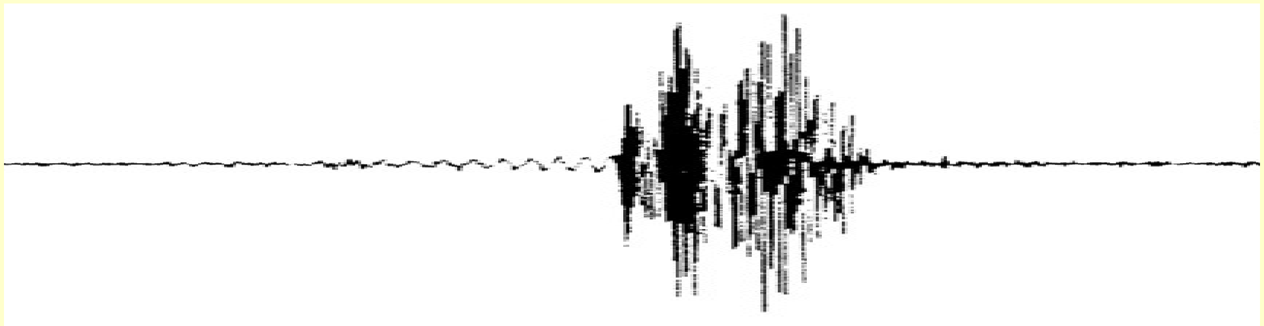
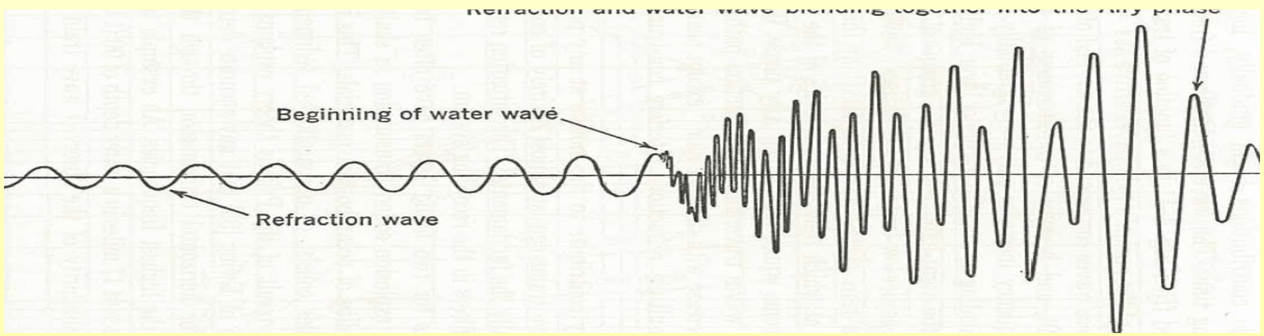
Normal modes revisited – some field observations



Interference noise, recorded by Rig Master; 1989



Modeling by Pekeris; 1948

by M. Landrø, NTNU and P. Hatchell, Shell

Objective

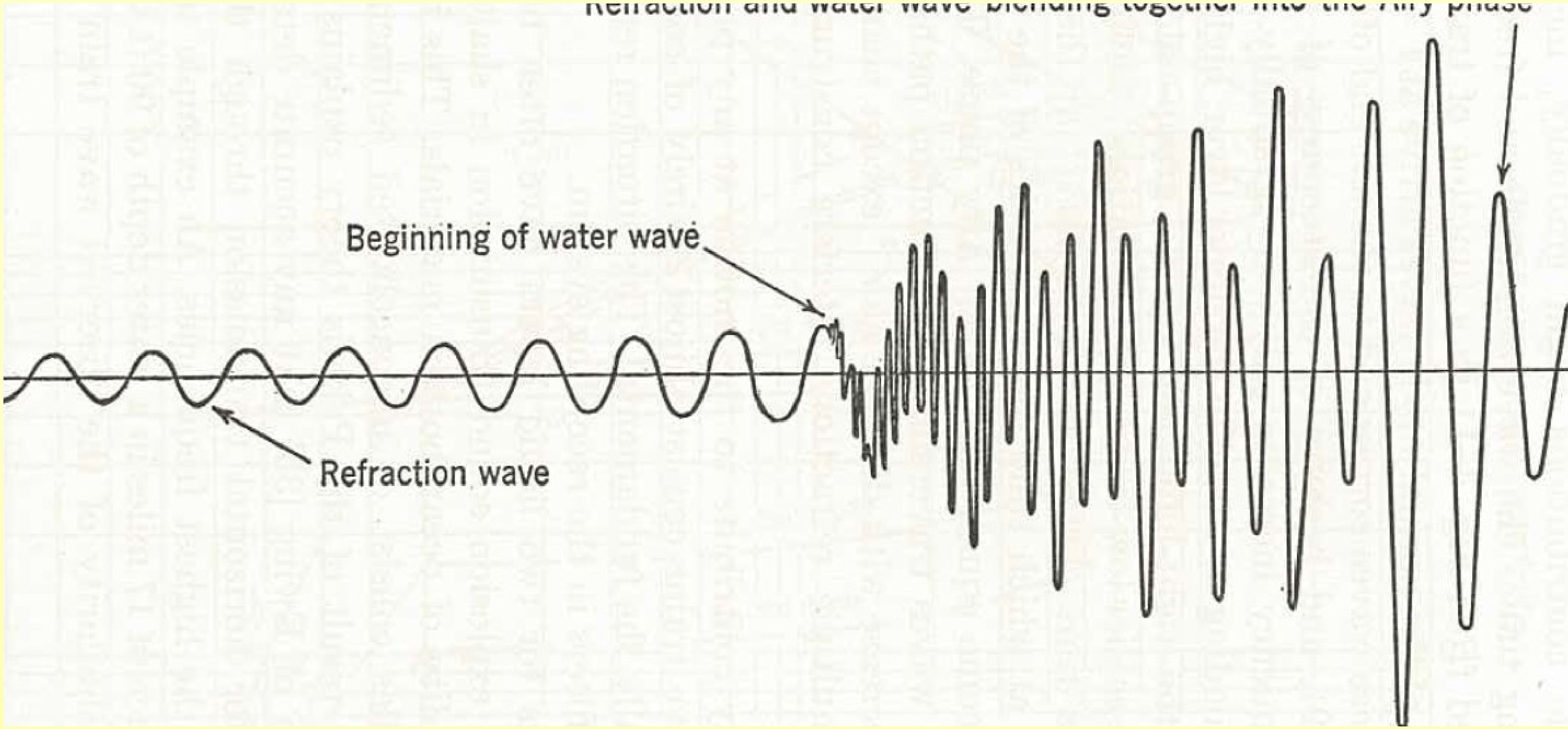
- **Improved understanding of ultrafar offset seismic signals**

Motivation

- **Exploit normal modes for monitoring changes within waterlayer and first layer below seabed**

- **Scaring effects on fish: Need to know signal characteristics versus water depth and subsurface properties**

Definitions used by Pekeris



REFRACTION WAVE **WATER WAVE**

Estimating subtle changes in water layer velocities

Analysis of Guided Waves Recorded on Permanent Ocean Bottom Cables

P.J. Hatchell* (Shell International Exploration & Production BV), P.B. Wills (Shell International Exploration & Production BV) & M. Landro (NTNU)

EAGE, London, 2007

Variation of NMO velocity between various surveys at Valhall is used to estimate subtle changes in water velocity: ~ 1.3 %! Such changes are important for accurate 4D time shift analysis.

