Acoustic seafloor mapping systems

September 14, 2010

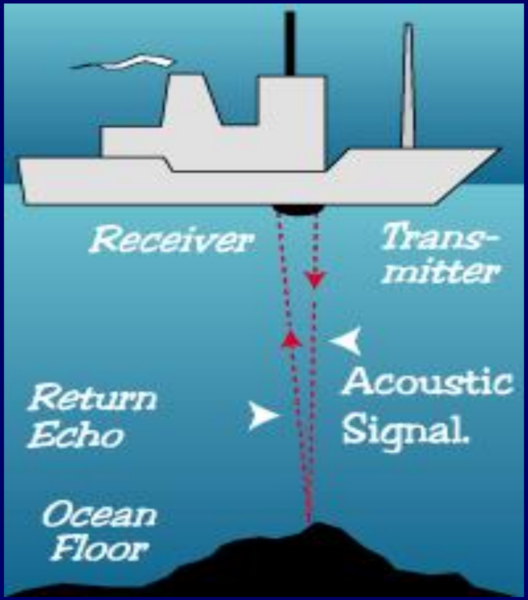
Delft Institute of Earth Observation and Space Systems

Delft University of Technology

Acoustic seafloor mapping techniques

- Single-beam echosounder (since 1920s)
- sidescan sonar (since 1960s)
- multi-beam echosounder (since 1970s)
- …

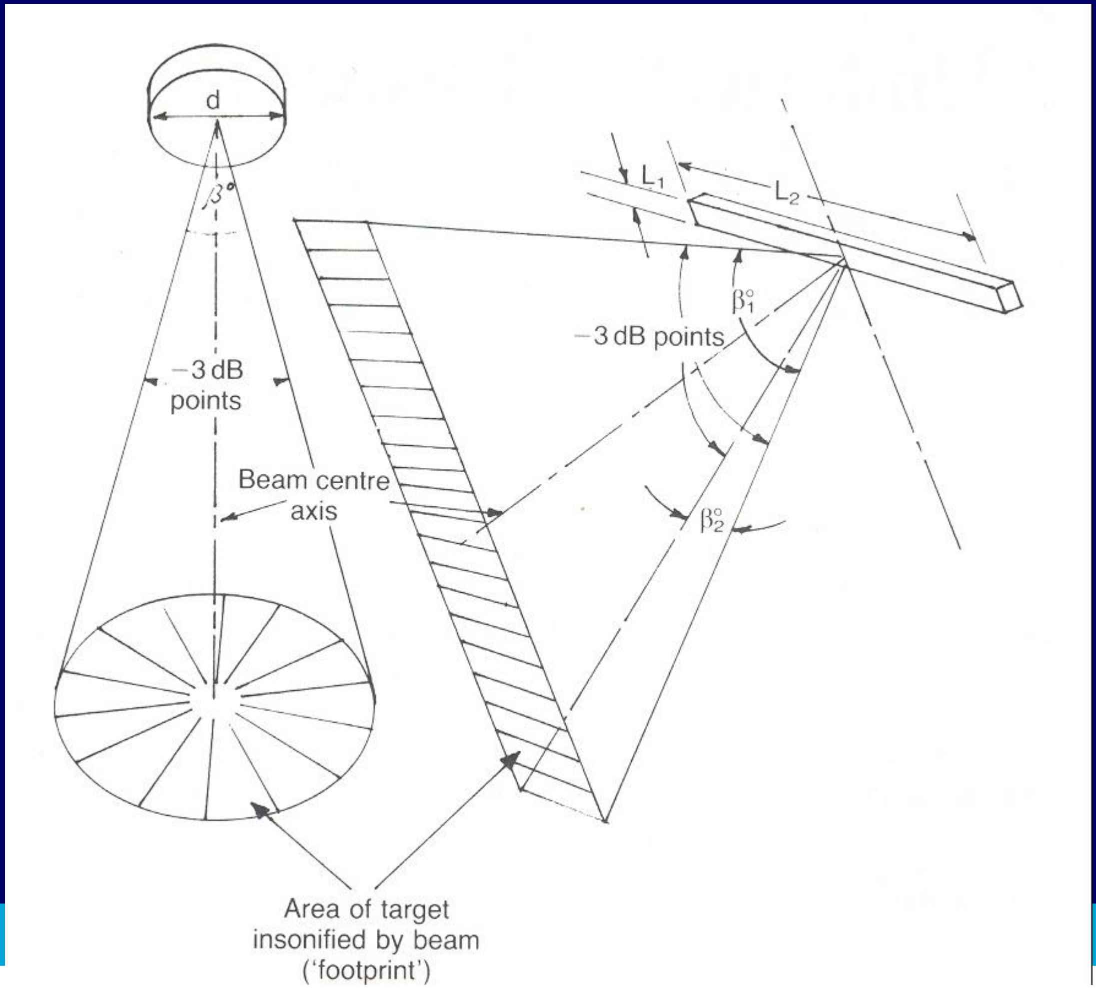
The single-beam echosounder (SBES)



$$H = \frac{ct}{2}$$

- Signal duration T : ~0.1-1 ms
- Beam width (angular aperture) β : ~10°
- Frequency f : ~10-500 kHz
- Source level SL : 200-230 dB

Transducer directivity pattern
Beam width β



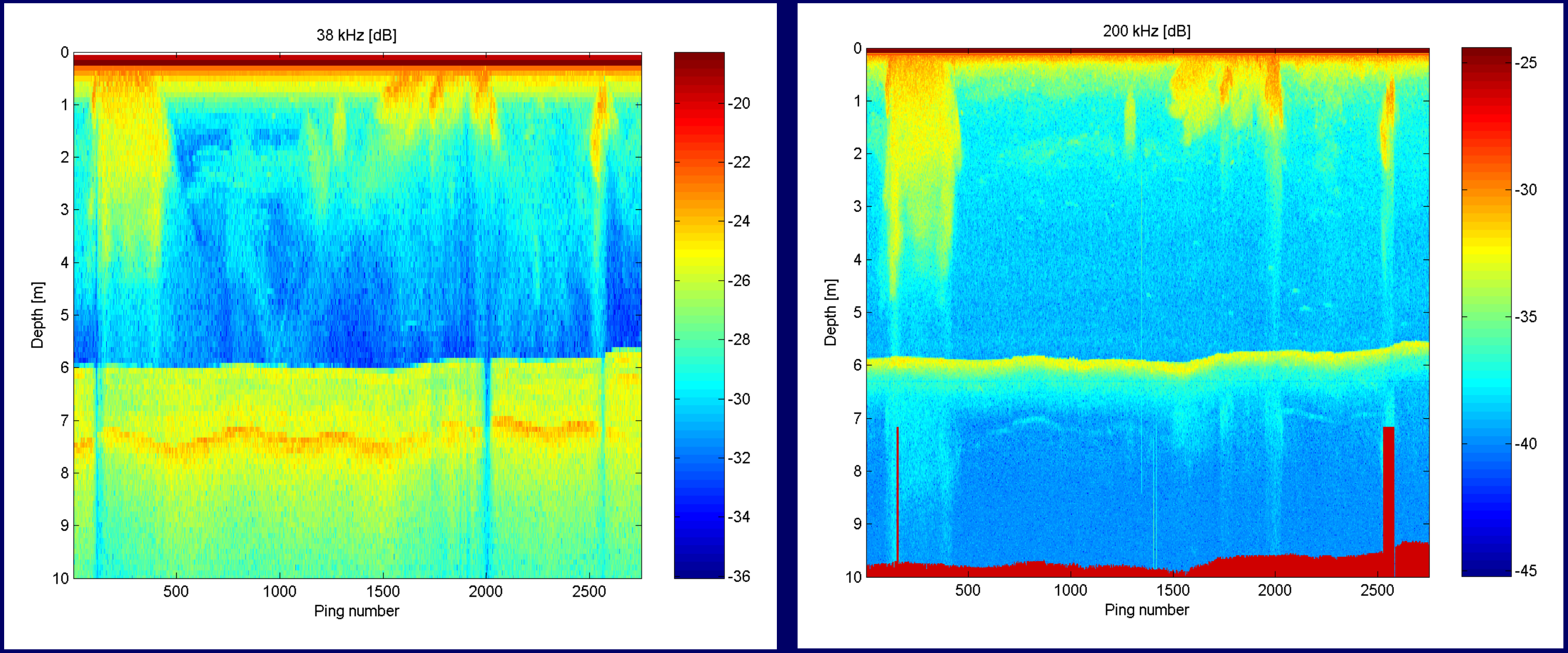
Circular:

$$\beta = 65\,\frac{\lambda}{d}$$

Rectangular:

$$\beta_{1,2} = 50\,\frac{\lambda}{L_{1,2}}$$

Modern digital single beam sounder:
effect of frequency choice (38 kHz or 200 kHz)



