Sonic Boom Penetration Under a Wavy Air-Water Interface

H.K. Cheng
Univ. Southern California, Los Angeles

Adam Fincham
LEGI-CNRS, Grenoble, France

C.J. Lee
Applied Sciences Laboratories, Inc. Hacienda Height, CA

Tony Maxworthy
Univ. Southern California, Los Angeles

John R. Edwards
Space & Missile Systems Center, Los Angeles AFB

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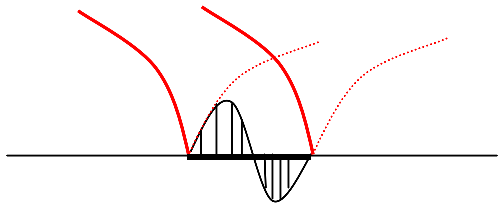
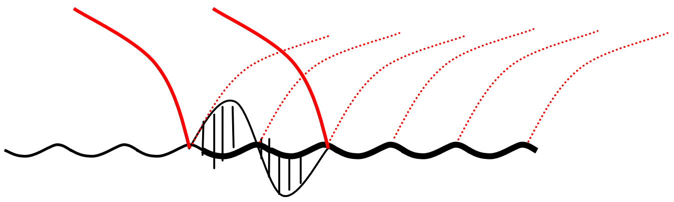
Underwater Acoustics in a moving frame:
Distinct difference between wavy and non-wavy interfaces

Sonic Boom over Flat Ocean (Sawyers model 1968)



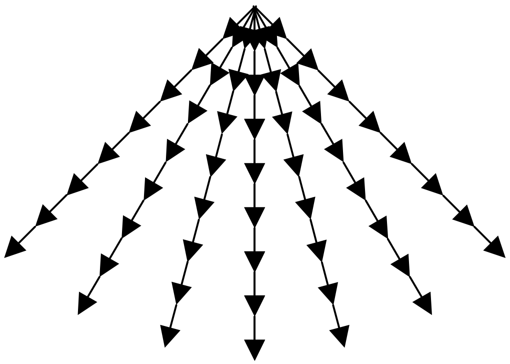
Source in **steady state**

Sonic Boom over Wavy Ocean (Cheng and Lee 2000)



Additional **time-dependant** source produced by wavy surface interaction

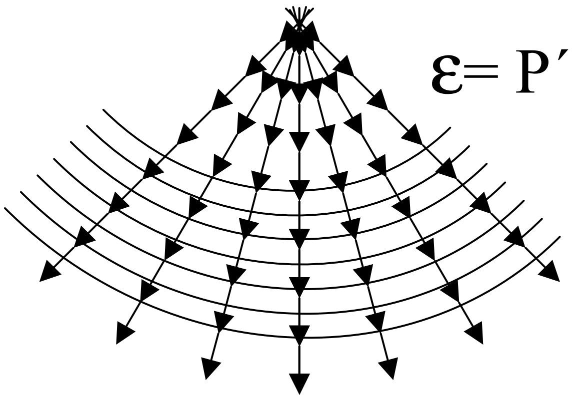
Time independent source



$|P_1| \sim \varepsilon / r$ (source)

$|P_1| \sim \varepsilon / r^2$ (dipole)