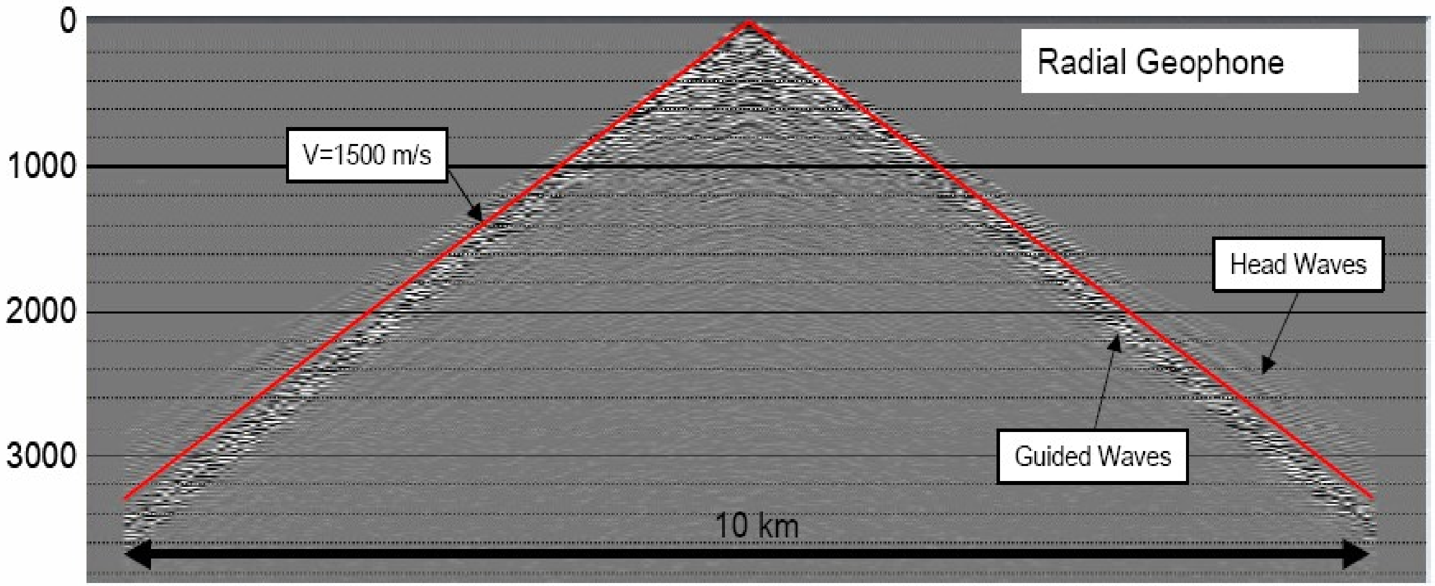
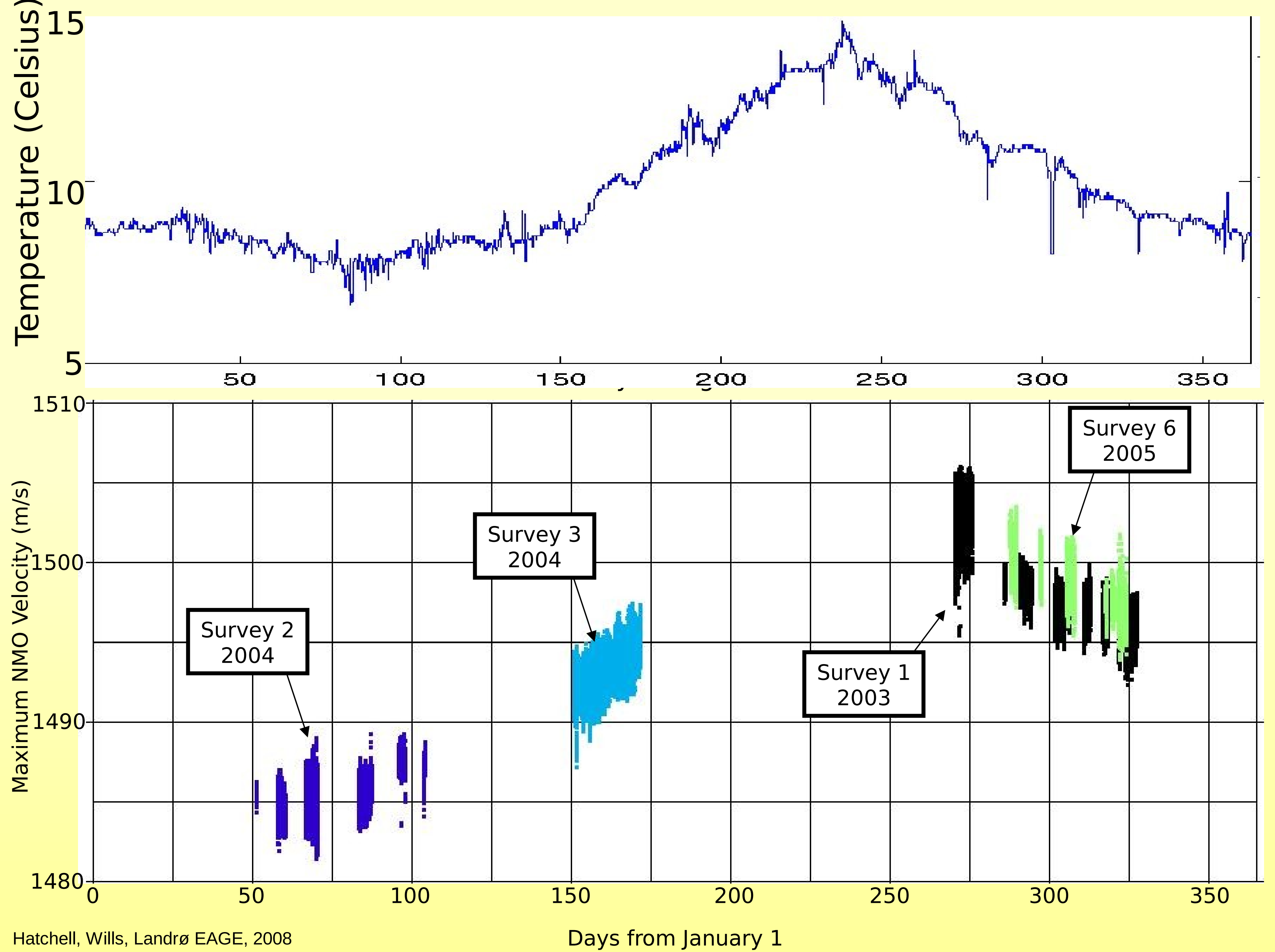


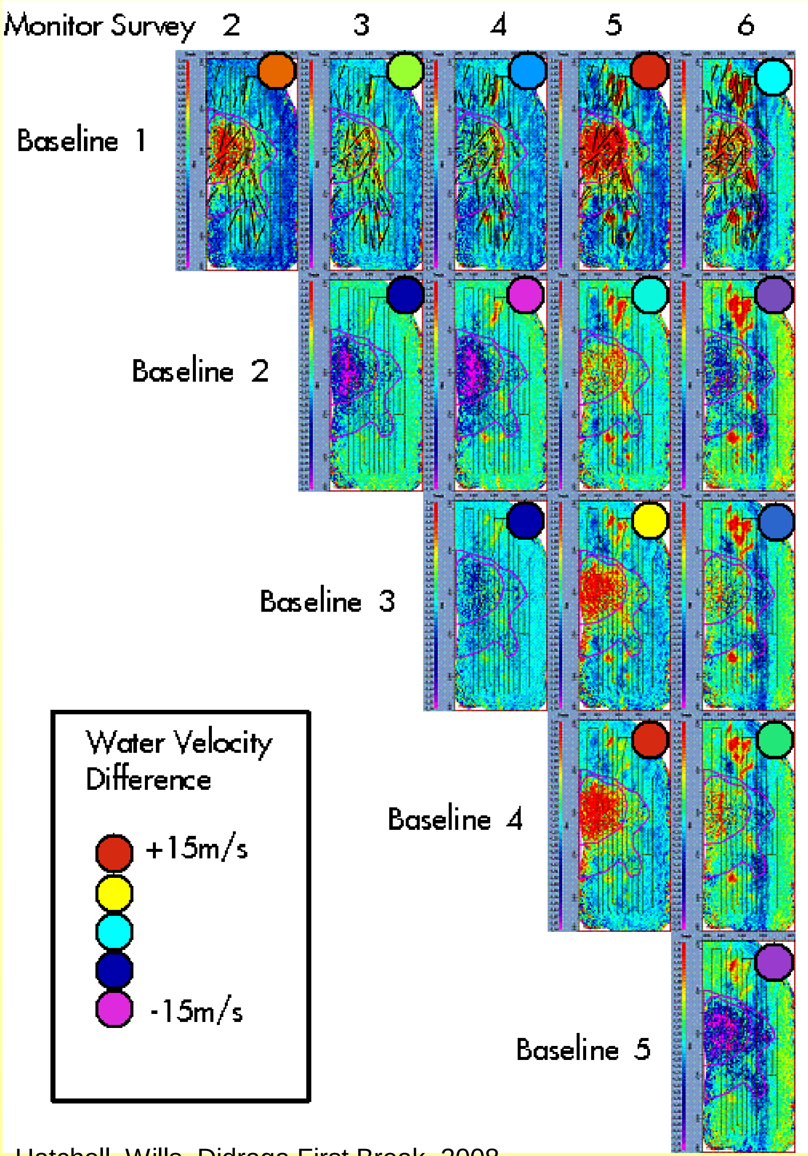
Figure 1: Radial geophone records from an array of airgun shots extending 5 km on either side of the geophone location. The shot spacing is 50m.