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Single-beam echo sounder
Transmission sequence

$$T_R > \frac{2H}{c} + T + \delta T$$

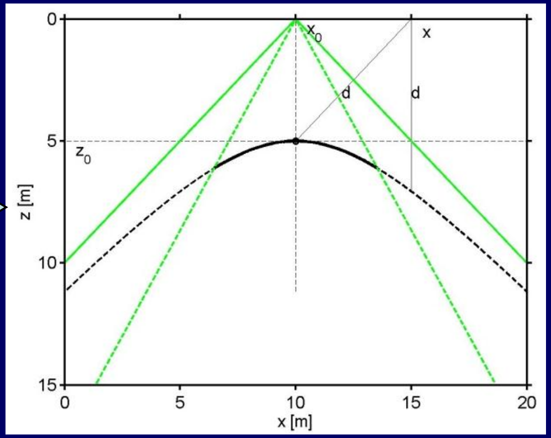
or

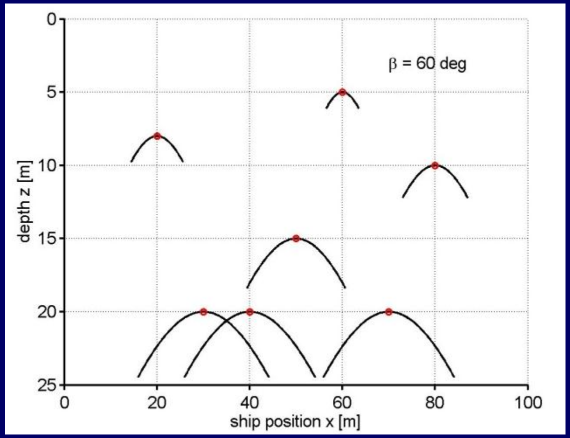
$$T_R > \frac{2nH}{c} + T + \delta T$$

Single-beam echo sounder
Measurement resolution

- Vertical resolution: $\delta z = \frac{cT}{2}$, $\delta z = \frac{c}{2B}$
- Horizontal resolution: $\delta x = 2\tan\left(\frac{\beta}{2}\right)H \approx \beta H$

$$\frac{z^2}{z_0^2} - \frac{(x-x_0)^2}{z_0^2} = 1$$





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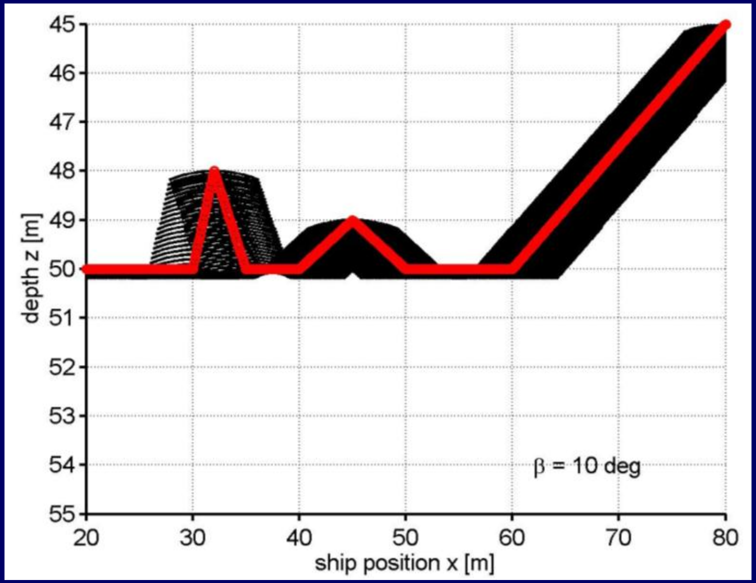
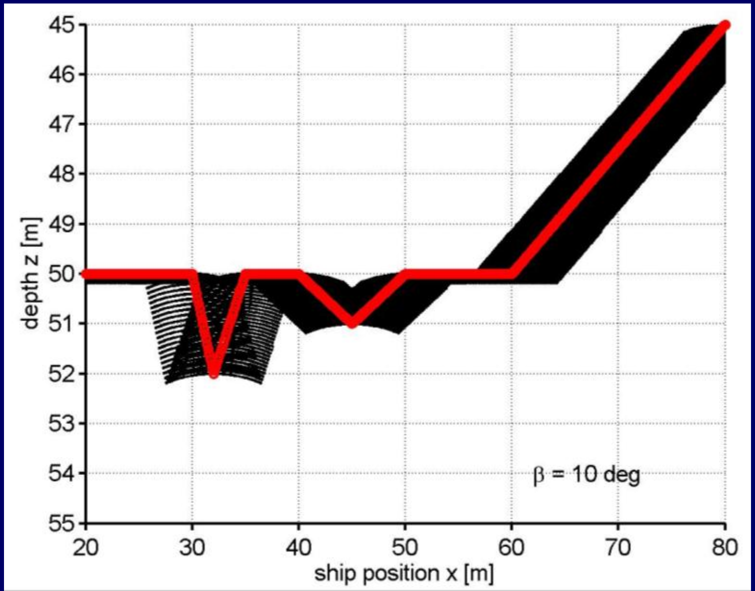
Horizontal resolution

shallow water





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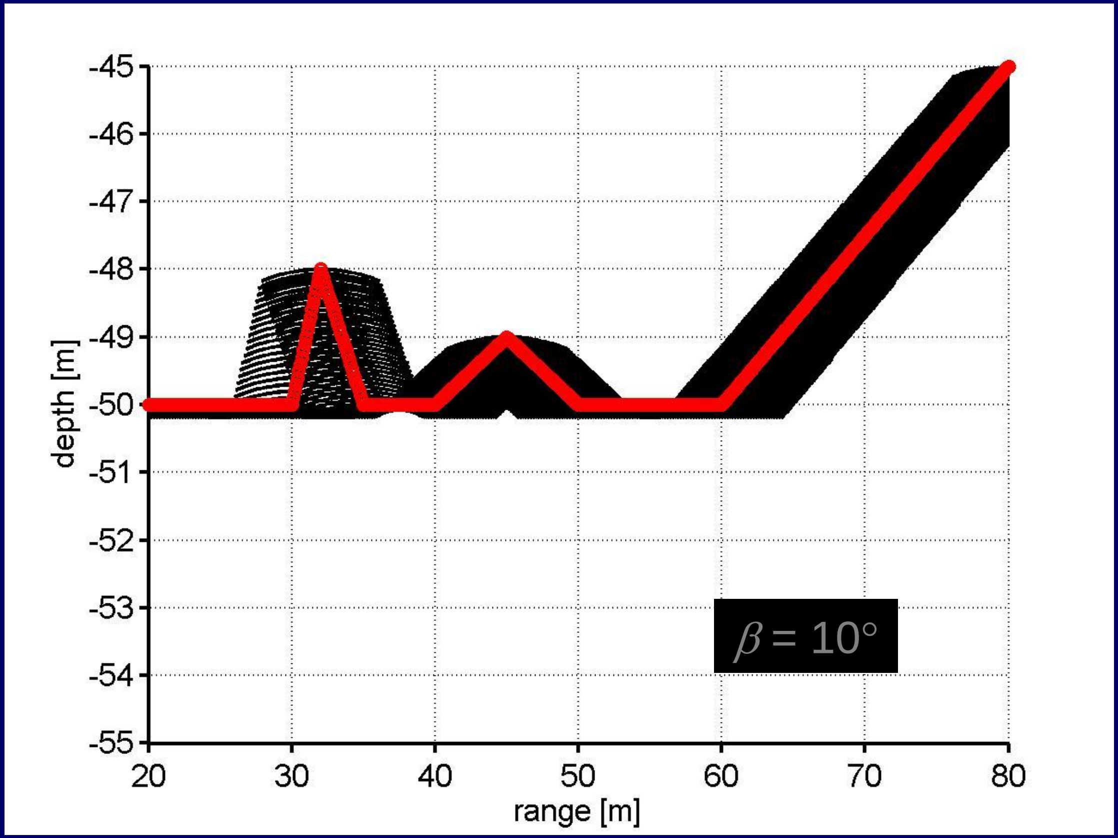
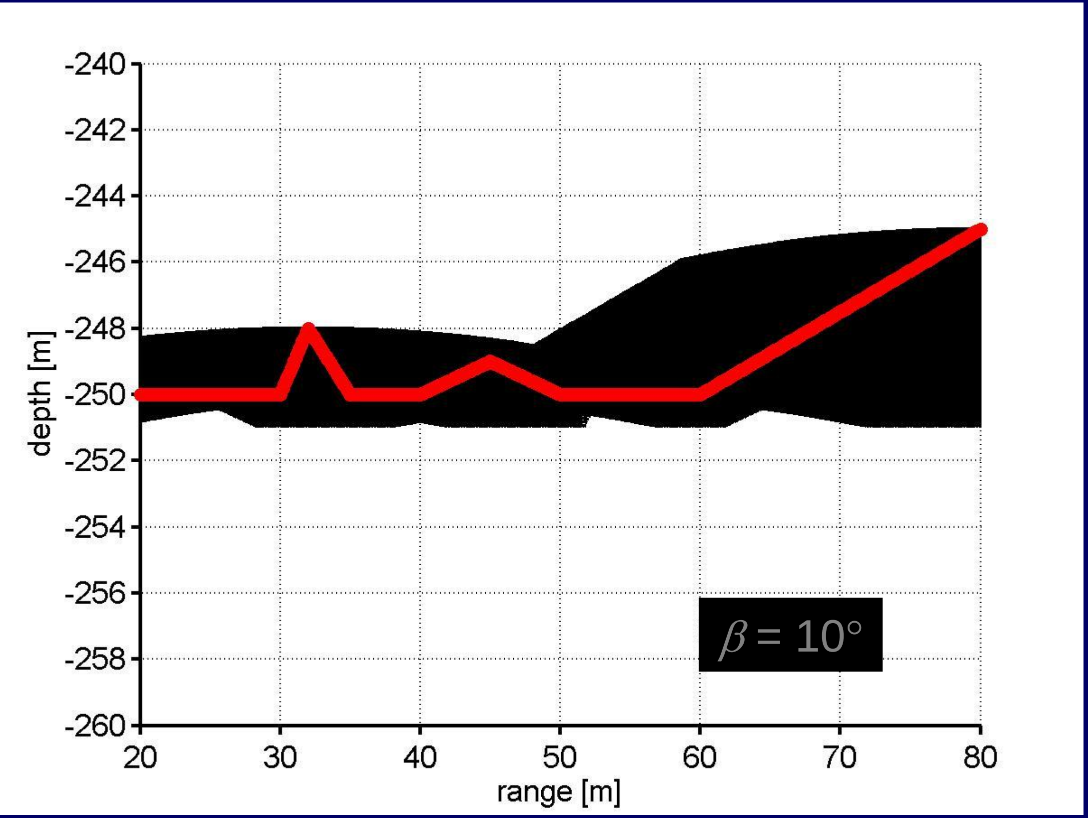
Horizontal resolution - continued
shallow water