Monochromatic acoustic source

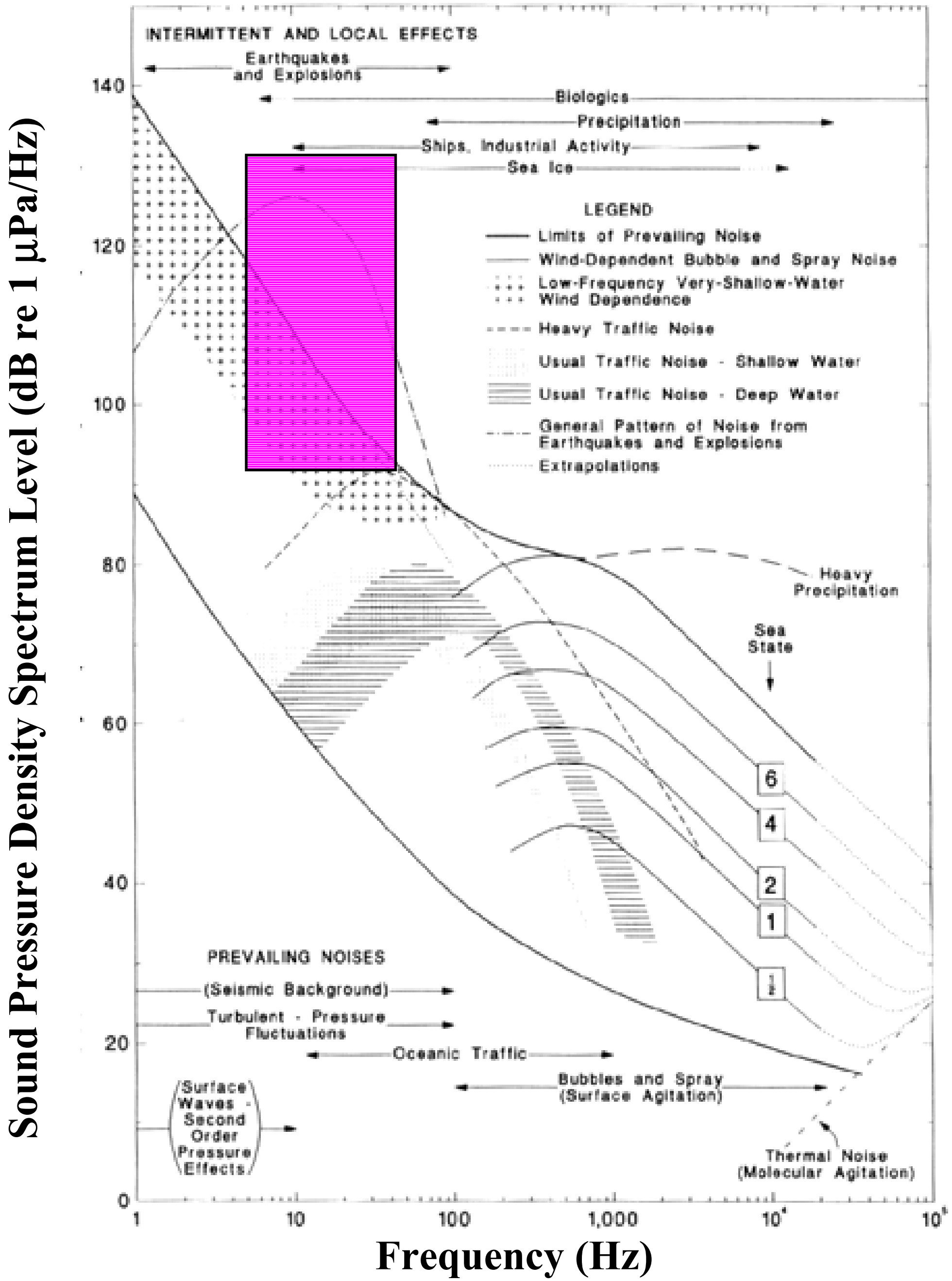


$\varepsilon = P'/P_a$

$P' \sim P_1' + P_2'$

$|P_2'| \sim \varepsilon\delta / r^{1/2}$ (Cylindrical spreading rule)

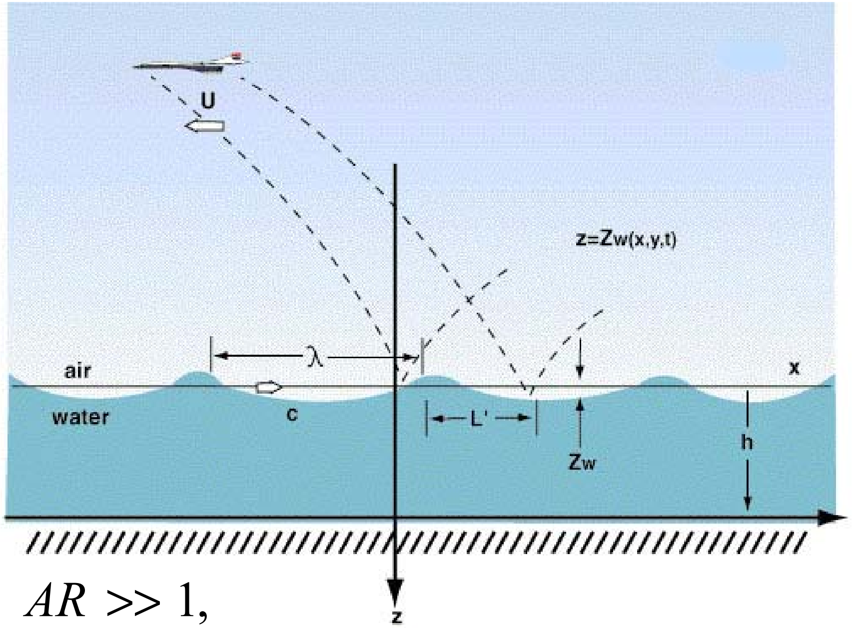
Comparison With Ocean Background Noise



Will the phenomena we are studying be in the frequency and dB range to have an effect on marine animals?

Sonic Boom Noise

REF: Marine Mammals and Noise; W. John Richardson, Charles Green, Jr., Charles I. Malme, & Denis H. Thompson



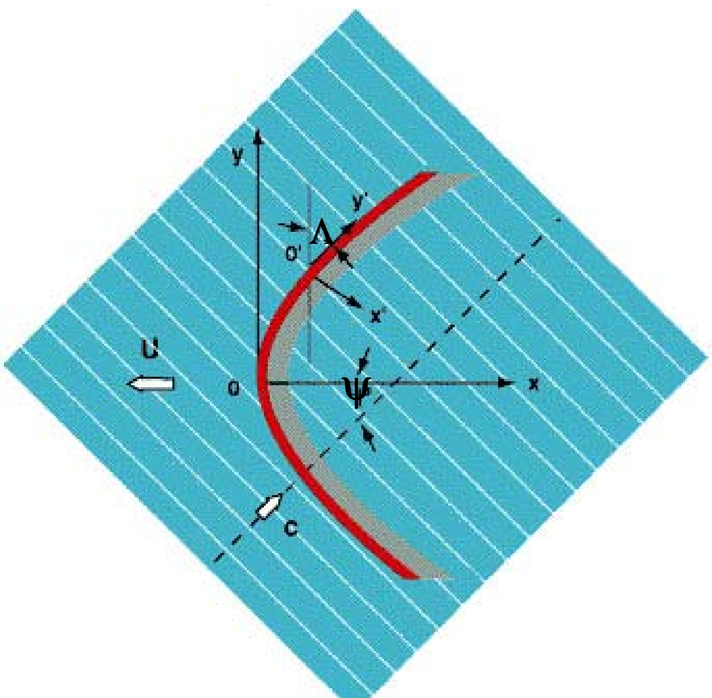
$AR >> 1,$

Model assumptions

$$\frac{\rho_w}{\rho_A} >> 1, \quad \frac{a_w}{a_A} > 1$$

$$1 < M_A < \frac{a_w}{a_A} \sim 4.53,$$

Max wave slope $\quad 2\pi\delta << 1,$



Sinusoidal surface wave train

$$Z_w = \delta\lambda e^{i(k_1 \underline{x} + k_2 \underline{y} - \omega t)}$$

In rest frame

$$Z_w = \delta\lambda e^{i(k_1' x' + k_2' y' - \Omega t)}$$

In moving frame

$$\Omega \equiv k(\overline{u}\cos\psi + c)$$

$$p' = p_1'(x,z) + p_2'(x,z,t)$$

Sawyers Flat Ocean $O(\varepsilon)$

Time-Dependent Disturbances, $O(\varepsilon\delta)$
Produced by interaction with Wavy Surface