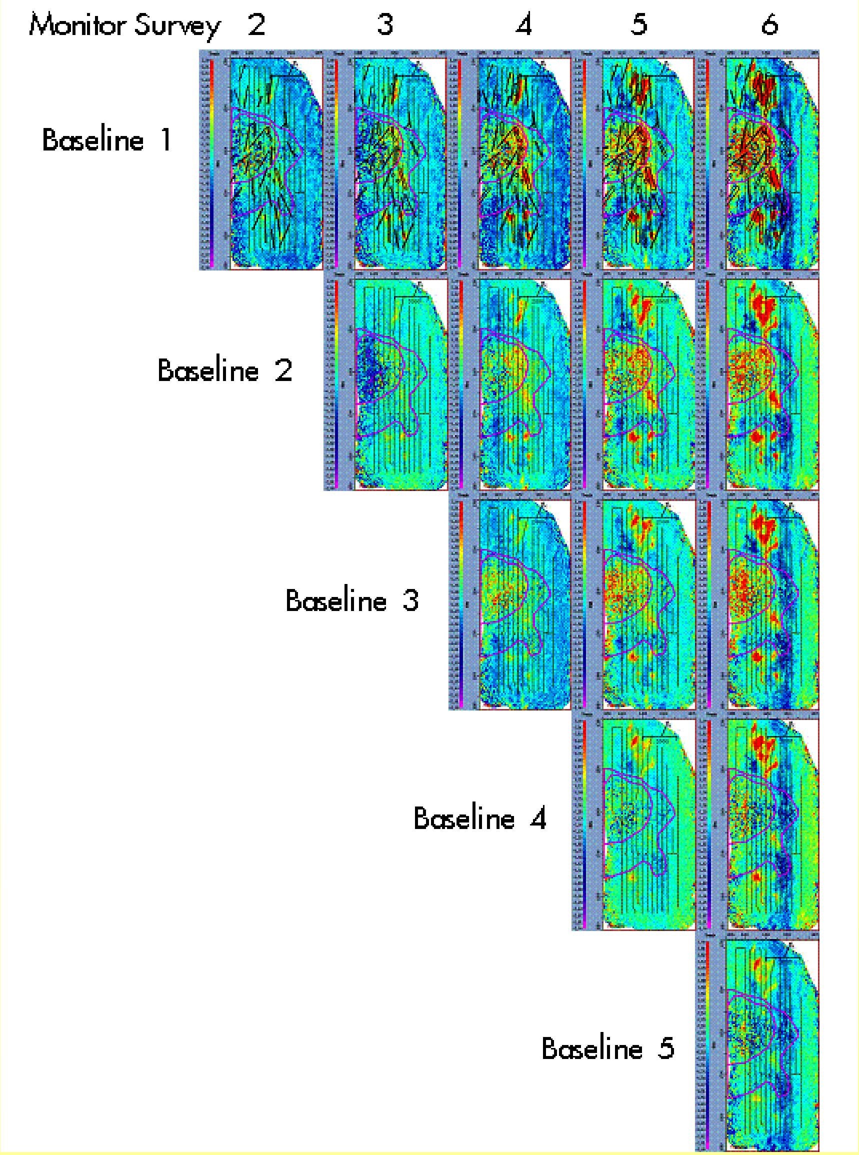
Hatchell, Wills, Landrø EAGE, 2008

Impact of water velocities/multiples on time-lapse time-shifts

Top reservoir timeshifts



After data adaptive removal

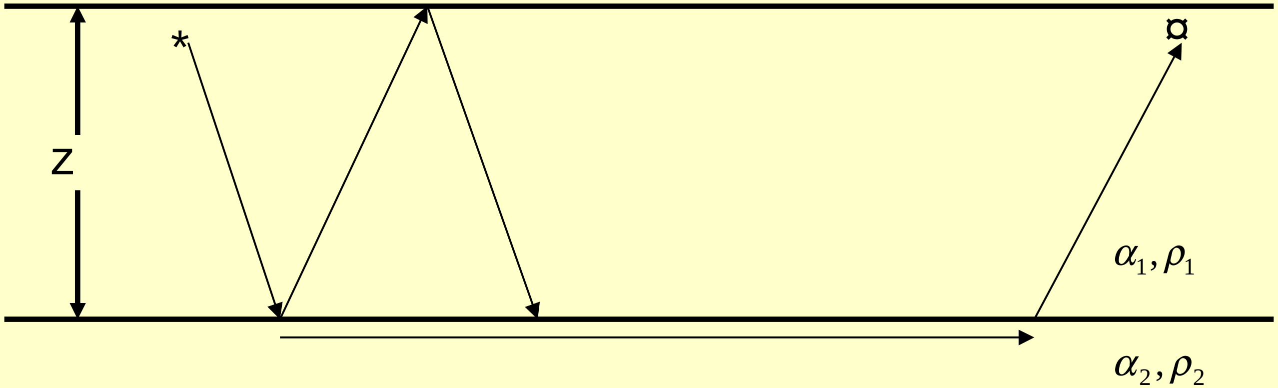


Hatchell, Wills, Didraga First Break, 2008

THEORY

(Ewing et al, 1957)

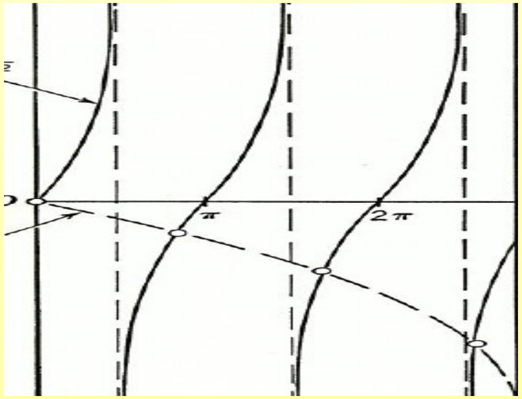
Acoustic case: Water layer over an infinite half-space:



The periodic equation:

$$\tan kH\sqrt{\frac{c^2}{\alpha_1^2}-1} = -\frac{\rho_2}{\rho_1}\frac{\sqrt{\frac{c^2}{\alpha_1^2}-1}}{\sqrt{1-\frac{c^2}{\alpha_2^2}}}$$

