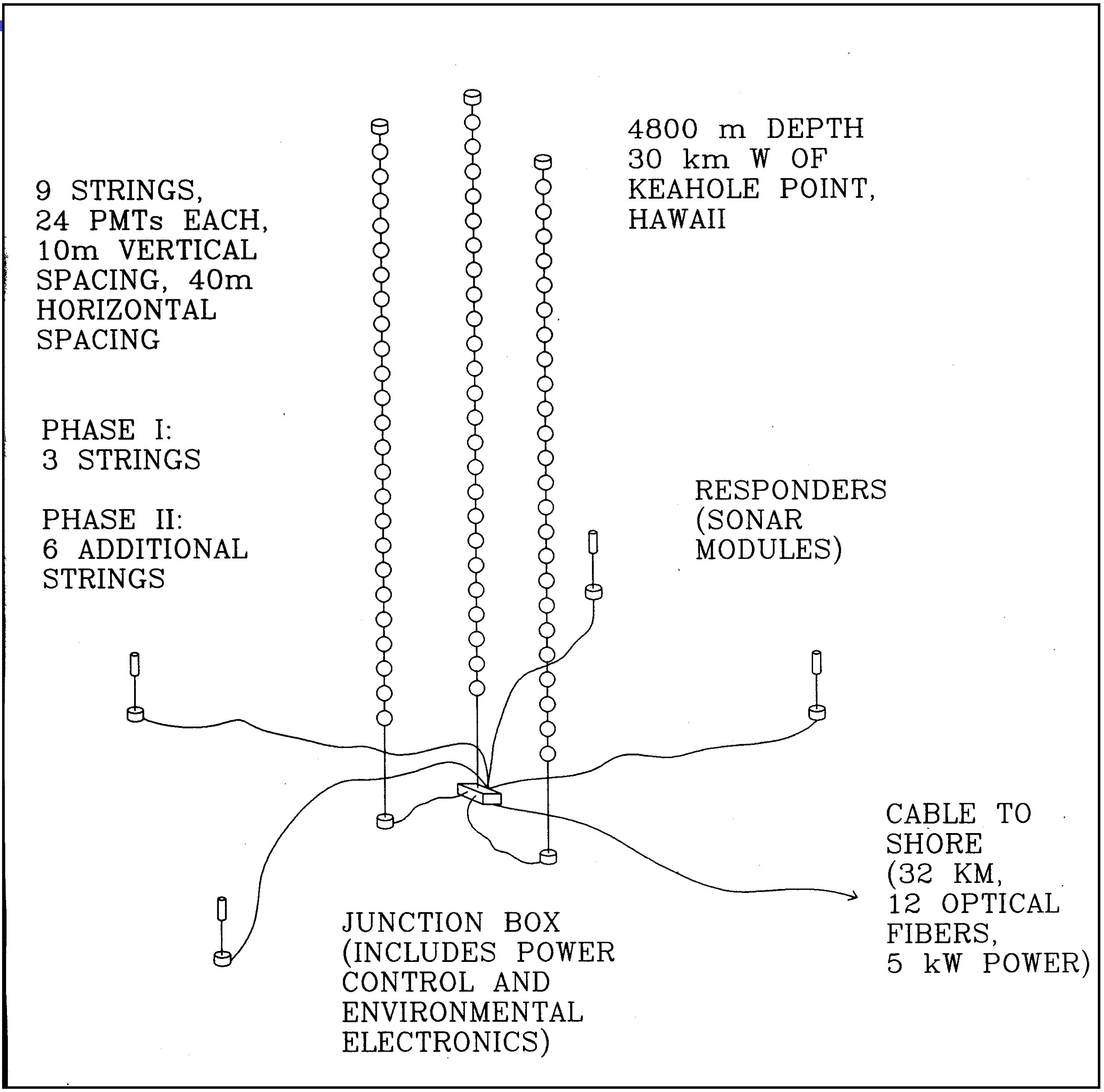
→ UW contribution: acoustic positioning system