Near field

$$p_1' = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{p'(x_1,0)\,dx_1}{(x_1-x)-i\bar{z}}$$

$$p_2' = \hat{p}_2(x,\bar{z})e^{-i\Omega t}$$

$$= \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} A(\xi)e^{i[\xi_1 x' + k_2' y' + \xi_3 \bar{z}' - \Omega t]}d\xi$$

$$\xi_3 = \xi_3(\xi_1, \Omega, k_2')$$

Far field (deep water)

$$p_1' \approx O\frac{\varepsilon}{|\bar{z}|^2}$$

$$p_2' \approx const\,\frac{A(\xi_*)e^{i[\xi_* x + \xi_3(\xi_*,\Omega)\bar{z}' - kt]}}{(1+\eta^2)^{3/4}}\frac{1}{\sqrt{\bar{z}}}$$

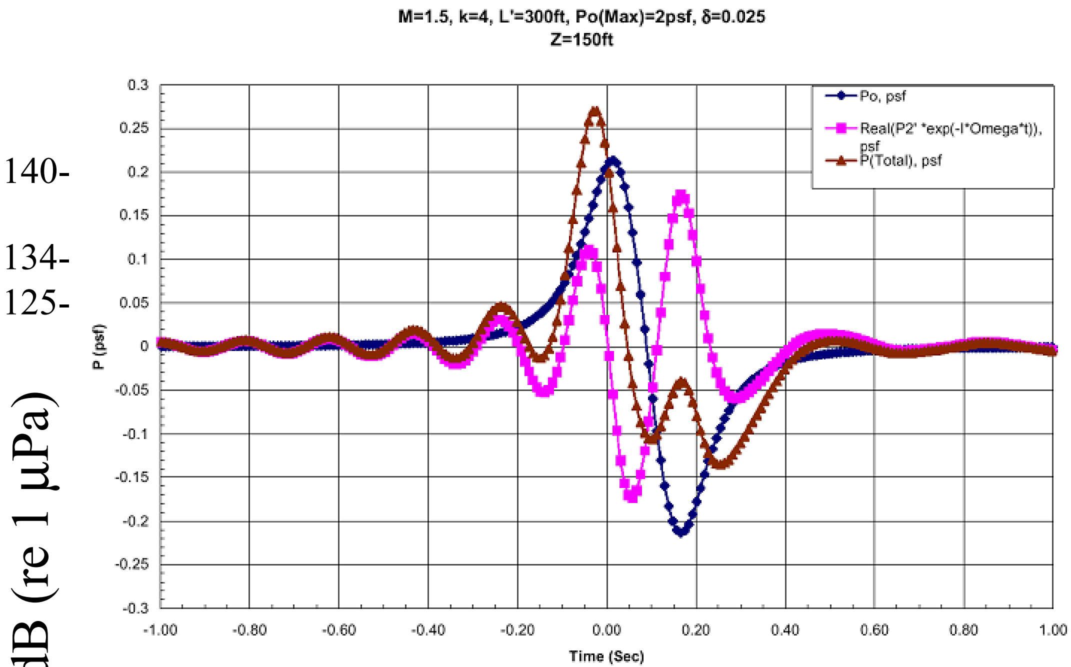
$$\approx O\left(\frac{\in\delta}{\sqrt{\bar{z}}}\right) \qquad \xi_* = \xi_*(\eta), \quad \eta = \frac{x}{\bar{z}}$$

Packet of Wavelets

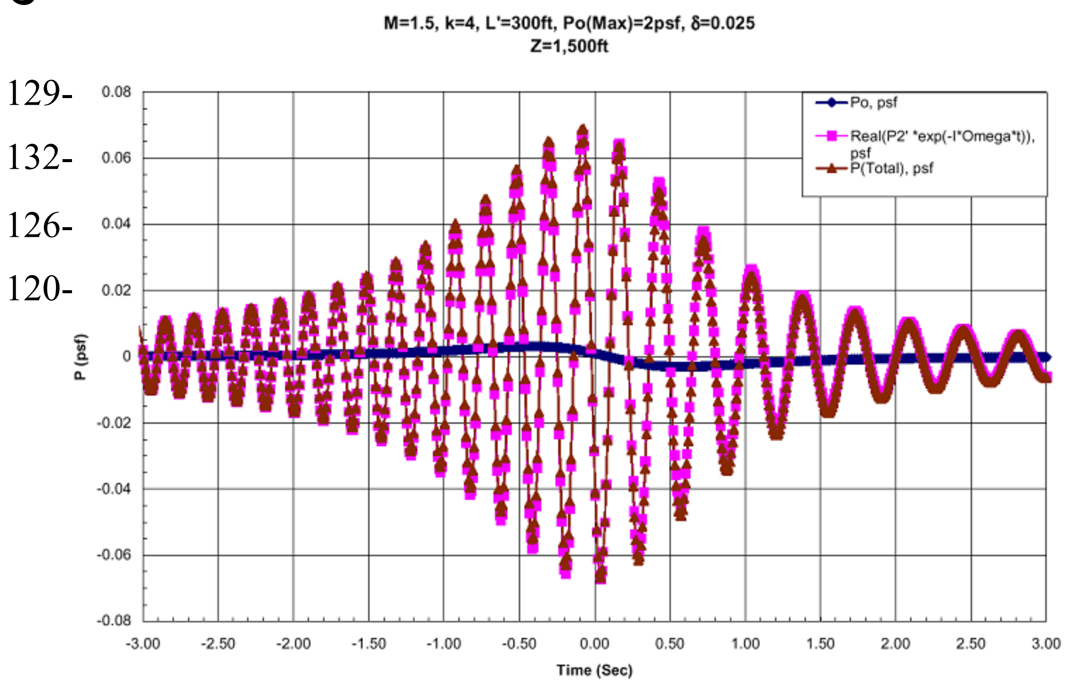
@ fixed z: Wave number and frequency varies slowly