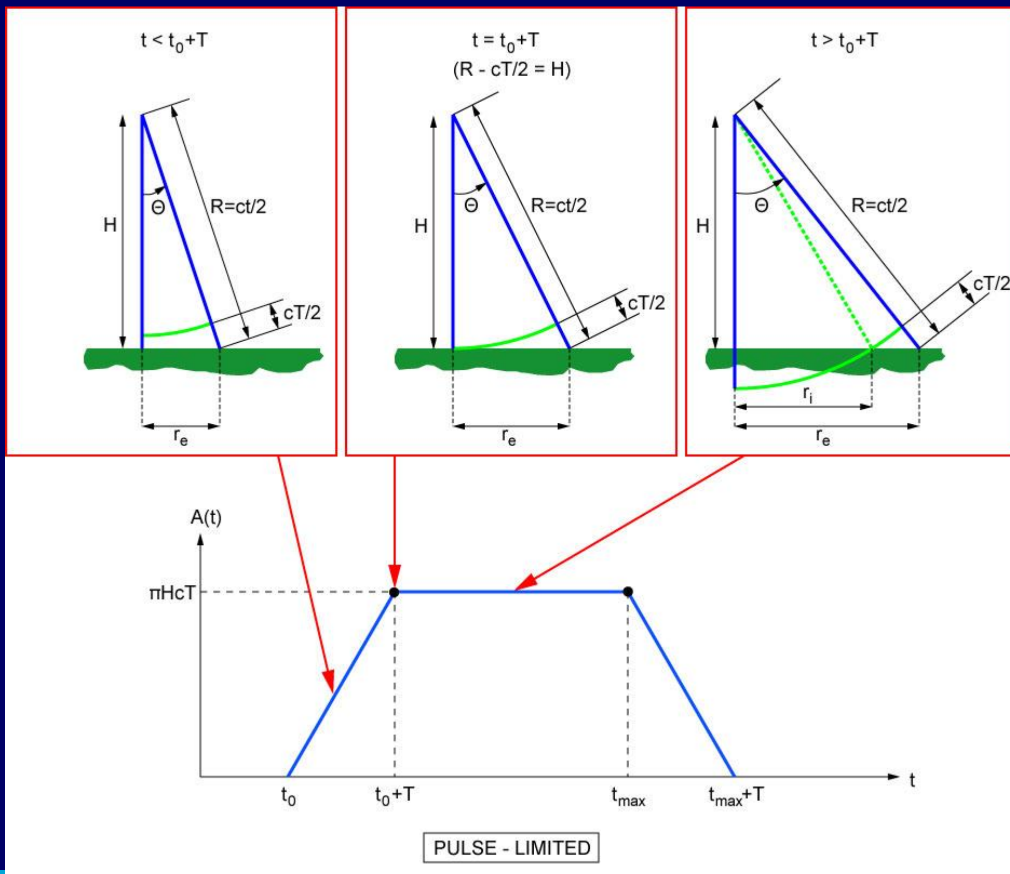


Horizontal resolution - continued
deeper water - same beam width



Single-beam echo sounder

Echo formation



Assumptions:

- A flat and horizontal seafloor
- A conical directivity pattern
- Only echo from water-seafloor interface

a) $t_0 = 2H/c$: impact point

b) From $t = t_0$ to $t = t_0 + T$:

$$A = \pi r_e^2 = \pi(R^2 - H^2) \approx \pi Hc(t - t_0)$$

c) From $t = t_0 + T$ to $t_{\max}$:

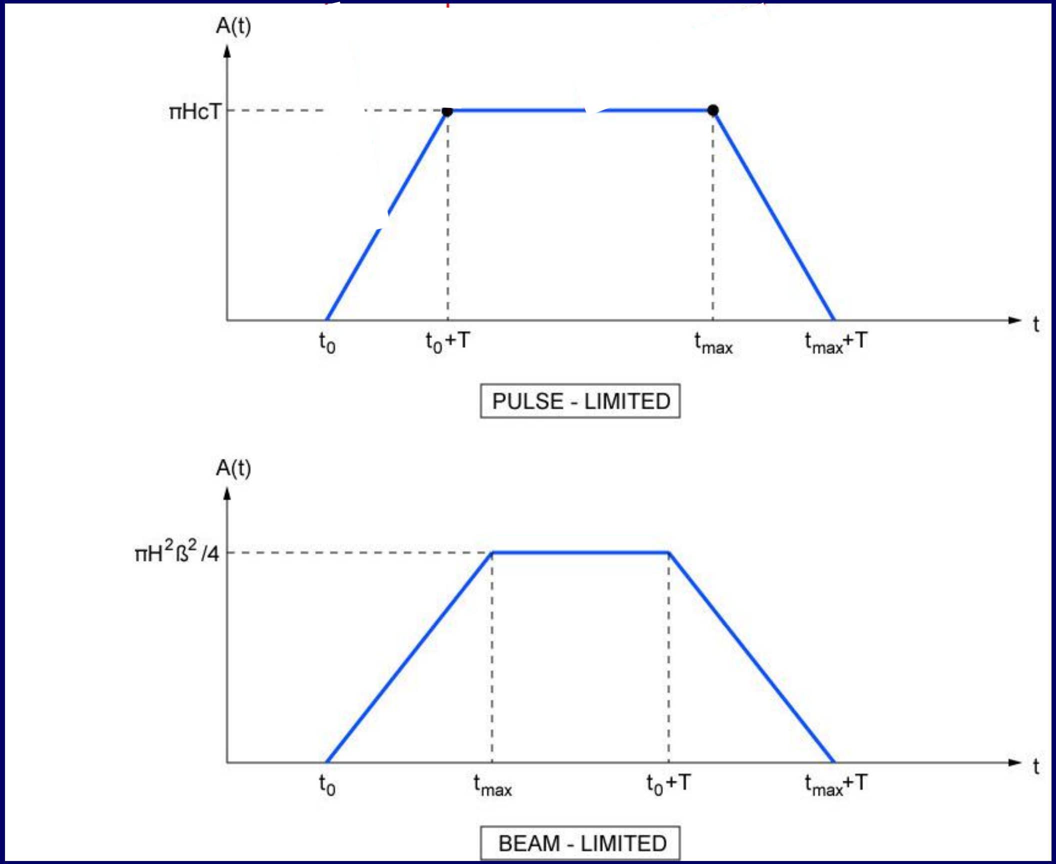
$$A = \pi(r_e^2 - r_i^2) = \pi\left(R^2 - \left(R - \frac{cT}{2}\right)^2\right) \approx \pi HcT$$

d) After $t_{\max} = t_0\sqrt{1 + \tan^2(\beta/2)} \approx t_0\left(1 + \frac{\beta^2}{8}\right)$

$$A = \pi(r_{e,\max}^2 - r_i^2)$$

with $r_{e,\max} = H\tan(\beta/2) \approx H\beta/2$

Single-beam echo sounder
Echo formation, continued



short-pulse or *pulse-limited regime:*

$$t_{\max} > t_0 + T$$

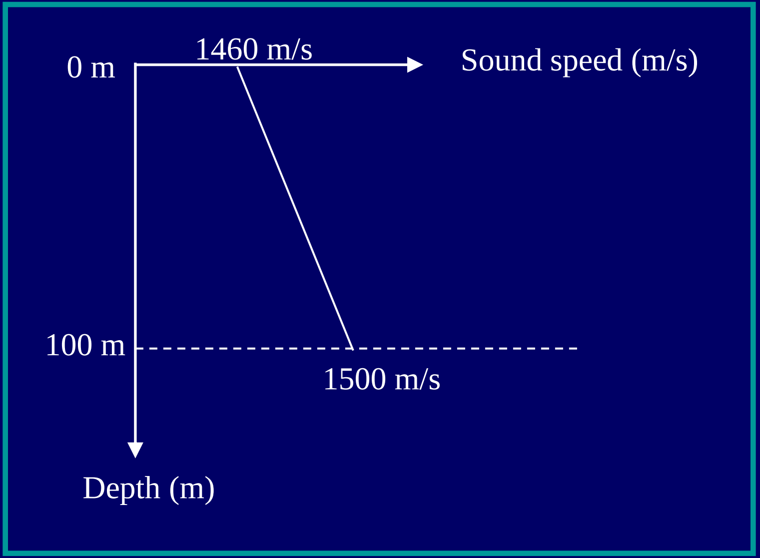
long-pulse or beam-limited regime:

$$t_{\max} < t_0 + T$$

Modified expressions for active area, see lecture notes!