* Arthur Roberts, Reviews of modern physics, 1992, Vol.64, p.259

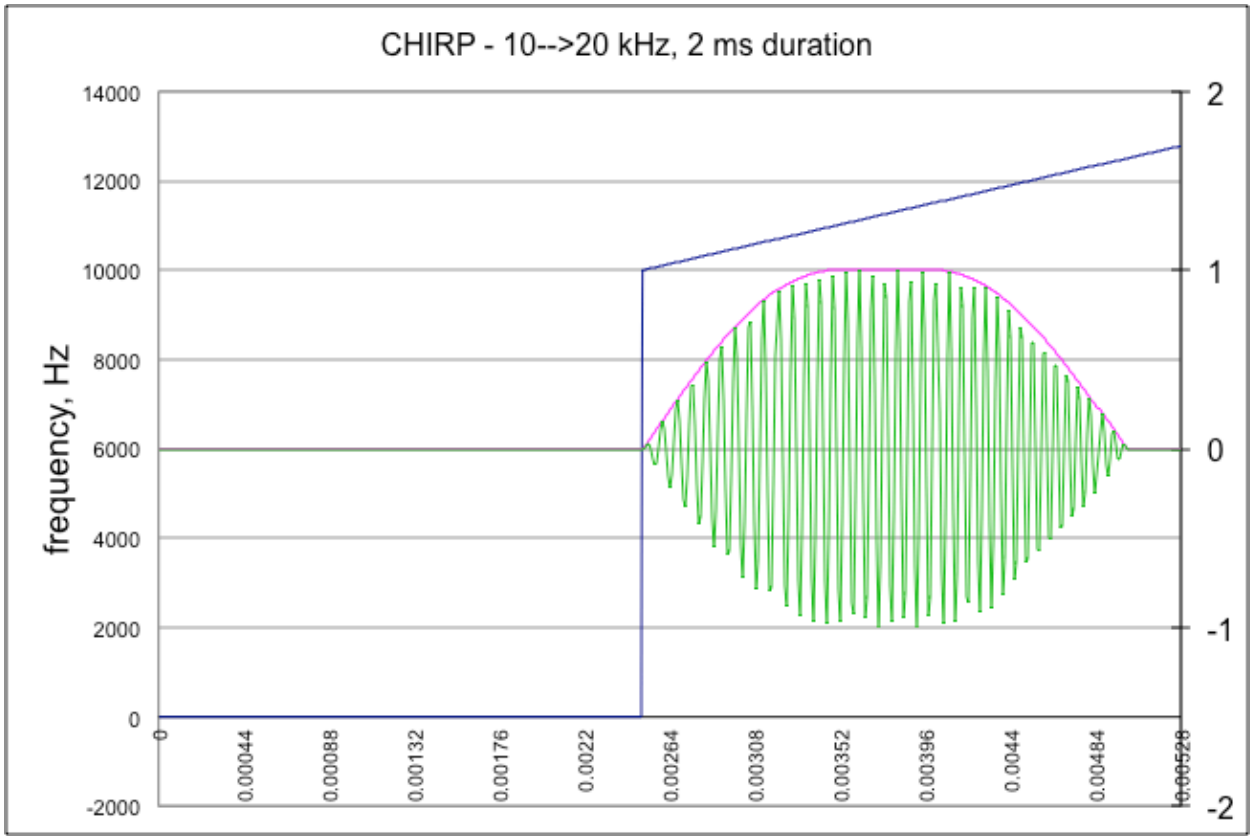
DUMAND

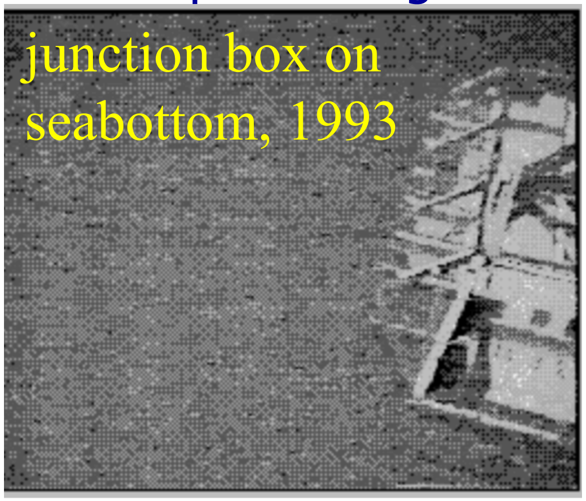
- Phase I deployment
  - 3 strings, each with 24 PMTs
  - Undersea junction box with 32 km fiber/power cable to lab at Kona
  - Acoustical positioning system:
    - Outlying pingers,
    - Hydrophones on strings
    - Junction box electronics measures delays