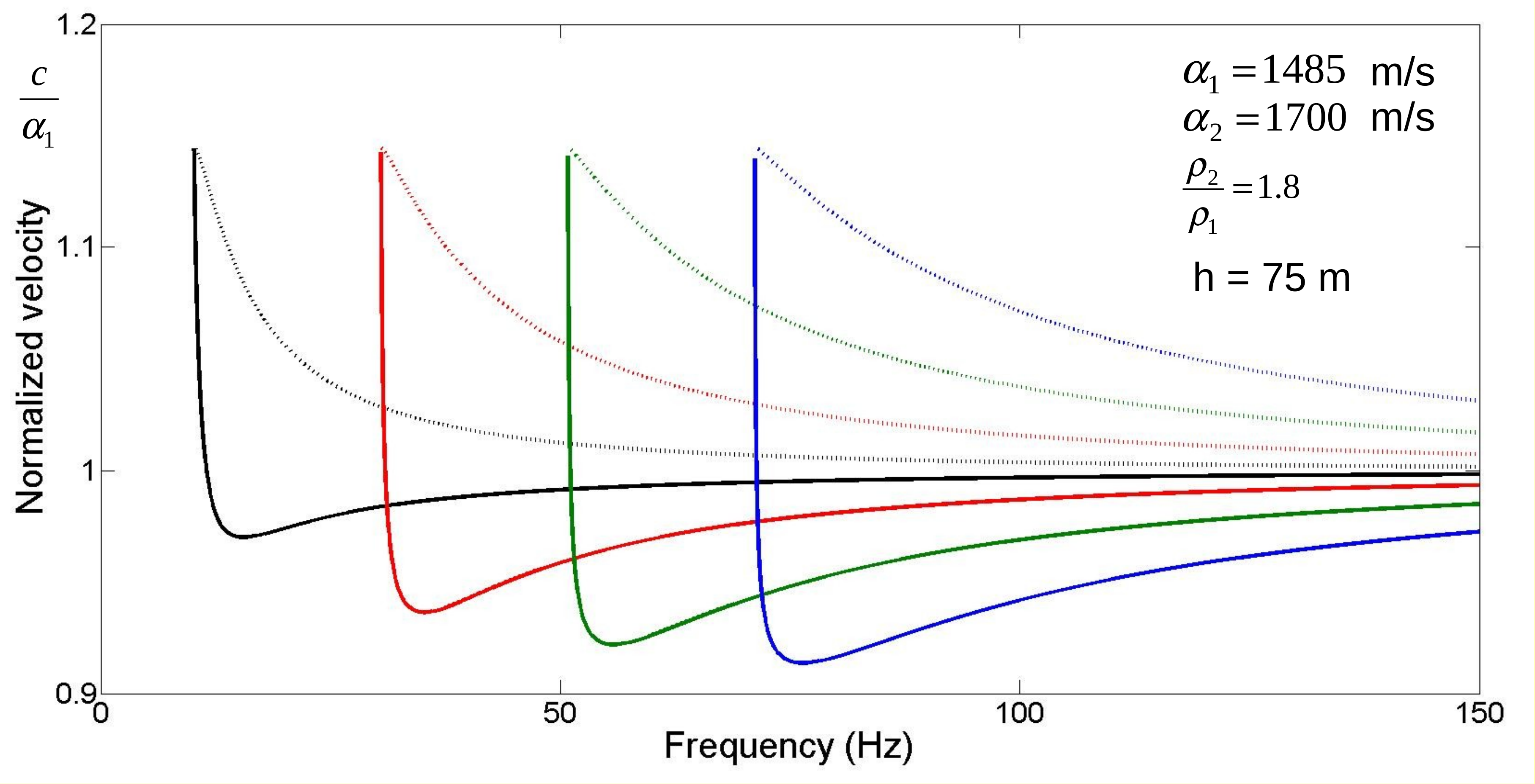
=>



C = phase velocity of normal mode

Solutions corresponding to different modes of propagation

Modeled normal modes (4 modes)



- Maximum phase and group velocity equal to velocity of second layer
- Minimum phase velocity equal to water velocity
- Minimum group velocity decreases with increasing mode number

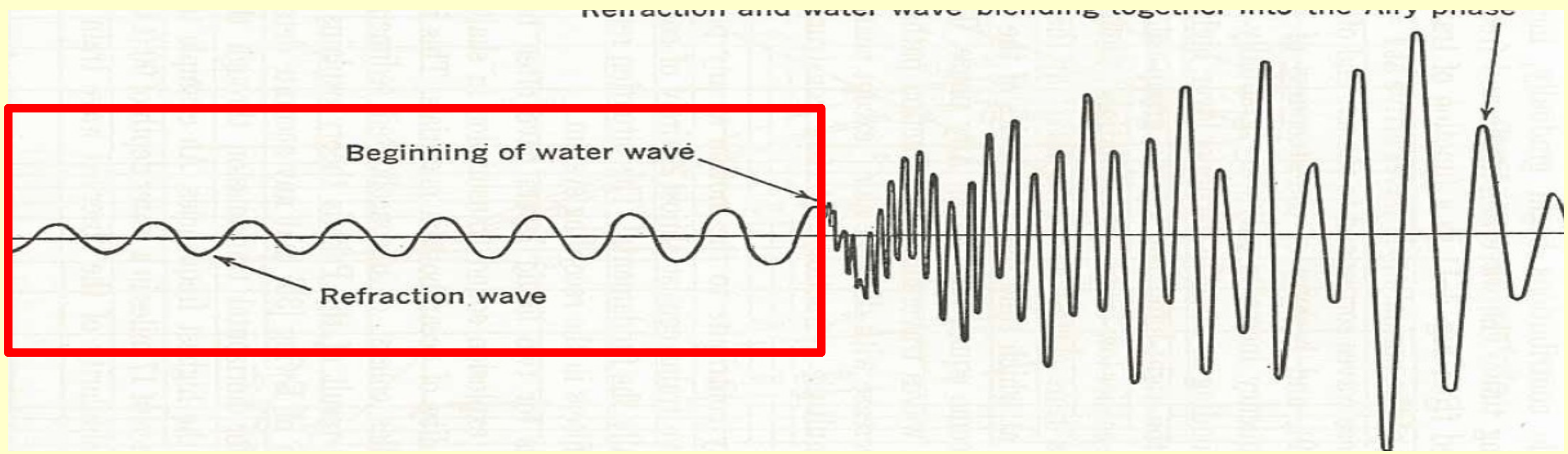
Fluid-solid interface (Press and Ewing, 1950)

$$\tan kH\sqrt{\frac{c^2}{\alpha_1^2}-1}=\frac{\rho_2\beta_2^4}{\rho_1 c^4}\frac{\sqrt{\frac{c^2}{\alpha_1^2}-1}}{\sqrt{1-\frac{c^2}{\alpha_2^2}}}\left[4\sqrt{1-\frac{c^2}{\alpha_2^2}}\sqrt{1-\frac{c^2}{\beta_2^2}}-(2-\frac{c^2}{\beta_2^2})^2\right]$$

$$\beta_2/c<<1$$

$$\tan kH\sqrt{\frac{c^2}{\alpha_1^2}-1}\approx-\frac{\rho_2}{\rho_1}\frac{\sqrt{\frac{c^2}{\alpha_1^2}-1}}{\sqrt{1-\frac{c^2}{\alpha_2^2}}}\left[1-i4\sqrt{1-\frac{c^2}{\alpha_2^2}}\frac{\beta_2^3}{c^3}\right]$$

The refracted wave

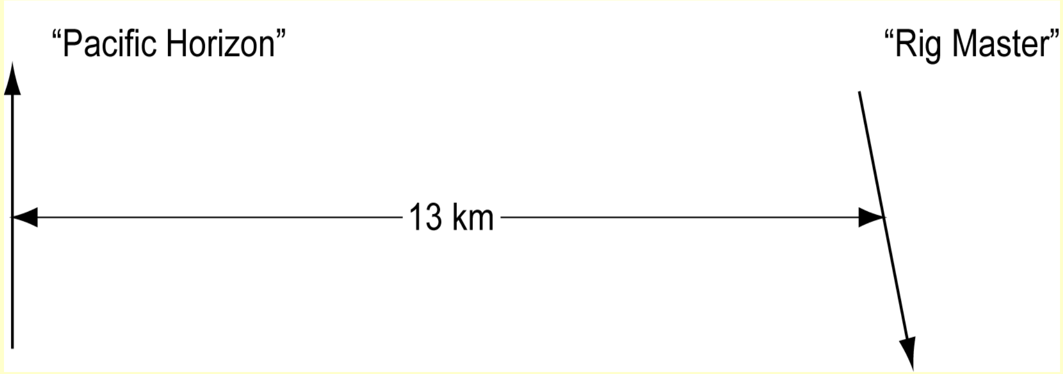


This wave is close to monochromatic – can we estimate the frequency?