Exercise handed out last lecture

Consider the following situation: We are taking measurements with a multi beam echo sounder system. The sound speed profile in the water column is as follows:

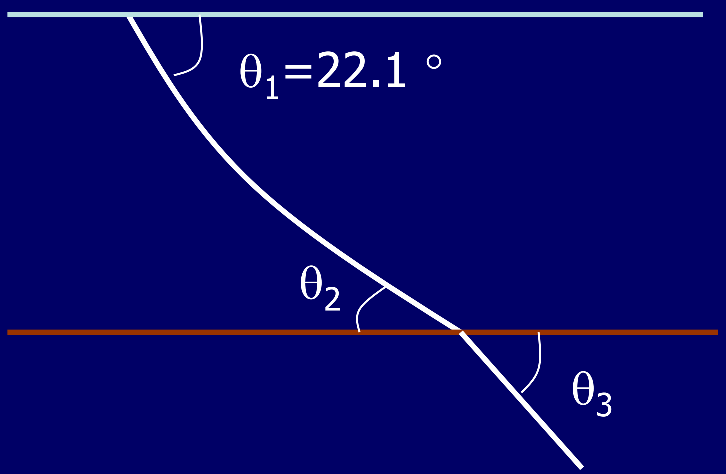


Take for the density in water column of 1g/cm3
The sediment is a clay sediment (sound speed of 1470 m/s, density in the sediment of 1.2 g/cm3)

a. Calculate for a sound ray emitted at an angle of 22.1 degrees with the horizontal, the angle of the ray at the bottom.
b. What is the reflection coefficient?
c. What happens to the sound if it arrives at the bottom, taking your above answers into account.

Exercise handed out last lecture, contn'd

- Step 1: make a sketch of the situation



c_1 = 1460 m/s, ρ_1 = 1 g/cm^3

c_2 = 1500 m/s, ρ_1 = 1 g/cm^3

c_3 = 1470 m/s, ρ_1 = 1.2 g/cm^3

- Step 2: Determine angles

$$\theta_2 = a\cos\left(\left(\frac{c_2}{c_1}\right)\cos\theta_1\right) = a\cos\left(\frac{1500}{1460}\cos 22.1\right) = 17.8^\circ$$

$$\theta_3 = a\cos\left(\left(\frac{c_3}{c_2}\right)\cos\theta_2\right) = a\cos\left(\frac{1470}{1500}\cos 17.8\right) = 21.1^\circ$$

$$\text{or} \quad a\cos\left(\left(\frac{c_3}{c_1}\right)\cos\theta_1\right) = a\cos\left(\frac{1470}{1460}\cos 22.1\right) = 21.1^\circ$$

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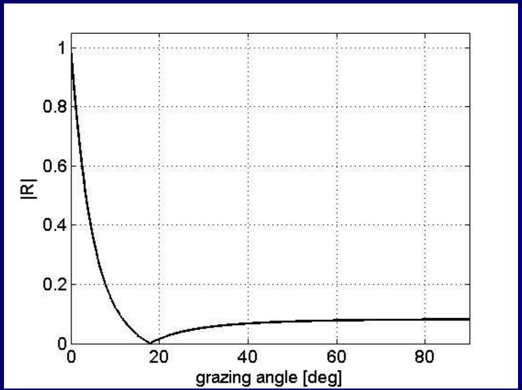
Exercise handed out last lecture, contn'd

- Step 3: make a sketch of the reflection coefficient

What is the situation, do we have an angle of intromission or a critical angle?
-> The sound speed in the sediment is lower than that in the water column directly above the sediment: no critical angle
-> $\left(\rho_2 c_2 = 1500\right) > \left(\rho_3 c_3 = 1470x1.2 = 1764\right)$, i.e., we have an angle of intromission

$$\theta_0 = \arctan\sqrt{\frac{1-\left(\frac{c_3}{c_2}\right)^2}{\left(\frac{\rho_3 c_3}{\rho_2 c_2}\right)^2 - 1}} = 17.8^\circ$$



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Exercise handed out last lecture, contn'd

- Step 4: What is the reflection coefficient

Based on the previous analysis we expect a reflection coefficient of 0.

Check:

$$R = \frac{\dfrac{\rho_3 c_3}{\sin\theta_3} - \dfrac{\rho_2 c_2}{\sin\theta_2}}{\dfrac{\rho_3 c_3}{\sin\theta_3} + \dfrac{\rho_2 c_2}{\sin\theta_2}} = \frac{\dfrac{1.2x1470}{\sin 21.1} - \dfrac{1500}{\sin 17.8}}{\dfrac{1.2x1470}{\sin 21.1} + \dfrac{1500}{\sin 17.8}} = 0$$

Exercise

- SBES with an opening angle of 10 degrees
- 4000 m of water depth

What is the horizontal resolution?

$$r_e = \frac{H\beta}{2} = \frac{4000x\pi x10}{2x180} = 349 \text{ m}$$

$$\delta\text{x} = 698 \text{ m}$$

$$\text{A} = \pi \text{r}_\text{e}^2 = 0.4 \text{ km}^2$$

Beam footprint

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Single-beam echo sounder
Maximum operating range

- Water depth: 5 km
- Dominant noise source: self noise
- Receiving bandwidth: 500 Hz
- Ship speed: 15 knots
- Echo-sounder: circular transducer with an area of 400 cm^2
- SNR should be at least 10 dB

Required specifications for the echo sounder, its frequency f in particular?

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Single-beam echo sounder

Maximum operating range, continued

$$SNR = EL - BGL$$

with

$$EL = SL - PL$$

$$BGL = NL_W - DI$$

$$DI = 10^{10}\log\frac{4\pi A}{\lambda^2}$$

, with A = 400 cm^2, DI = 19.5 dB at 20 kHz

$$SL = 170.8 + 10^{10}\log P + DI$$

For P = 50 Watt: SL = 207 dB re 1 μPa at 20 kHz.