@ fixed η: Wave number and frequency remain invariant

Numerical solution for typical ocean parameters



100 meters depth



500 meters depth

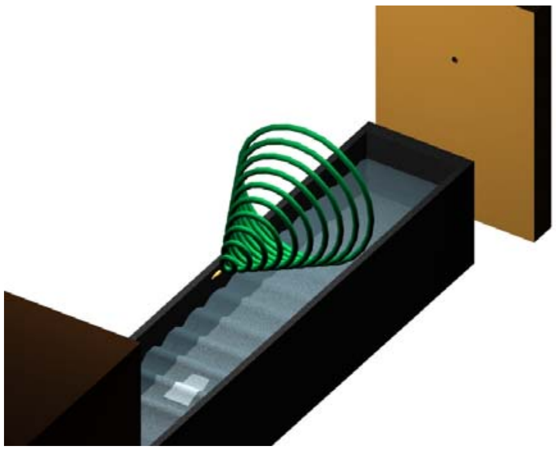
Laboratory study

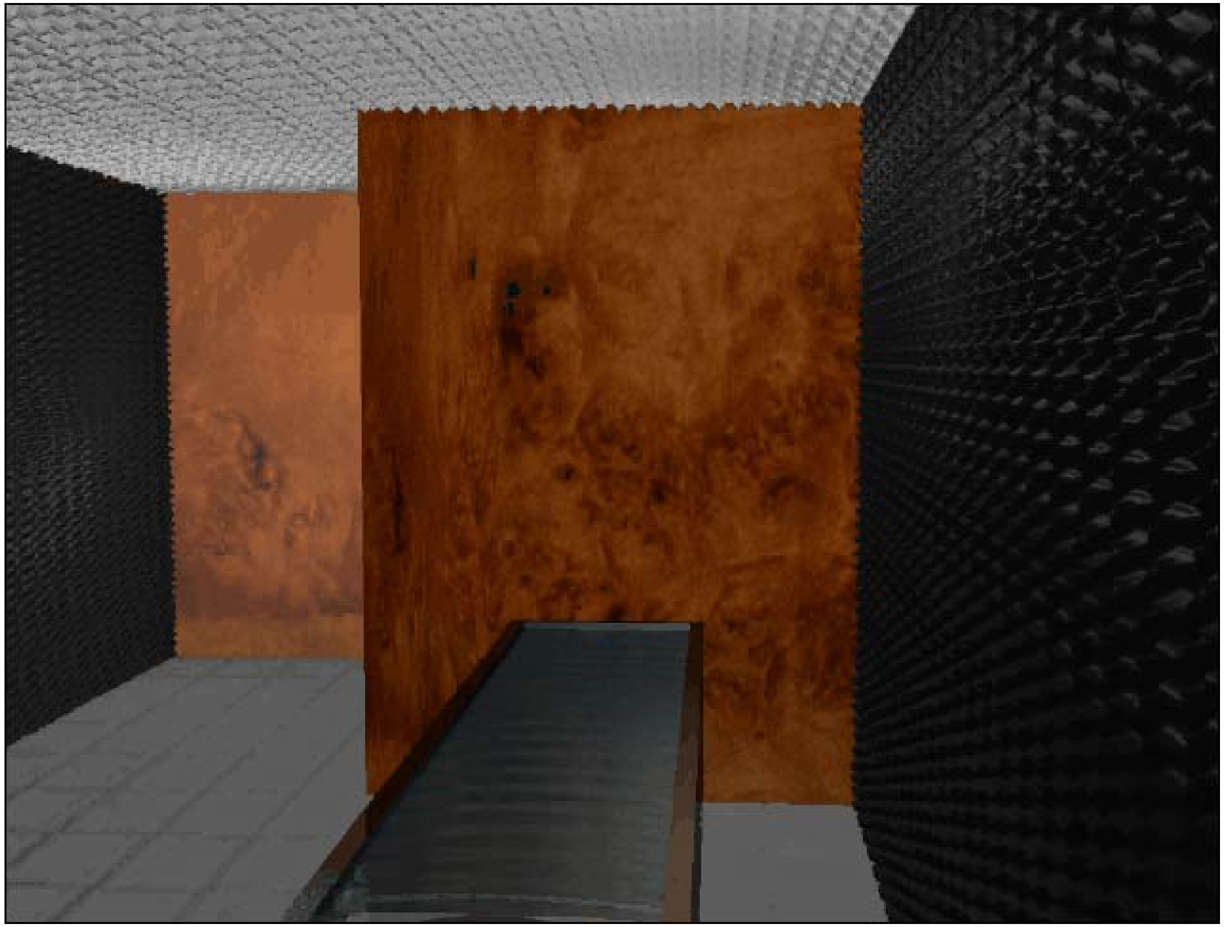
Motivation: Cheng, H. K. and Lee, C. J. (2000) Theoretical and Numerical study

Primary Objective: To answer basic question,

"Can we detect the difference between a wavy and flat surface?"