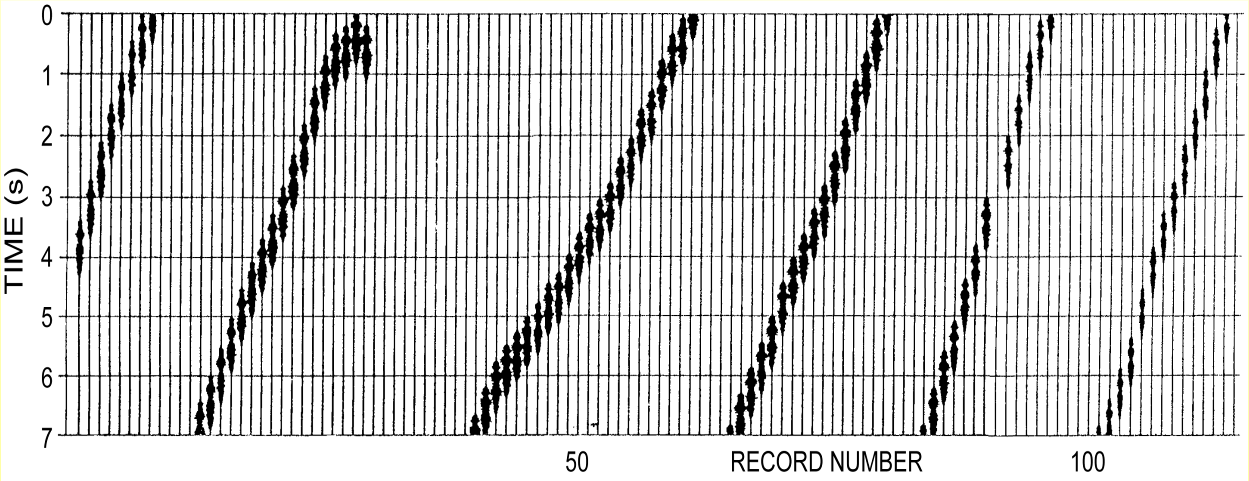
Assuming a phase velocity close to that of the second layer, we find from the period equation:

$$k_n H \approx (2n-1)\frac{\pi}{2\sqrt{\frac{\alpha_2^2}{\alpha_1^2}-1}} \quad \Rightarrow \quad f_n = \frac{(2n-1)\alpha_1\alpha_2}{4H\sqrt{\alpha_2^2-\alpha_1^2}}$$

Data acquisition



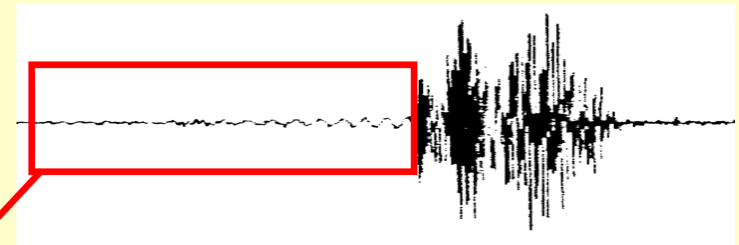
Data acquired by M/V Rig Master February 1989 in the Ekofisk area, North Sea. Part of the "Marine Seismic Noise" project performed by Seres in 1989.

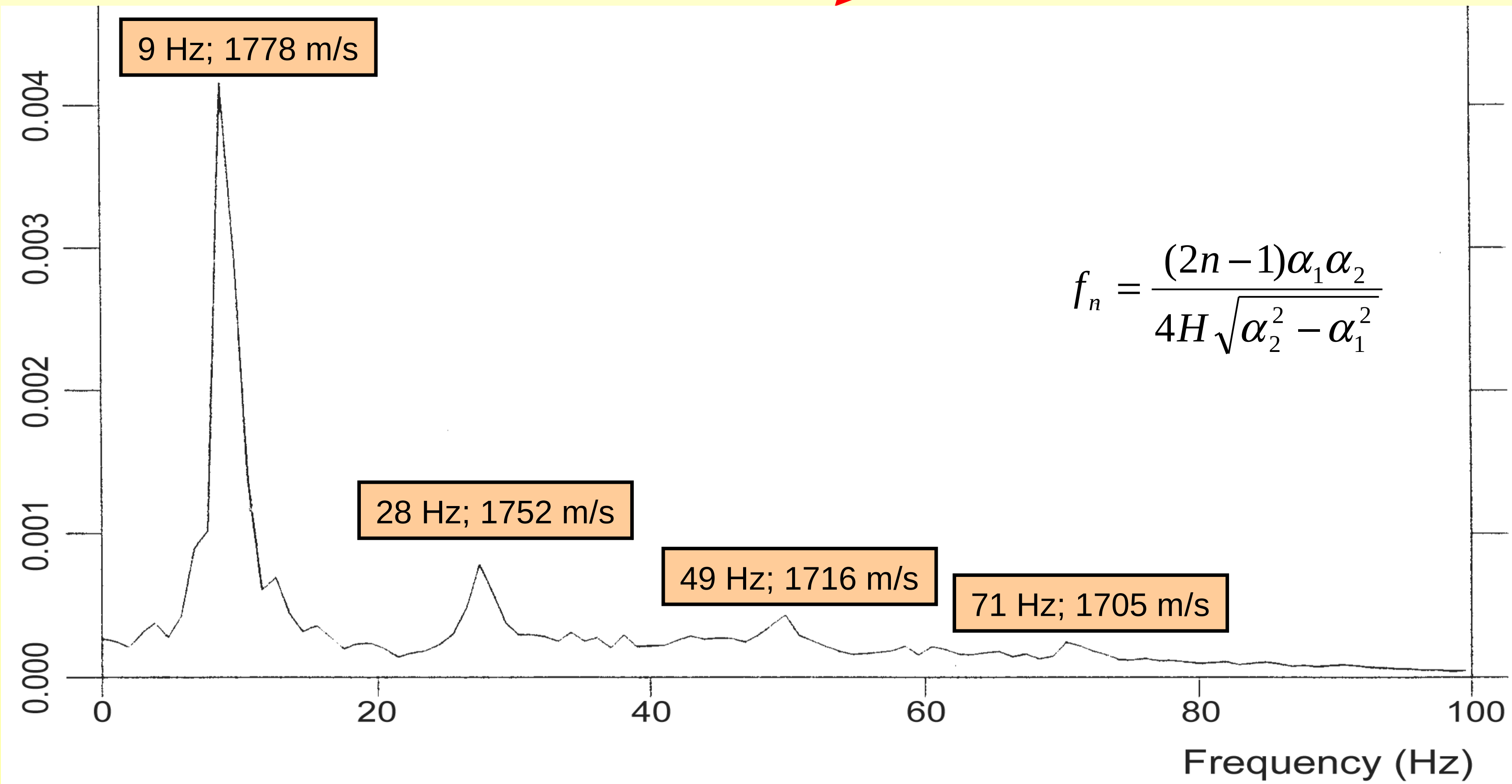


113 records of the mid-streamer trace

Ref.: Seismic interference noise recorded by M/V Rig Master, by M. Landrø and S. Vaage, 1989