$$NL_W = NL + 10^{10}\log W$$

with

$$NL = 33 + 1.8v - 20^{10}\log\left(\frac{f}{12}\right)$$

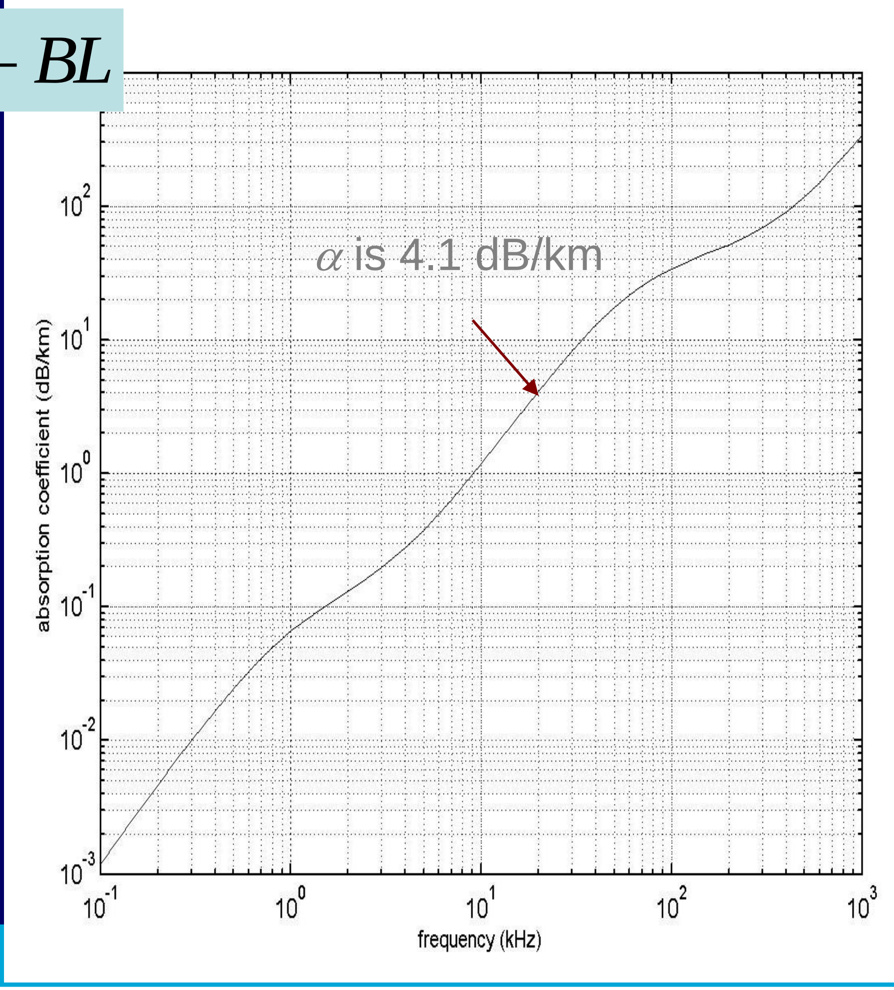
NL_w amounts to 82.6 dB at 20 kHz

Single-beam echo sounder
Maximum operating range, continued

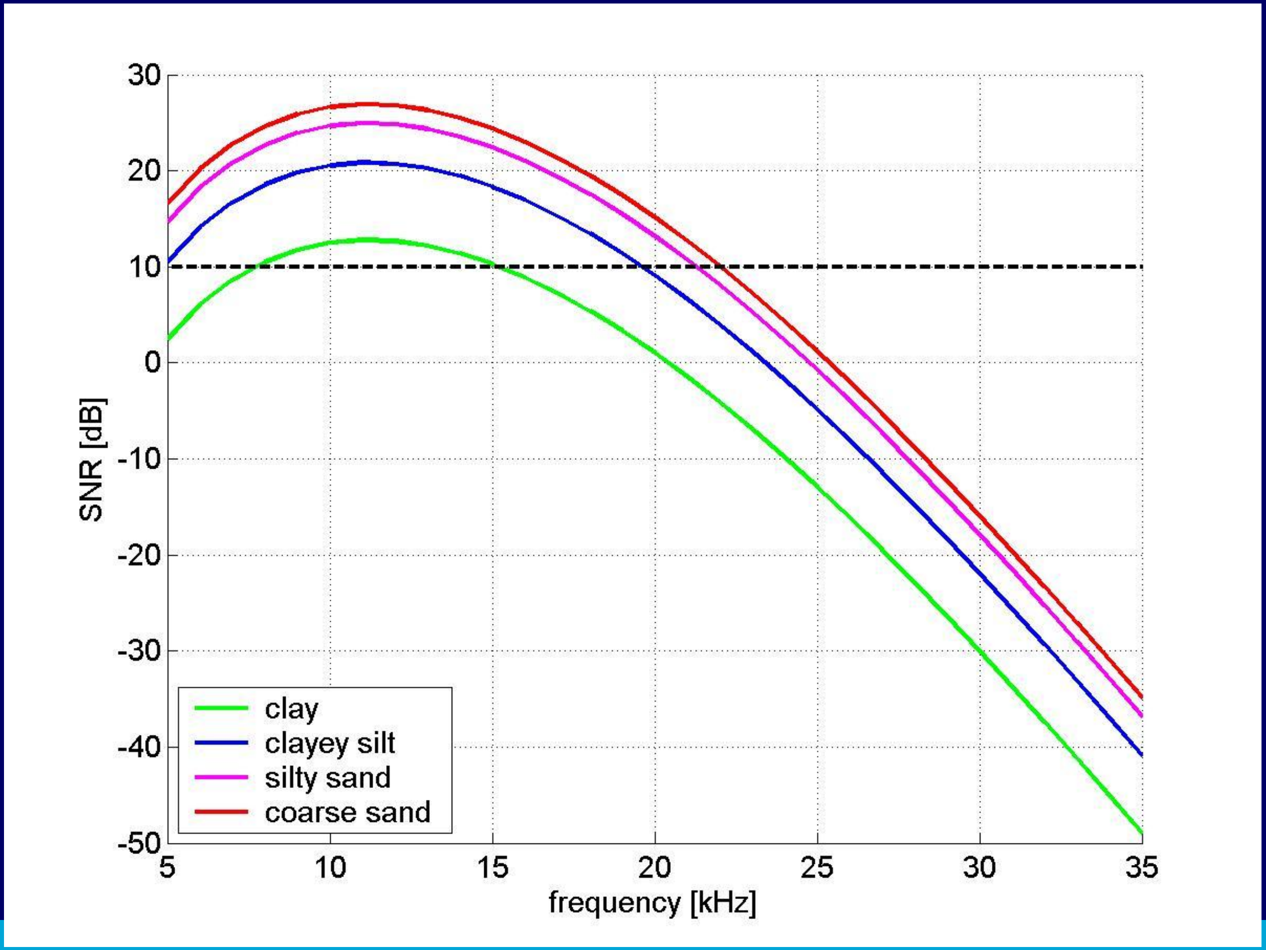
$$PL = 60 + 20^{10}\log(2H) + 2\alpha H + BL$$

$$BL = -20^{10}\log\frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}$$

Clay : BL = 22 dB
Coarse sand : BL = 7.7 dB



Single-beam echo sounder
Maximum operating range, continued



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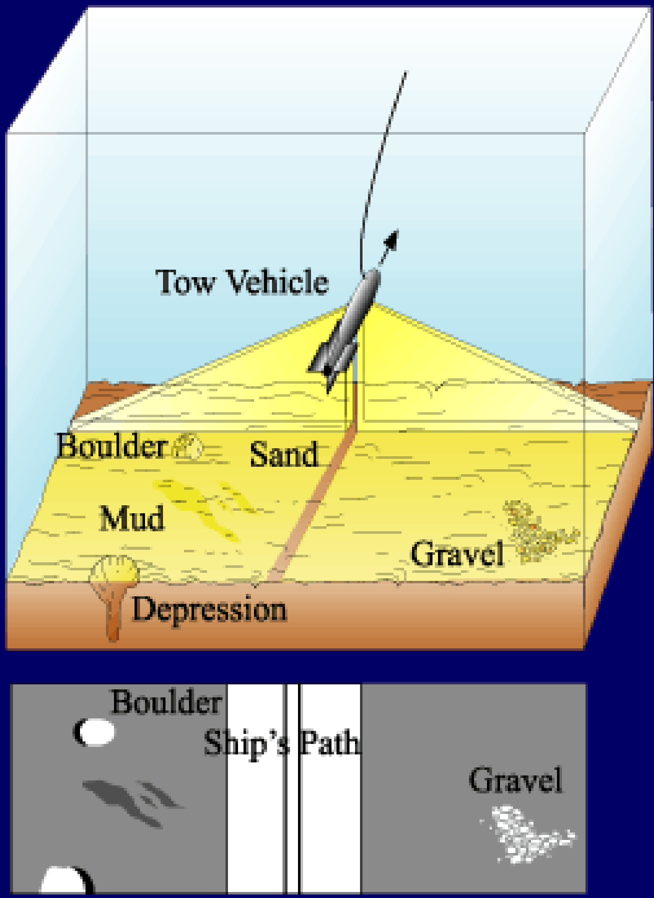
The sidescan sonar system

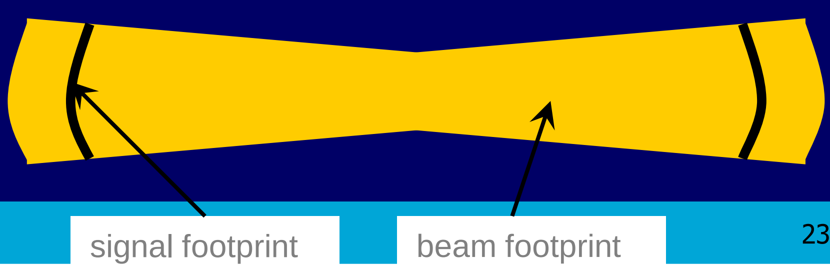


- Signal duration T : ~less than 0.1 ms
- Beam width (angular aperture) β : ~1° in horizontal plane, ~85° in vertical plane
- Frequency f : several 100 kHz

Transmission sequence:

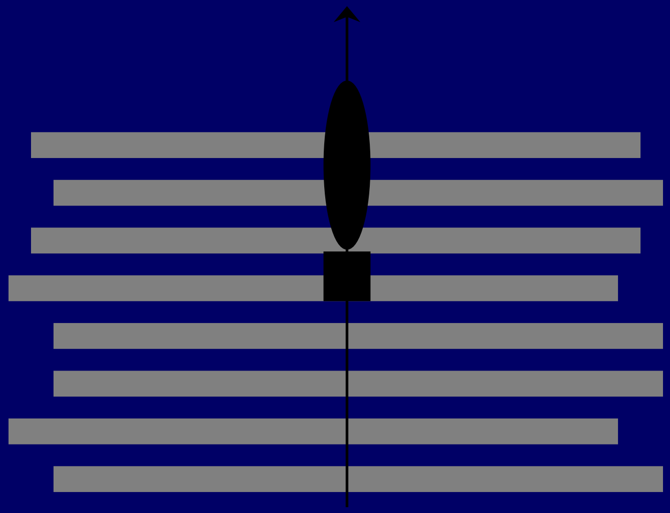
$$T_R > \frac{2R_{\max}}{c}$$

Footprint:



Sidescan sonar
Image reconstruction

Measurements consist of backscattered intensity as a function of time.