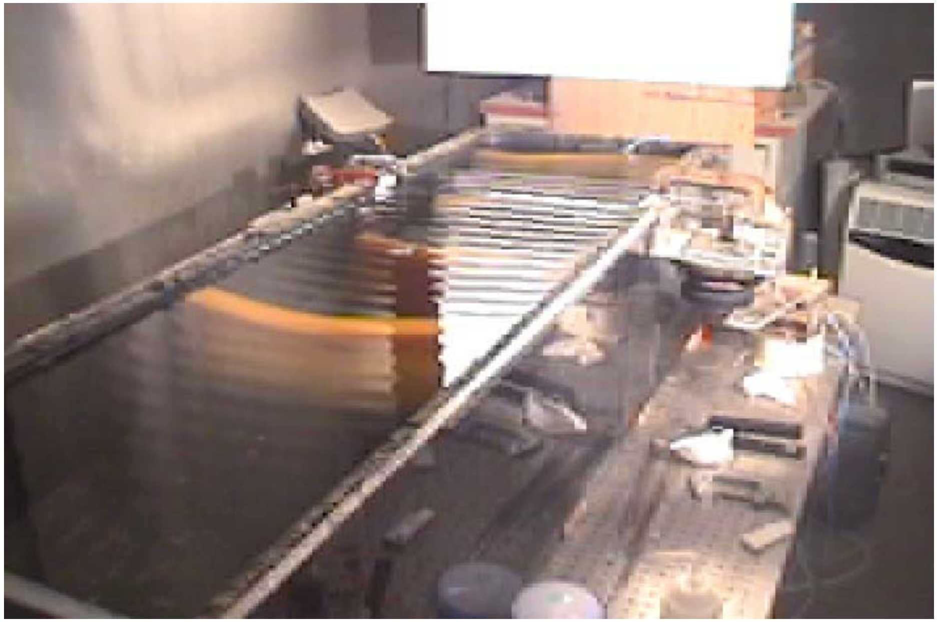
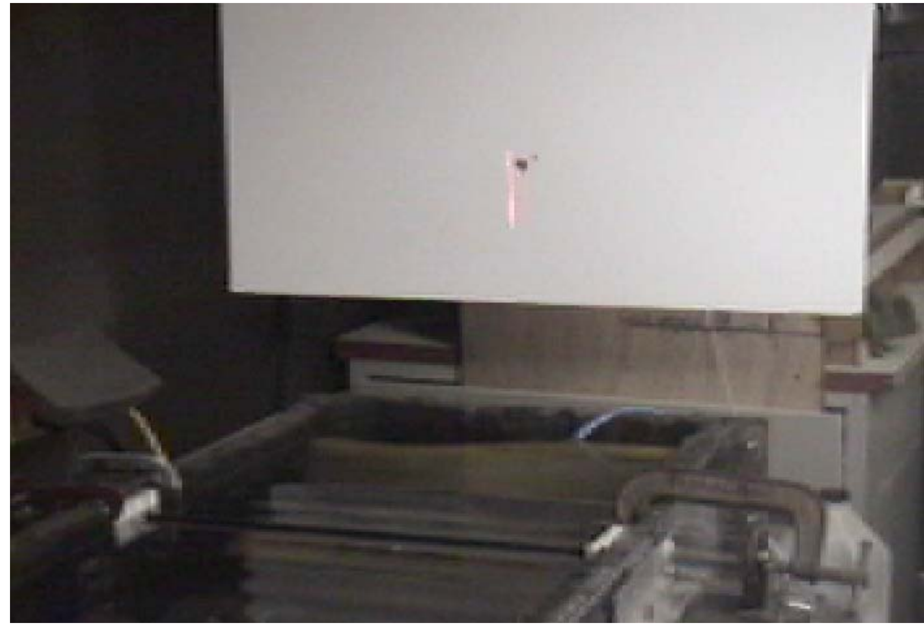
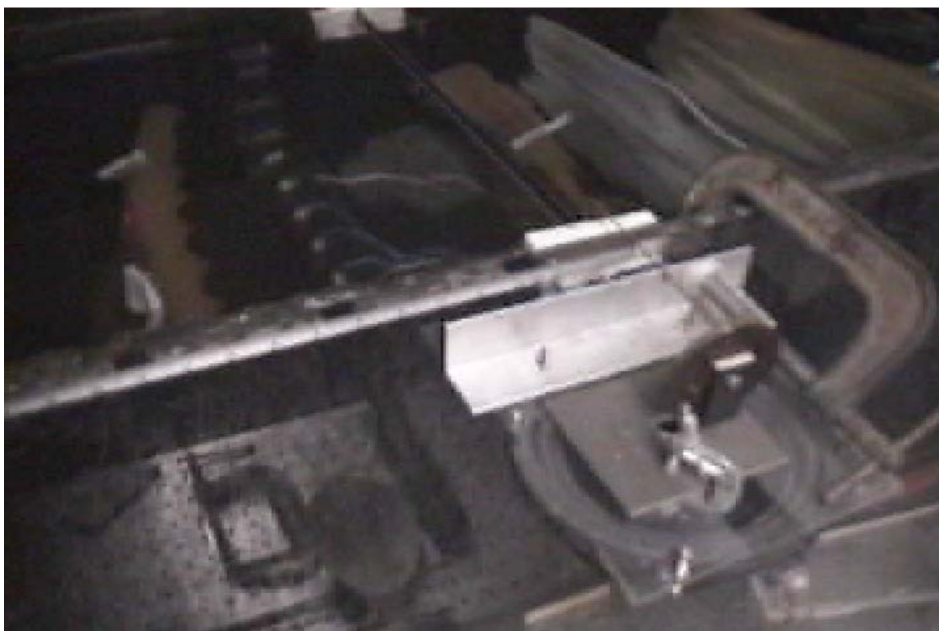
Method: Experimental Laboratory study