Chirp sonar system for positioning PMTs

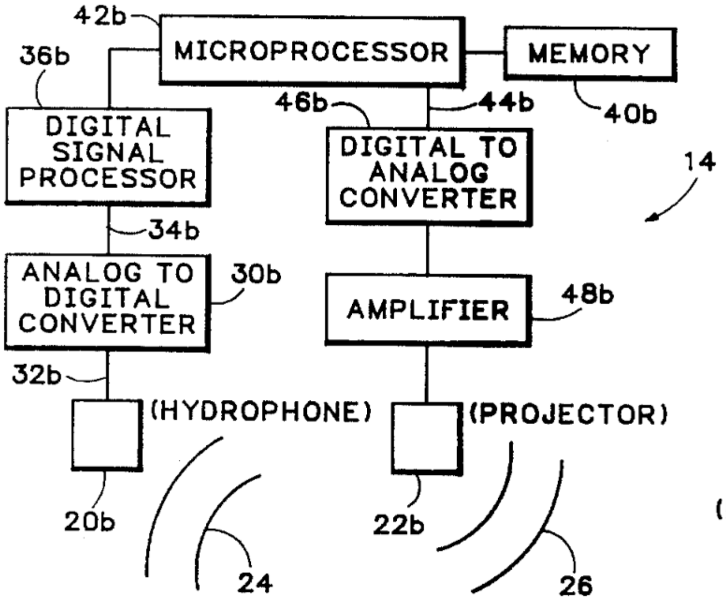
- Conventional system
  - Pinger emits short constant-f pulse at ~10 kHz
  - hydrophone on string finds transit time
  - Problem: resolution of arrival time too coarse to meet specs
- Solution: FM pulse (chirp)
  - Fourier methods allow definition of arrival time to allow ±10 cm positioning

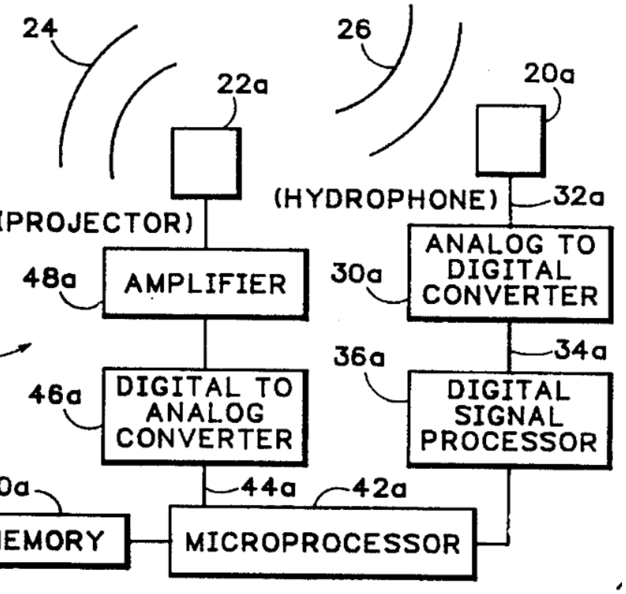


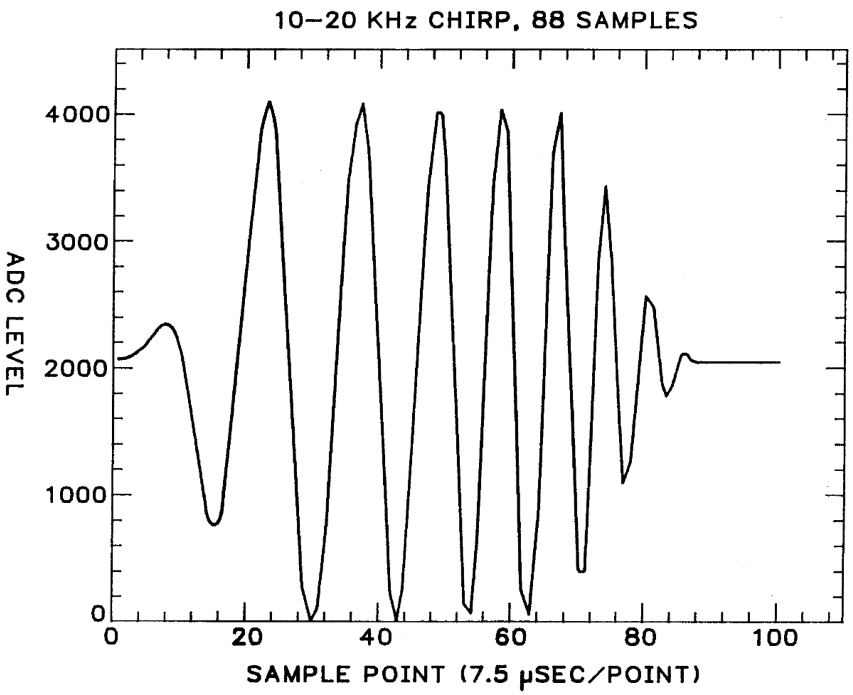

junction box on seabottom, 1993

US Patent 5,469,403

- US Navy held up patent application for 5 years (too similar to something they were working on…)







DIGITAL SONAR SYSTEM
Inventors: Kenneth K. Young; R. Jeffrey Wilkes, both of Seattle, Wash.
Assignee: Board of Regents of the University of Washington, Seattle, Wash.