For a flat seafloor:

$$y = \sqrt{R^2 - H^2} = \sqrt{\frac{c^2 t^2}{4} - H^2}$$

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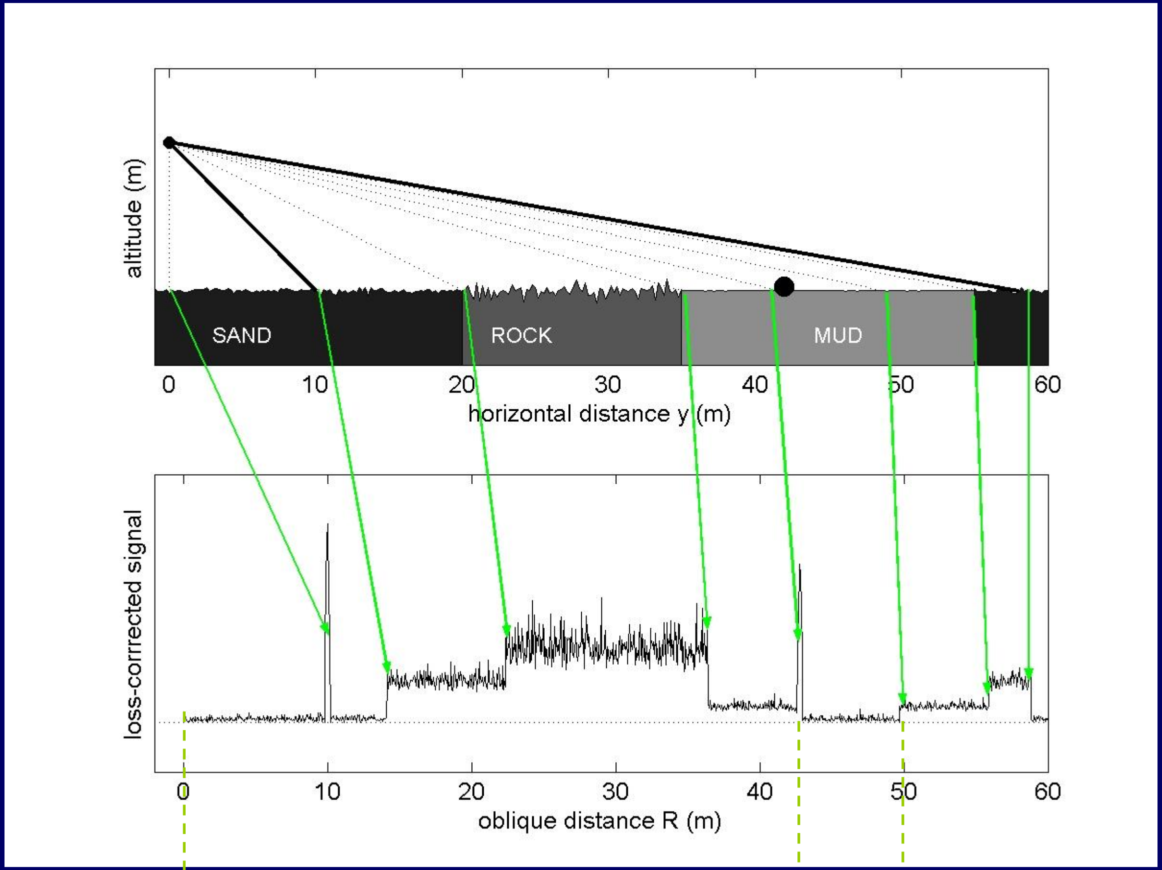
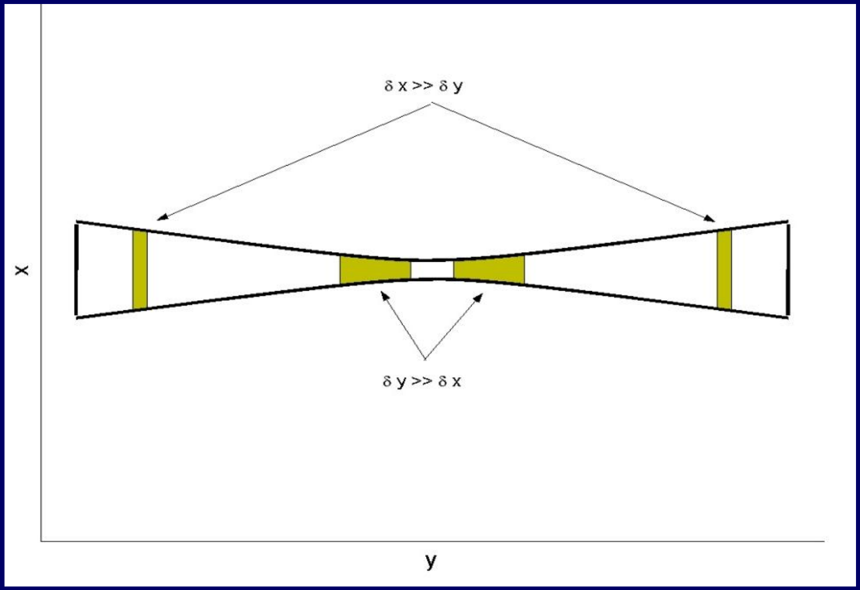
Sidescan sonar
Echo formation



Obstacle height: $h = \dfrac{H\ \Delta t}{t_F}$

Sidescan sonar
resolution

Along track x ↓



Across track y →

Across track y: $\delta y = \dfrac{cT}{2\sin\theta}$

$\delta y = cT/2$ for $\theta \to 90°$

$\delta y = \sqrt{HcT}$ for $\theta = 0°$

Along track x: $\delta x = R\beta$

Sidescan sonar
coverage

To ensure 100 % coverage:

$$\delta x = H\beta$$ (insonified strip is narrowest near vertical)

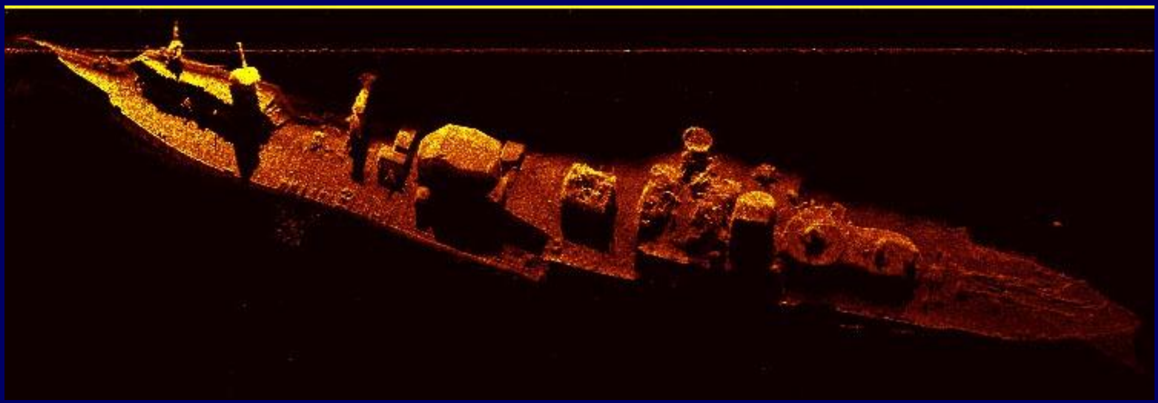
$$\delta x = v T_R$$ (sonar distance between two pings)

$$T_R = \frac{2R_{\max}}{c}$$

$$\longrightarrow \quad v \le \frac{cH\beta}{2R_{\max}} = \frac{c\beta}{2}\cos\theta_{\max}$$

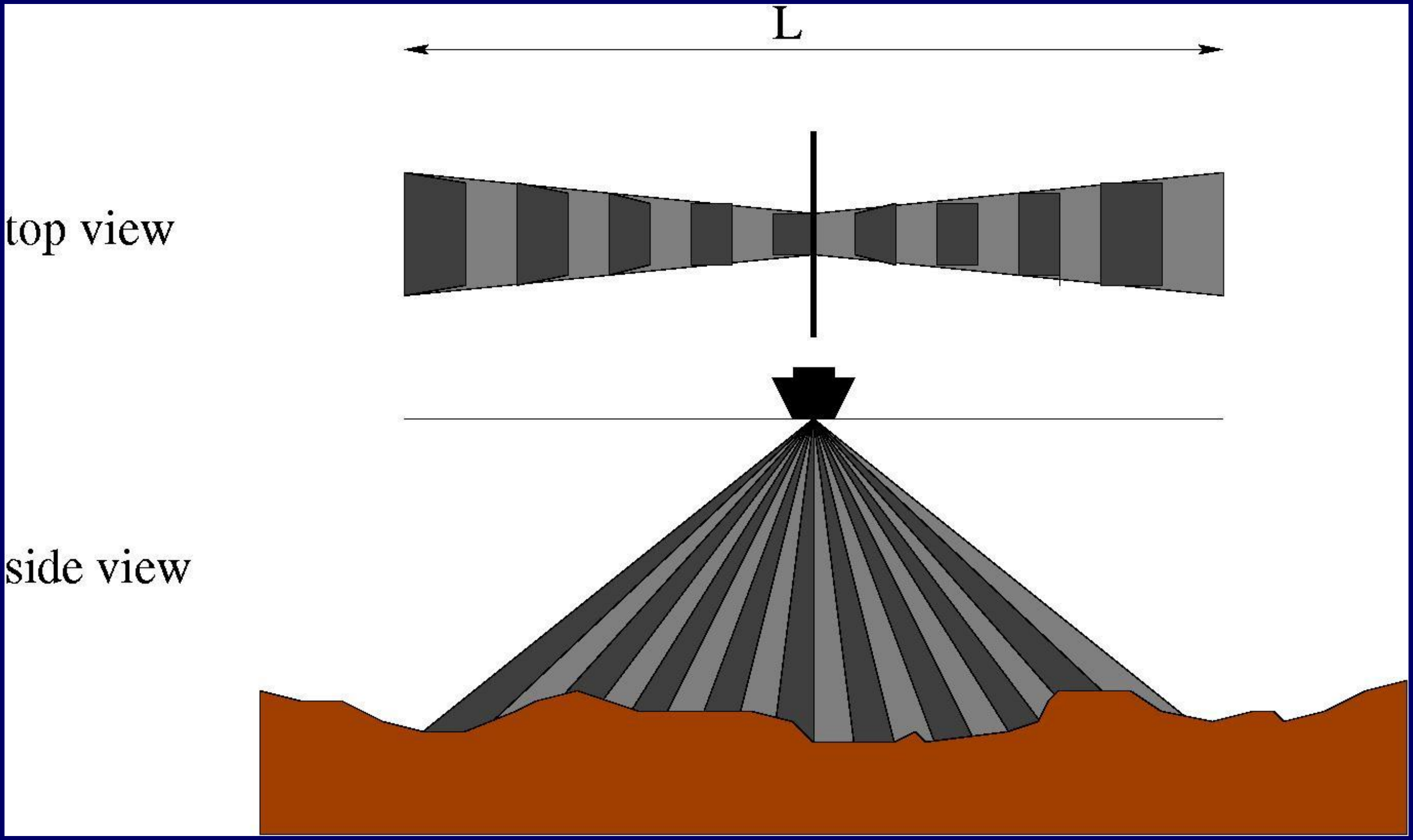
(i.e., 100 % coverage condition independent of *H*)