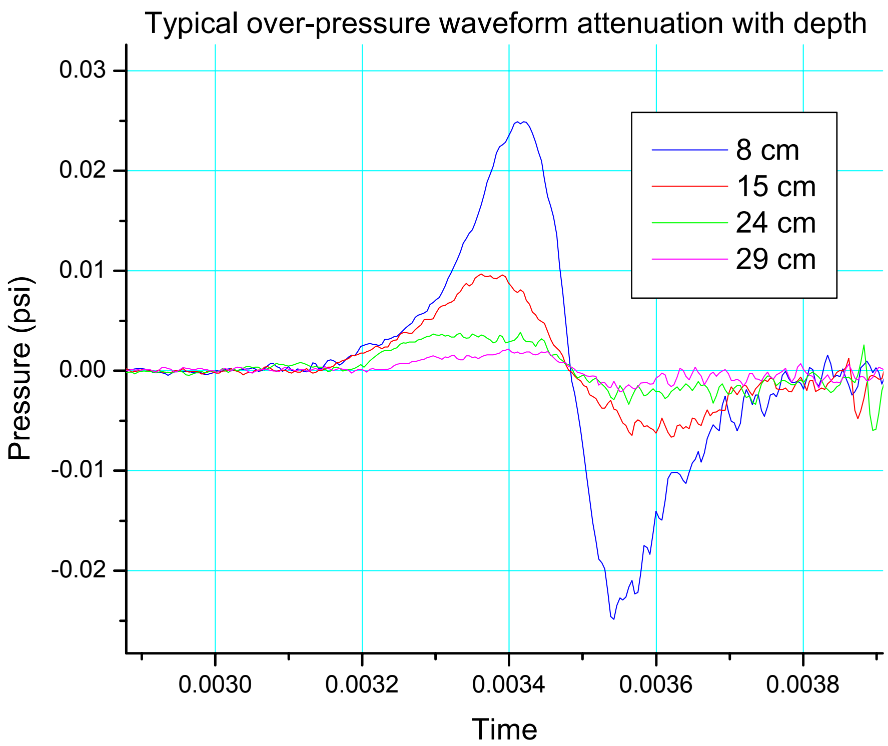


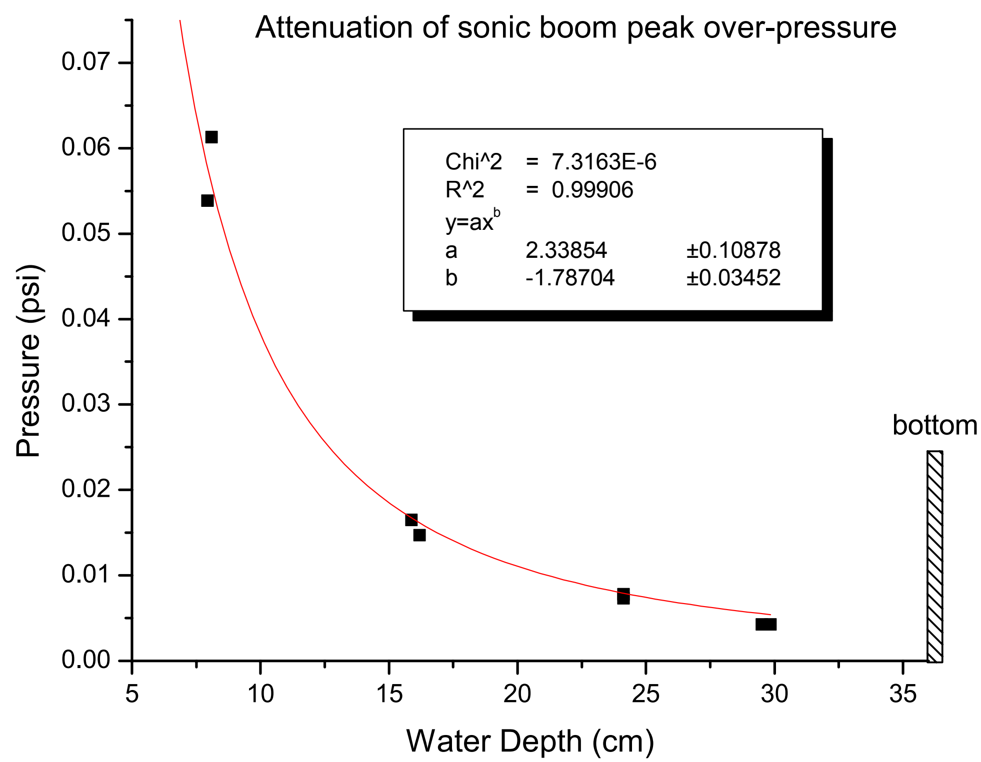


Lab setup

(approximate scale)