Refraction wave => estimates of α_2

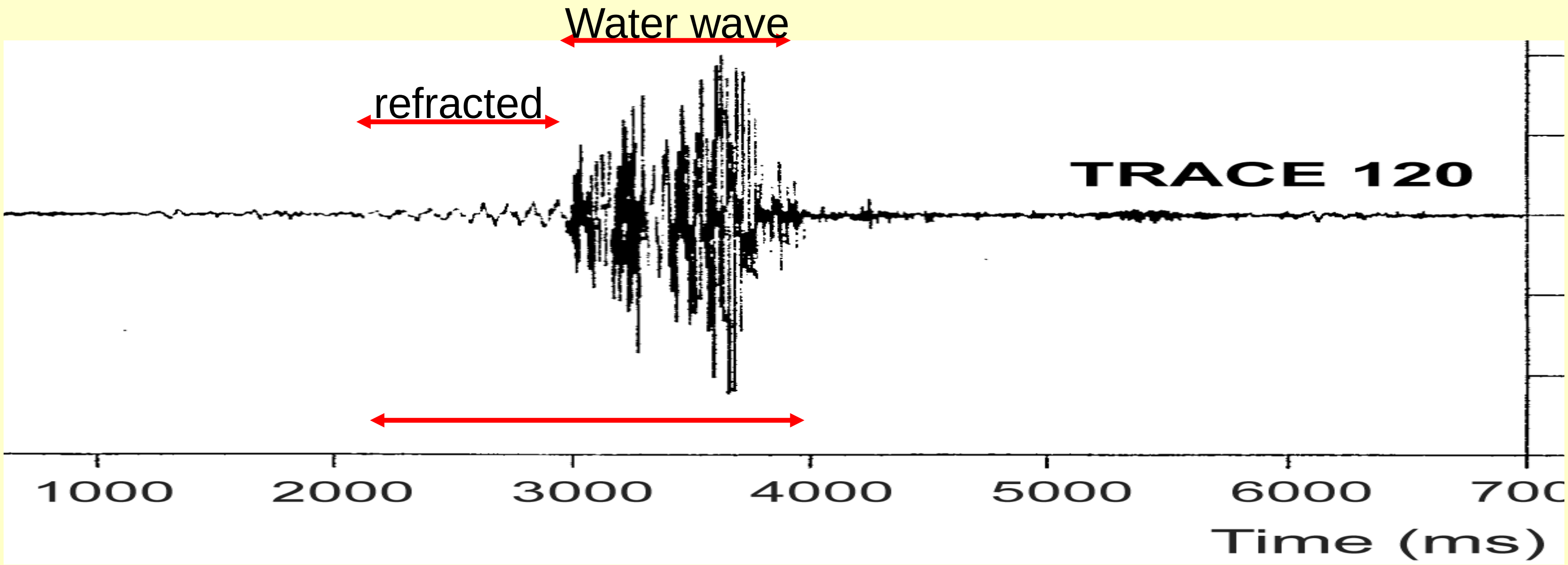




$$f_n = \frac{(2n-1)\alpha_1\alpha_2}{4H\sqrt{\alpha_2^2-\alpha_1^2}}$$

Low frequencies see ”deeper” into earth => velocity decrease with frequency

Comparing traveltimes



Direct wave thorugh water: $t_D = \frac{s}{\alpha_1}$

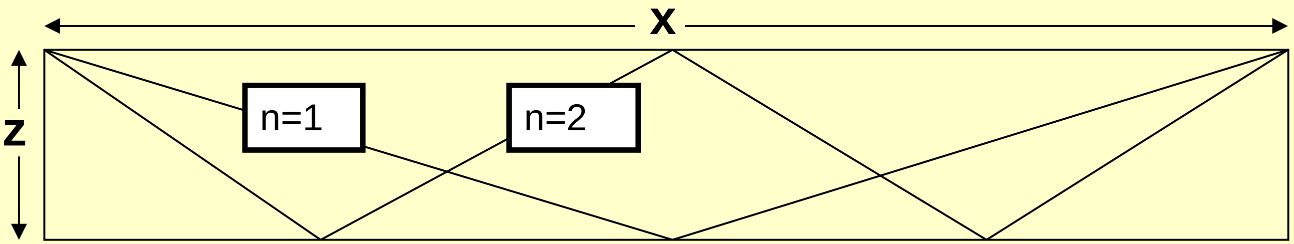
Arrival of critical reflections: $t_C = \frac{s\alpha_2}{\alpha_1^2}$

Duration of water wave: $\Delta t_W = \frac{s\alpha_2}{\alpha_1^2} - \frac{s}{\alpha_1} \approx 1.41s$

Refracted wave: $t_R = \frac{s}{\alpha_2} + \frac{2H\sqrt{\alpha_2^2 - \alpha_1^2}}{\alpha_1\alpha_2}$

Duration of interference noise: $\Delta t_{IN} = t_C - t_R = 2.6s$

Simple raytracing considerations – water wave

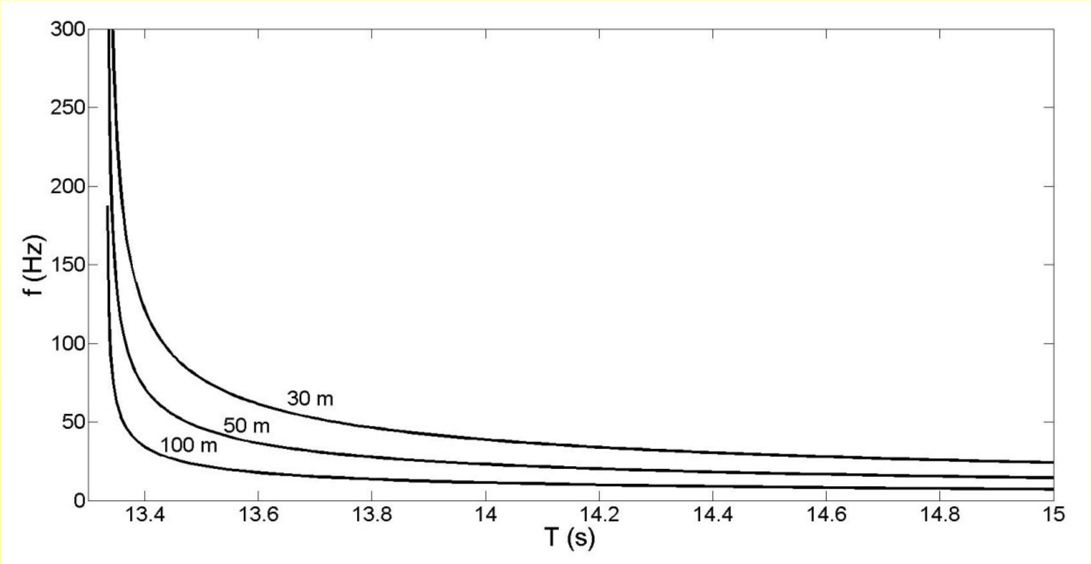


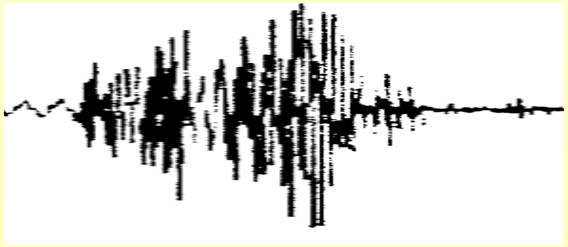
$$R_n = \sqrt{x^2 + 4n^2 z^2}$$

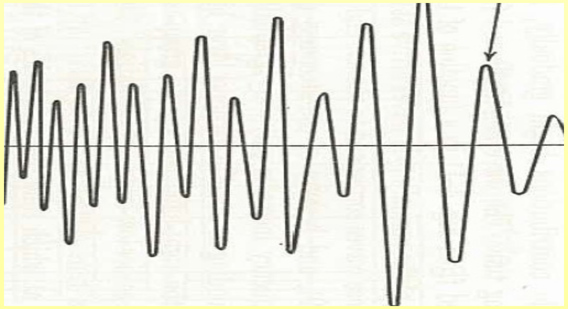
Characteristic frequency between two bounces:

$$f_n = \frac{1}{T_{n+2} - T_n} = \frac{\alpha_1}{R_{n+2} - R_n}$$

Assuming that x >> z: $f_n \approx \frac{\alpha_1 x}{8(n+1)z^2}$ and $T_n = \frac{R_n}{\alpha_1}$