Sidescan sonar
Examples



Multi-beam echo sounders (MBES)

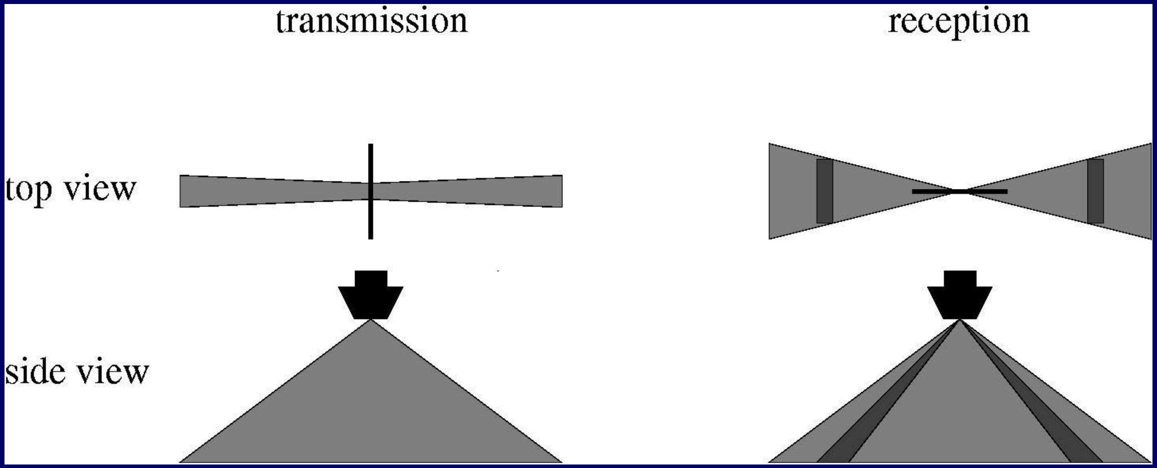
simultaneous measurement of bathymetry and backscatter



MBES
MBES types

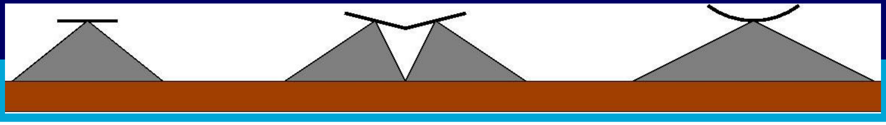
- Deep water systems: operating at $f \sim 12$ kHz.
  The large dimensions of the transducer array limits their installation to deep-sea vessels.
- Shallow water systems: operating at $f \sim 100\text{-}200$ kHz.
  Mapping of the continental shelf.
- High-resolution systems: operating at $f \sim 300\text{-}500$ kHz.
  Local studies (shipwreck location, inspection of underwater structures). Small size allows for installation on small ships, tow fishes or autonomous underwater vehicles (AUV).

MBES
transmission and reception arrays



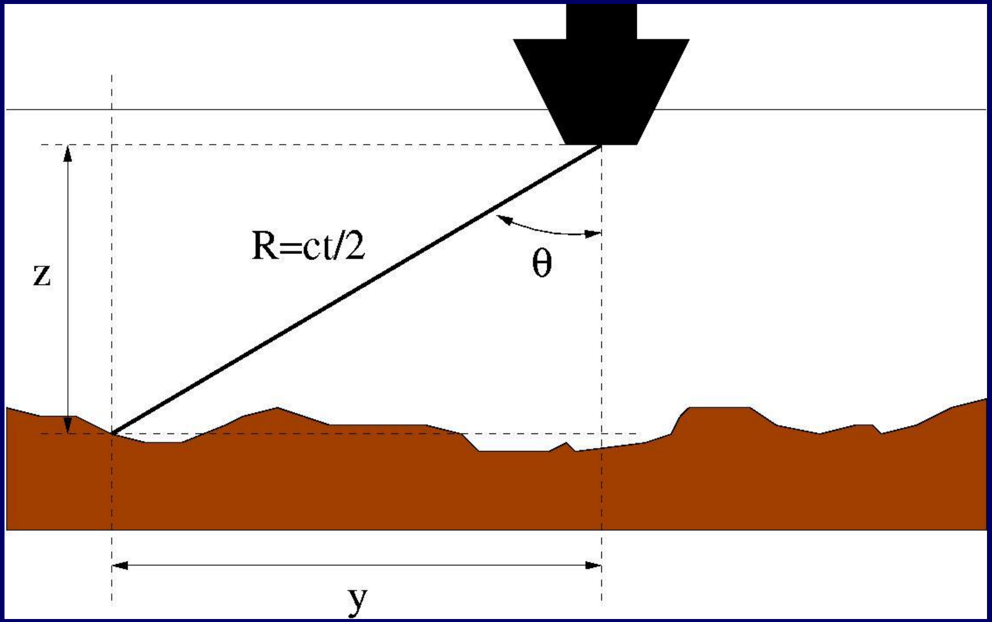
Transmission
(determines along-track resolution δx)

Reception (using beamforming)
(determines across track resolution δy)



MBES
bathymetry (topography) measurement

Joint measurement of time *t* and angle θ



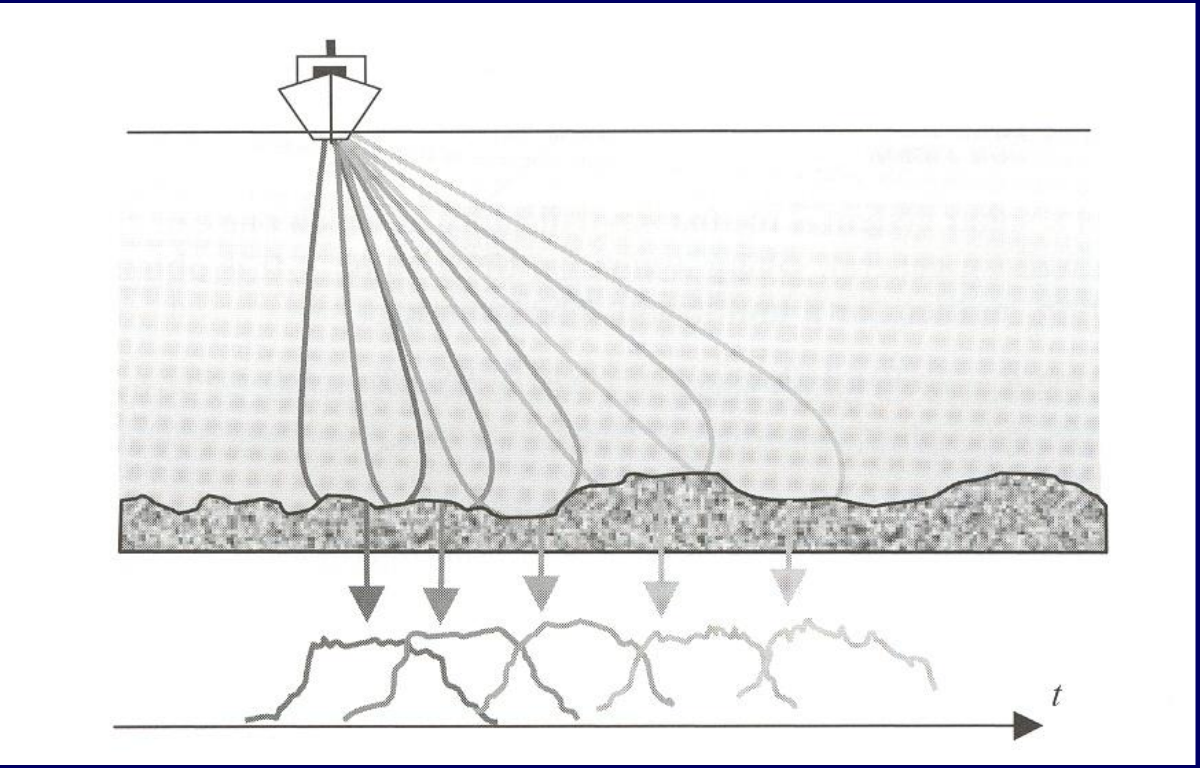
$$y = R(t)\sin\theta = \frac{ct}{2}\sin\theta$$

$$z = R(t)\cos\theta = \frac{ct}{2}\cos\theta$$

(when ssp is constant, otherwise ray tracing is necessary)

MBES imaging

Combining time signals after beamforming:



Compared to SSS:
backscatter pixels are now at the correct position because of bathymetry measurement capability !!!