Measured flat water peak over-pressure attenuation

$$|P_1| \sim \varepsilon / r^2$$

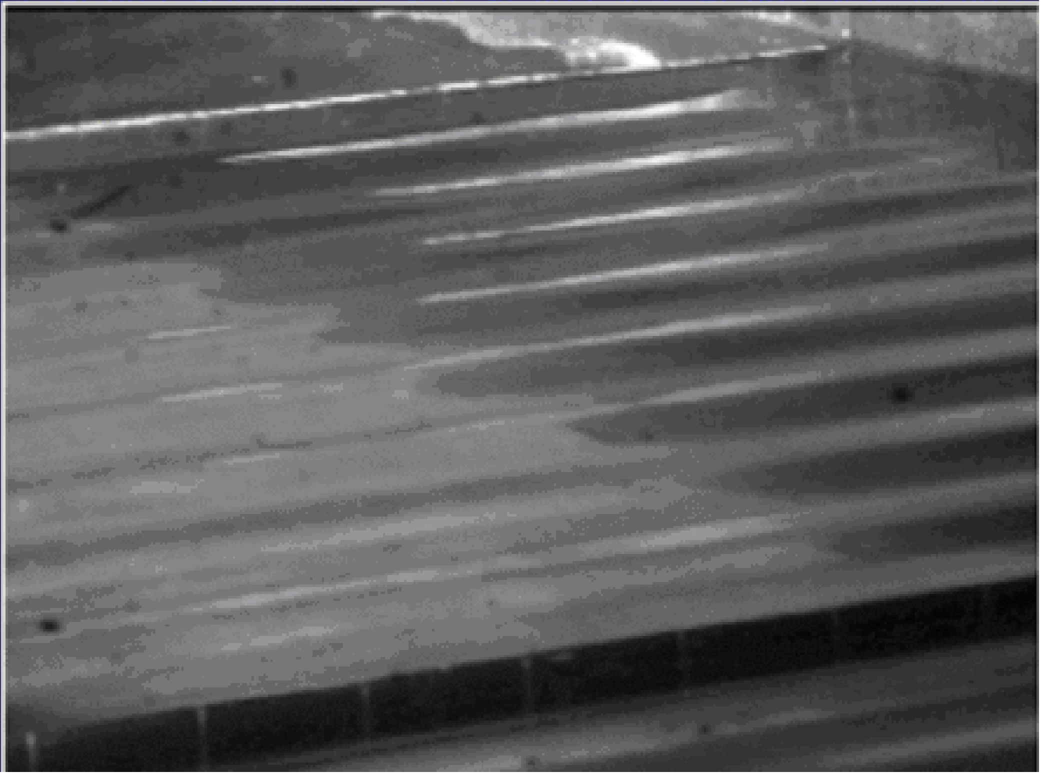
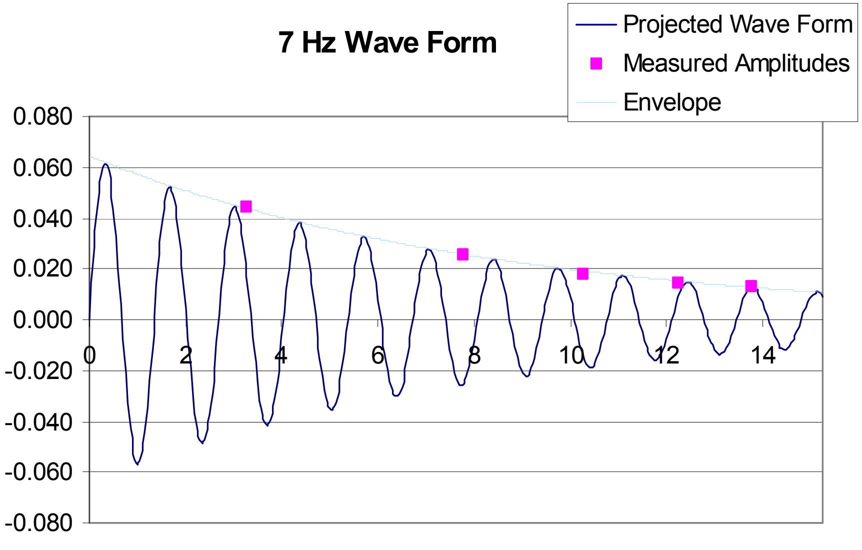
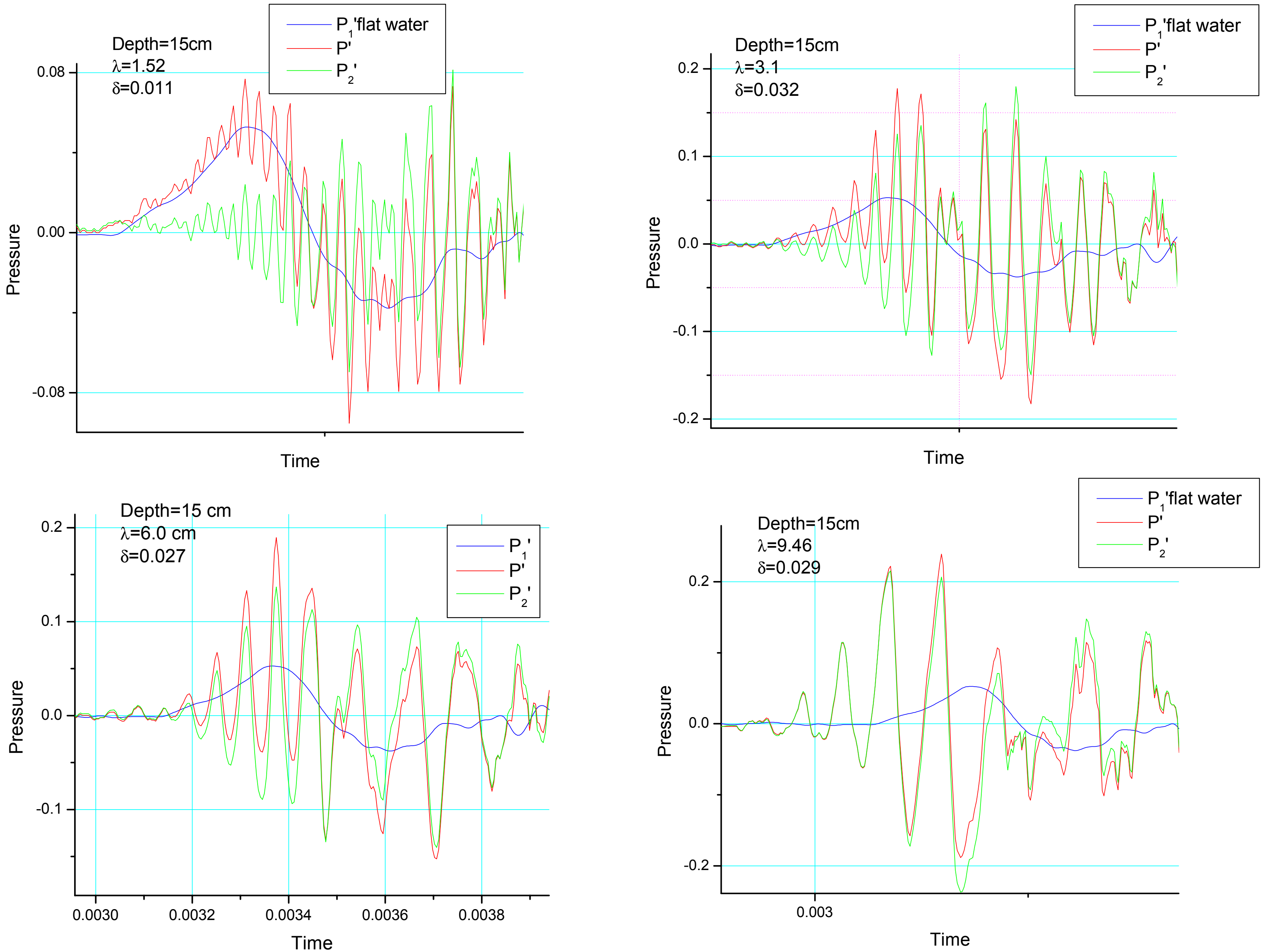