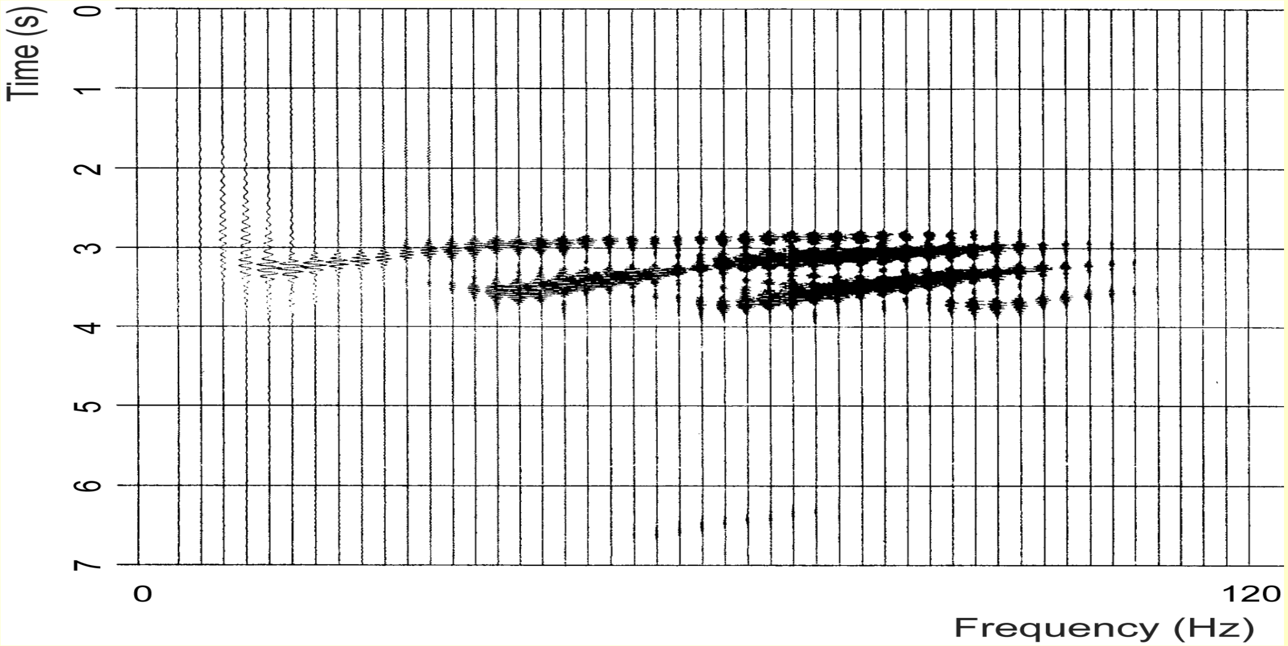




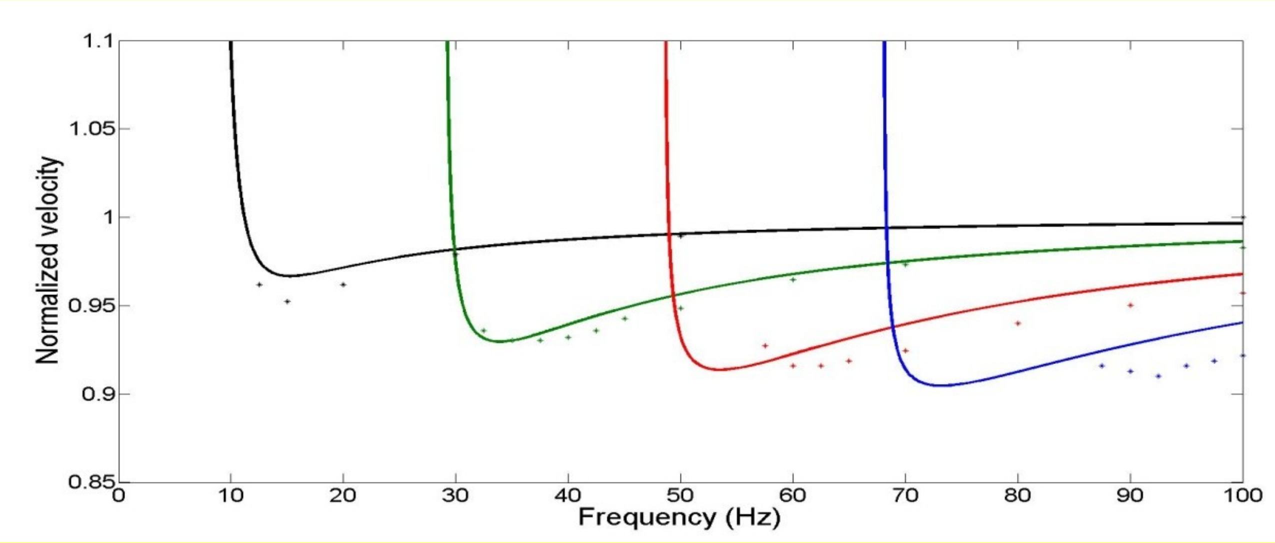


Frequency content of water wave decreases with increasing recording time

Observation of normal modes

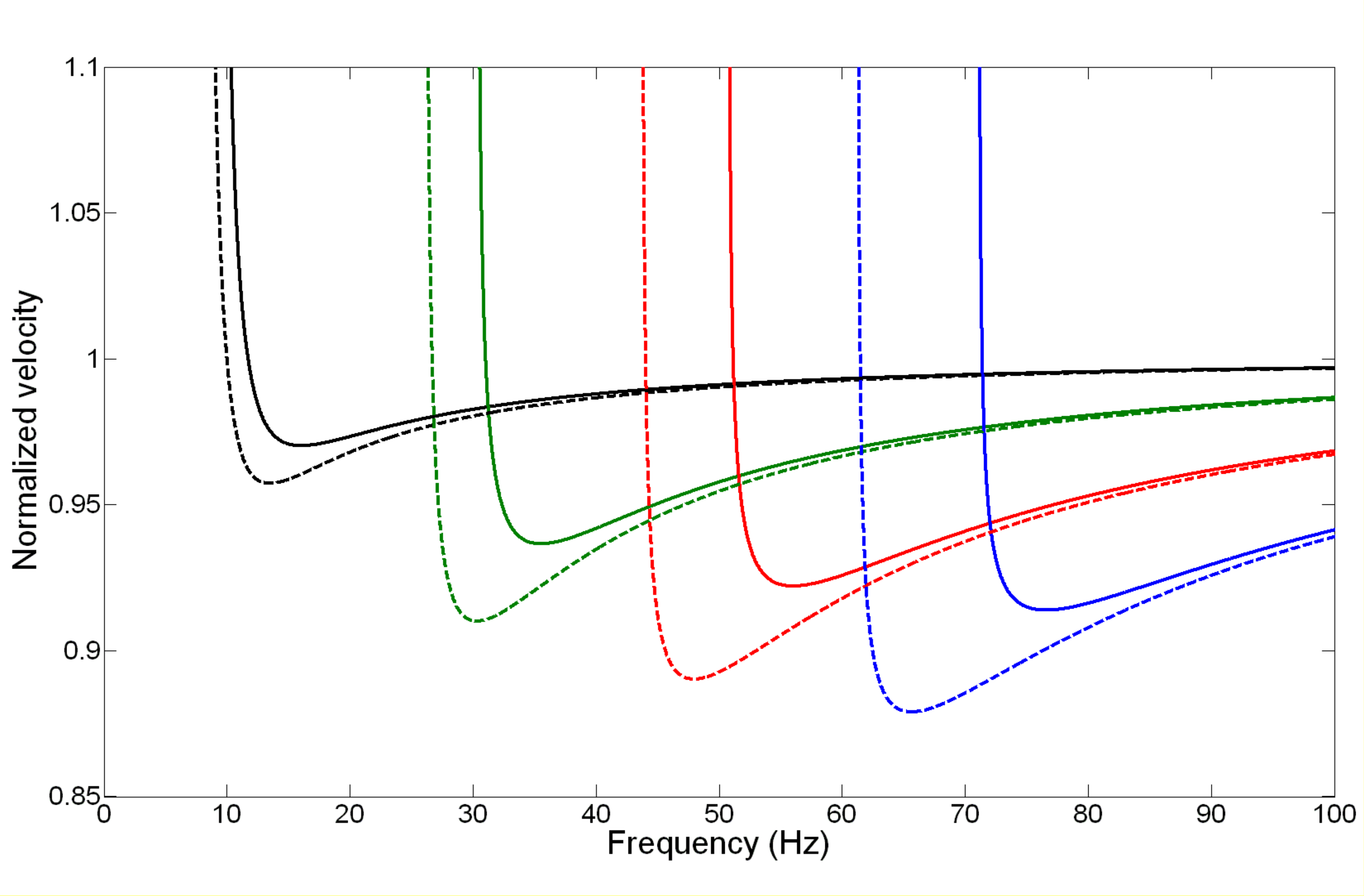


4 modes interpreted – assumping that the trends represent group velocity – hard to see phase velocity on this plot