MBES
bathymetry measurement errors

Basis:

$$y = R(t)\sin\theta = \frac{ct}{2}\sin\theta$$

$$z = R(t)\cos\theta = \frac{ct}{2}\cos\theta$$

Errors in range *R*:

$$\delta z_R = \delta R\cos\theta$$

$$\delta y_R = \delta R\sin\theta$$

Errors in angle θ:

$$\delta z_\theta = R\sin\theta\,\delta\theta = H\tan\theta\,\delta\theta$$

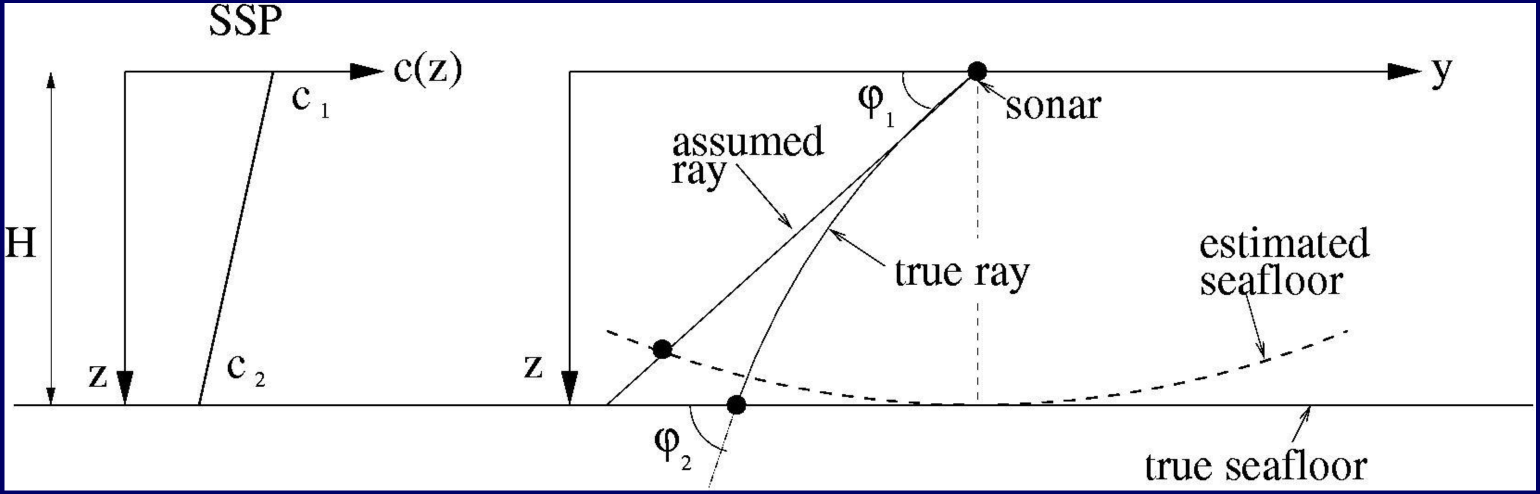
$$\delta y_\theta = R\cos\theta\,\delta\theta = H\,\delta\theta$$

Prediction of bathymetry measurement accuracy with MBES is an important research item !!!

Types of errors:

- Errors in the acoustic measurement itself (acoustic noise, non-stable backscattered signal);
- Movements of the support platform (finite accuracy of the attitude sensors);
- Inaccuracies in sound speed corrections.

MBES
Refraction correction



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MBES

Refraction correction, continued

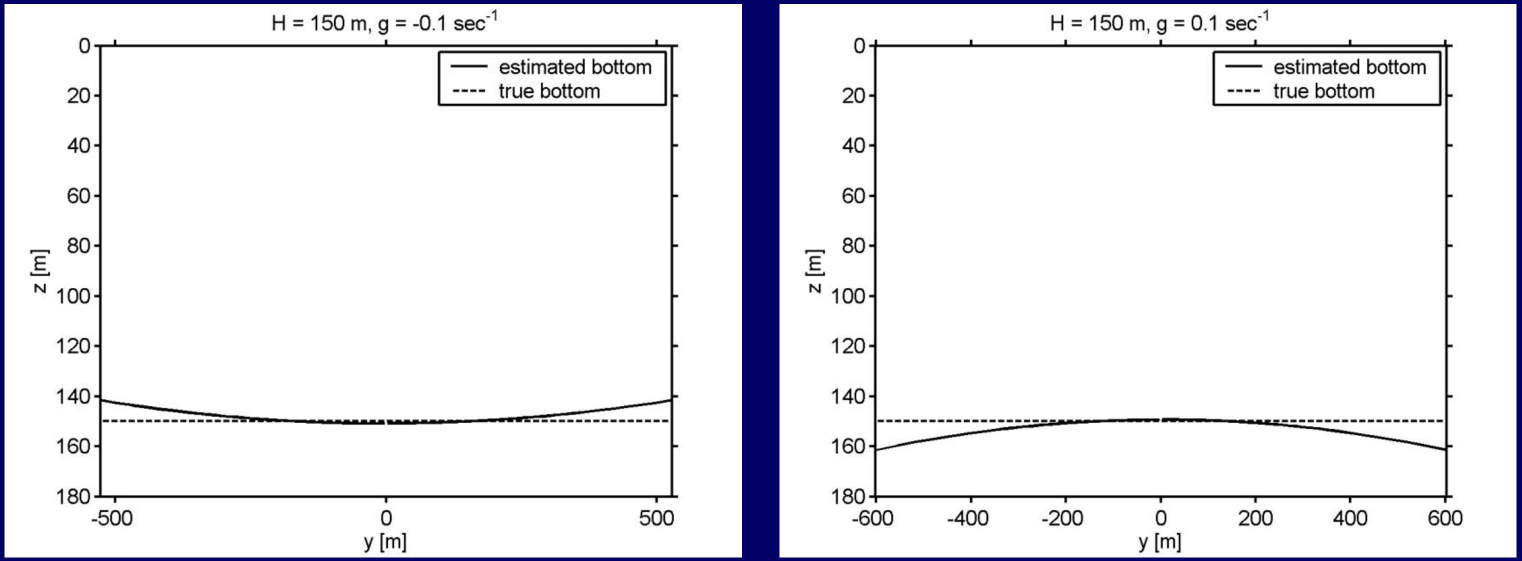
$$c(z) = c_1 + g\ z$$ with $c(H) = c_2$

$$t = \int \frac{ds}{c(z)}$$, with $ds = \sqrt{dy^2 + dz^2}$ and $dz = \tan\varphi\ dy$: $ds = dz / \sin\varphi$

Snell's law: $$\frac{\cos\varphi_1}{c_1} = \frac{\cos\varphi(z)}{c(z)} = \frac{\cos\varphi(z)}{c_1 + gz} \Longrightarrow dz = \frac{c_1}{g}\frac{\sin\varphi}{\cos\varphi_1} d\varphi$$

$$t = \int_{\varphi_1}^{\varphi_2} \frac{1}{c_1}\frac{\cos\varphi_1}{\cos\varphi}\frac{1}{\sin\varphi}\frac{c_1}{g}\frac{\sin\varphi}{\cos\varphi_1} d\varphi = \frac{1}{g}\int_{\varphi_1}^{\varphi_2} \frac{1}{\cos\varphi} d\varphi = \frac{1}{g}\ln\frac{\tan\left(\frac{\pi/2-\varphi_2}{2}\right)}{\tan\left(\frac{\pi/2-\varphi_1}{2}\right)}$$

MBES
Refraction correction, continued



MBES
resolution

Along track resolution

$\delta x = R\theta_L$ for bathymetry & imaging

Across track resolution

For imaging: $\delta y = \dfrac{cT}{2\sin\theta}$ ($\delta y = \sqrt{HcT}$ for $\theta \to 0°$)

For bathymetry: $\delta y = \dfrac{H}{\cos^2\theta}\theta_T$ - $\delta y = \dfrac{cT}{2\sin\theta}$

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MBES
Repetition period and coverage

$$v \le \frac{c\theta_L}{2}\cos\theta_{\max}$$

<u>Global mapping of the deep oceans (H = 4 km)</u>

θ_{max} = 75°, θ_L = 1.5°

v: 5 m/s or 10 knots (100 % coverage)

Swathe: $L = 2H\tan\theta_{\max} = 30\ \mathrm{km}$

Area covered per second: $vL = 0.15\ \mathrm{km}^2/\mathrm{sec}$ 13000 km^2 per day

Surface of Earth's deep oceans: 350x10^6 km^2 ⟹

Required for global mapping: 2.7x104 days = 74 years
With 50 deep water MBES systems (situation in 2002): ~**1 year**

A typical MBES result