Additional topic for tonight: Doppler Effect for moving source/receiver

- Unlike light, sound has a preferred reference frame: the medium
- If sound source and observer are in relative motion, observed frequency will differ from source's frequency $c = \lambda f$
- For **observer** moving *relative to medium* with speed u, apparent propagation speed c' will be different:

  (sign depends on relative direction of *u*) $c' = c \pm u$

  - Wavelength cannot change – source is producing waves of constant length in the medium, and same length in moving coordinate system (motion does not change lengths except near light speed!)
  - Observed frequency has to change, to match apparent speed and fixed wavelength: $f' = \dfrac{c'}{\lambda}$
  - So if observer is moving (speed *u*) relative to source at rest in medium, apparent frequency *f'* is:

$$f' = \frac{c'}{\lambda} = \frac{(c+u)}{(c/f)} = f\frac{(c+u)}{c} = f\left(1+\frac{u}{c}\right)$$

+ sign if u is toward source,
Minus sign if away from source

Doppler effect:

- If **source** is moving (speed *u*) relative to observer at rest in medium, then
  - Frequency remains constant (same time interval between wavefront emissions from source)
  - But source now chases its own waves (or runs away from them): wavelength in the medium is shorter or longer
    - Wave speed = c
    - Time between successive peaks = T
    - Distance between peaks = $cT - uT$ = wavelength
    - Frequency of wave in medium (and for observer):

$$f' = \frac{c}{\lambda'} = \frac{c}{(c-u)T} = \frac{c}{(c-u)} f = f\left(\frac{1}{1-u/c}\right)$$

minus sign if toward observer,
+ sign if away from observer.
Notice: different f for observers on opposite sides of the source!

- Notice the central role of the medium in both cases

Doppler effect summary:

- General case
  - For either source or observer (or both) moving relative to medium,

$$f' = f \frac{\left(1 \pm \frac{u_{OBS}}{c}\right)}{\left(1 \mp \frac{u_{SRC}}{c}\right)}$$

c = speed of sound in medium
u = speed of source/observer in the medium
(both are unsigned = always taken as positive)

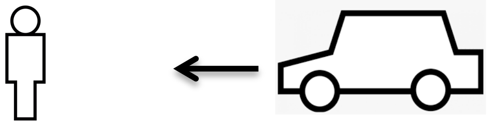
Use upper sign if source and observer move toward each other,

lower sign if source and observer move away from each other

Examples

- Car moving with u=18 m/s sounds horn with f=550 Hz, in still air at 20C.

What f’ is heard by observer on sidewalk?



Moving source, observer at rest in air:

$$f' = f\left(\frac{1}{1-u/c}\right) = 550Hz\left(\frac{1}{1-\left(18\text{m/s}/343\text{m/s}\right)}\right) = 550Hz\left(1.055\right) = 580Hz$$

Car toots again while at stop sign. What f’ is heard by bicyclist with u=7.2 m/s toward the car?

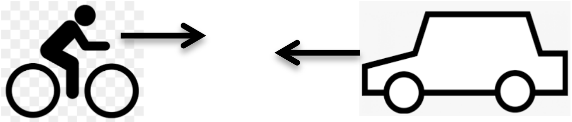
Moving observer, source at rest in air:

$$f' = f\left(1+\frac{u}{c}\right) = 550Hz\left(1+\frac{7.2\text{m/s}}{343\text{m/s}}\right) = 550Hz\left(1.02\right) = 562Hz$$

Road-raging driver toots horn yet again, when car is again moving with u=18 m/s. Now what f’ is heard by bicyclist?

Source and observer both in motion relative to air, approaching each other

$$f' = f\frac{\left(1+\frac{u_{OBS}}{c}\right)}{\left(1-\frac{u_{SRC}}{c}\right)} = 550Hz\frac{\left(1+\left(7.2\text{m/s}/343\text{m/s}\right)\right)}{\left(1-\left(18\text{m/s}/343\text{m/s}\right)\right)} = 550Hz\left(1.07\right) = 590Hz$$



Repeat: Presentations begin next session!

- Schedule has been posted (next slide) on the course website
  - Assignments were made randomly except for few who volunteered
- Turn in your (complete) draft slides on Tuesday 2/28 in Canvas
  - In fairness to those presenting in early time slots
  - You can tweak your slides until day of presentation, but do not add whole new sections
- BE SURE your talk is no longer than 15 minutes!
  - Practice talk to a friend (or the mirror) to check timing
  - Rule of thumb: should have no more than 15 slides for 15 min
    - Skip inessentials! Outline of talk, section title slides, etc
    - List your references on a final slide to be left on the screen when done
- On the day of your presentation:
  - Send me (wilkes@uw.edu) a file with your slides by 6 pm
  - TEST your audio to make sure your voice can be heard clearly