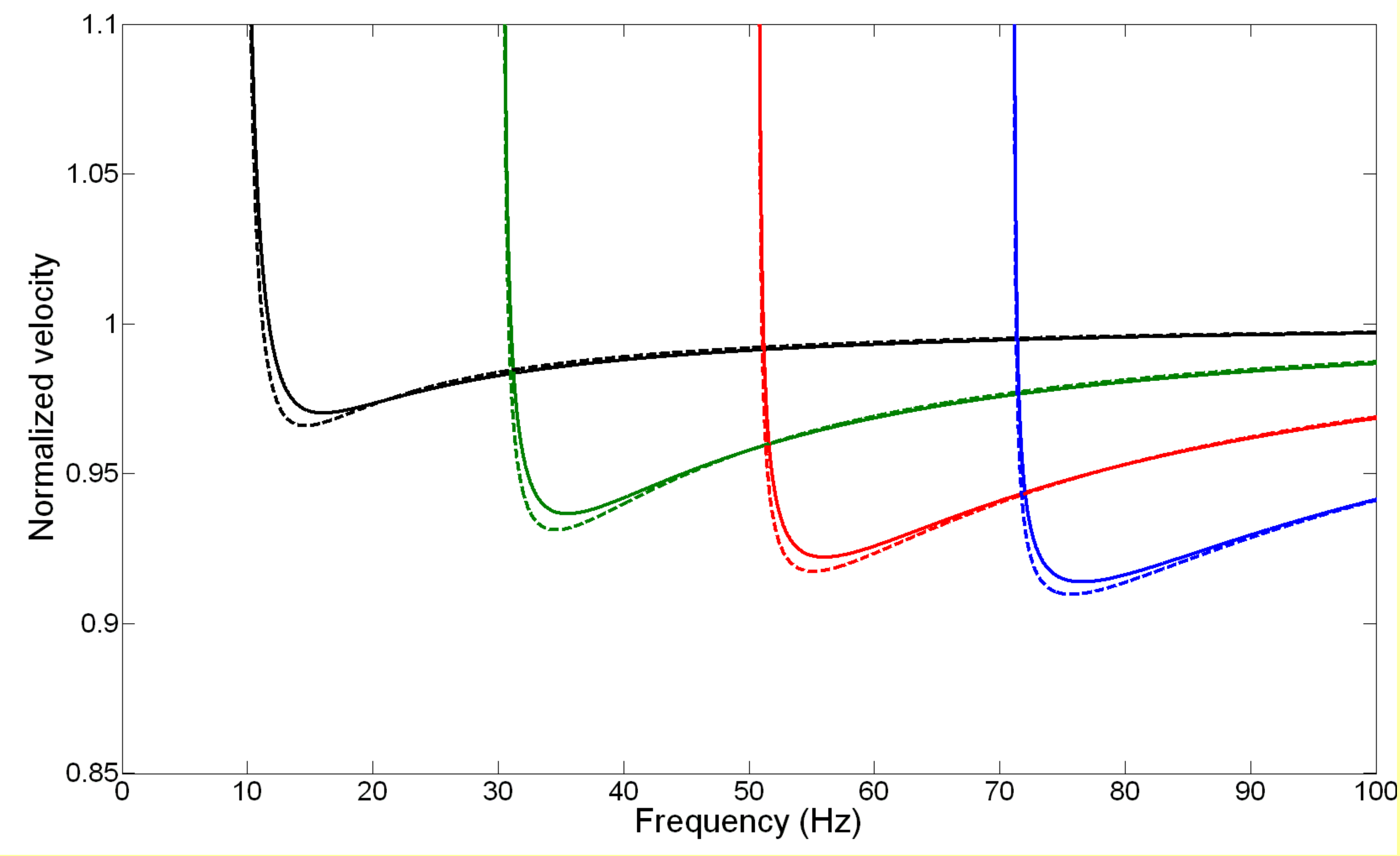


Modeling of 4 first modes assuming v2=1725 m/s and a density ratio of 1.8. Dots represent **group** velocity estimates from top figure

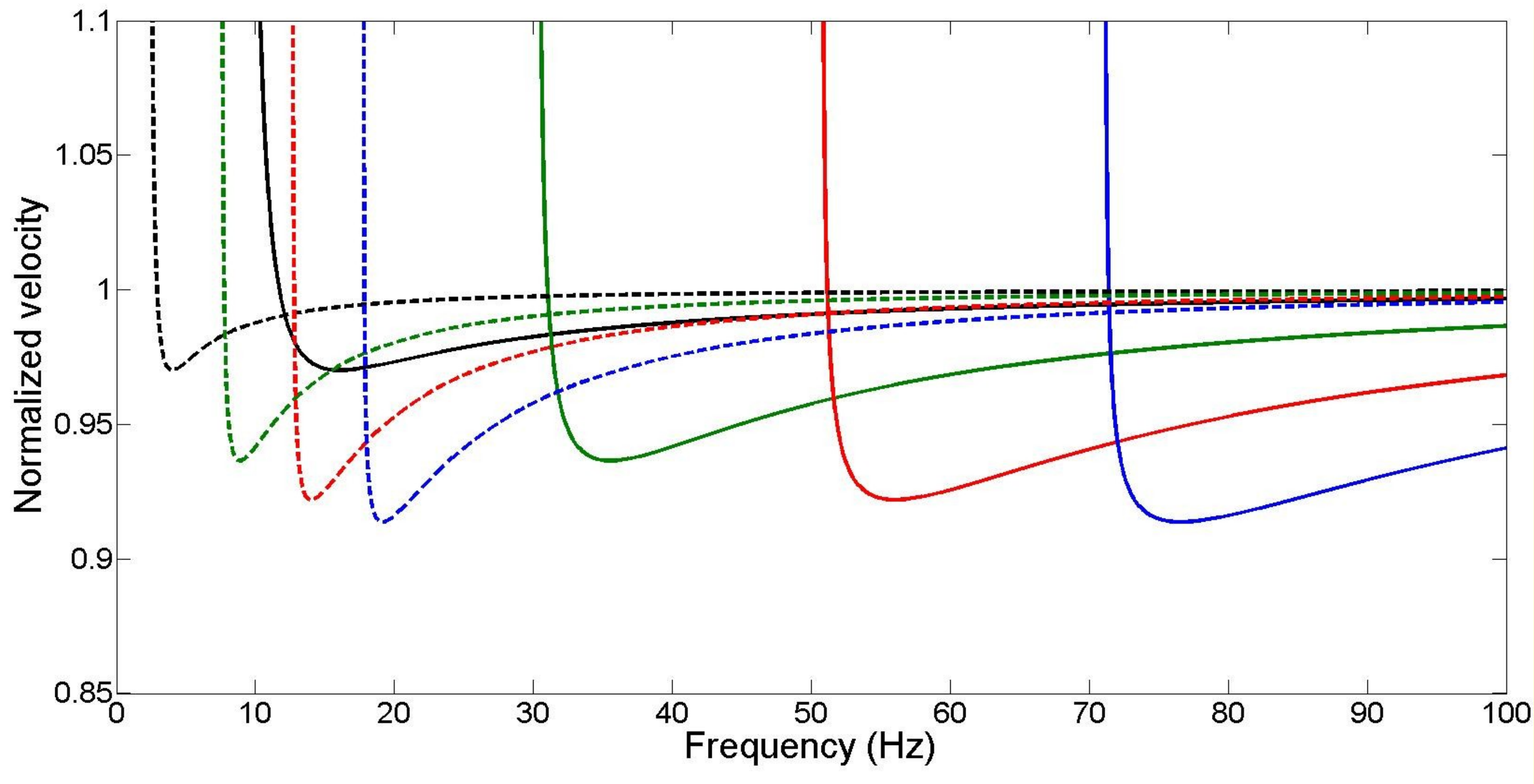
Effect of velocity change in layer 2 from 1700 m/s (solid) to 1800 m/s (dashed)



Effect of density change in layer 2 from 1.8 (solid) to 2.2 (dashed)



Effect of changing the water depth from 75 (solid) to 300 m (dashed)



Conclusions

- **4 normal modes interpreted at 13 km offset data from Ekofisk**
- **Group velocity versus frequency observations fit well with theory**
- **No clear observations of phase velocity versus frequency**
- **Frequency analysis of refraction wave shows 4 distinct peaks corresponding to slightly decreasing velocities of second layer**

Future work

- Include field data for various water depths
- Explore possibilities for 4D analysis of near seabed effects
- Explore possibilities for estimating variations in water velocities (4D calibration of time shifts)

Acknowledgments

- PGS (Seres) for permission to use the data

- NFR for financial support to the ROSE project at NTNU