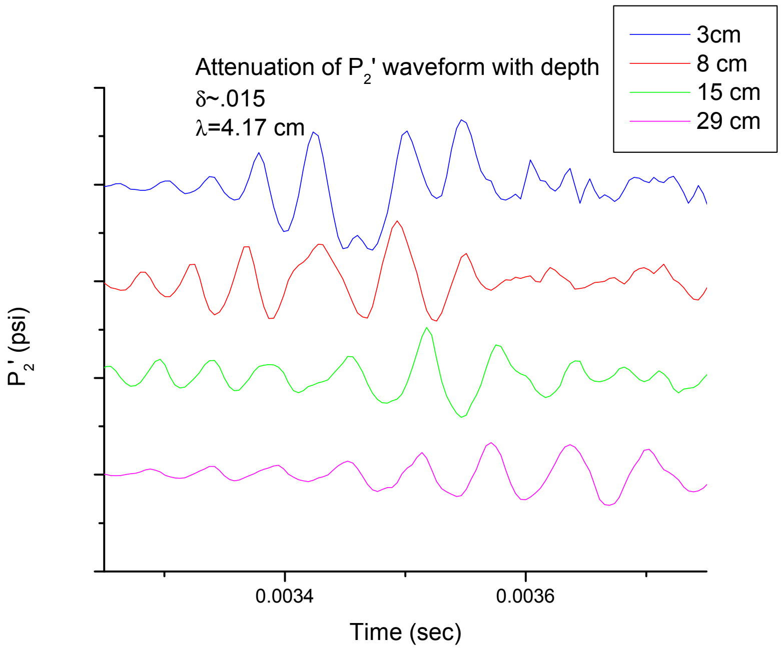
Image of a typical laboratory generated surface wave field



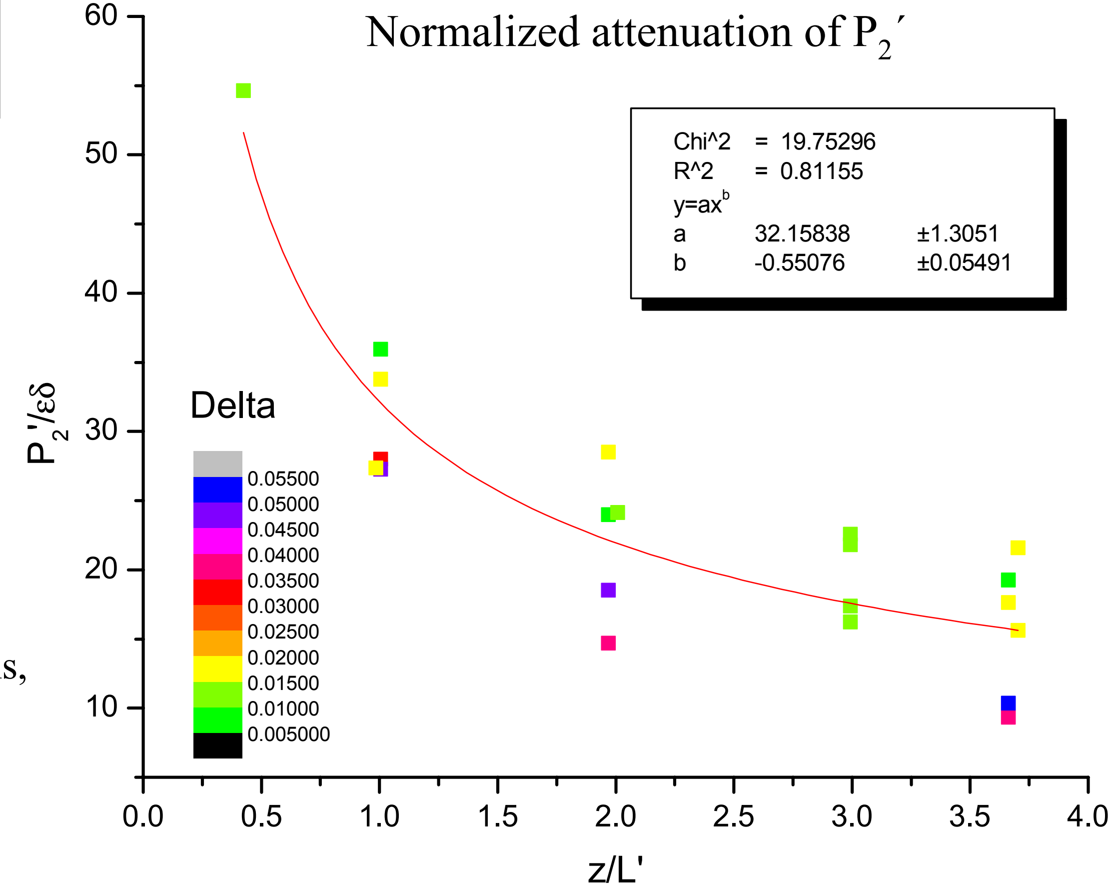
Surface wave height decay away from the paddle



Data for some different experimental conditions

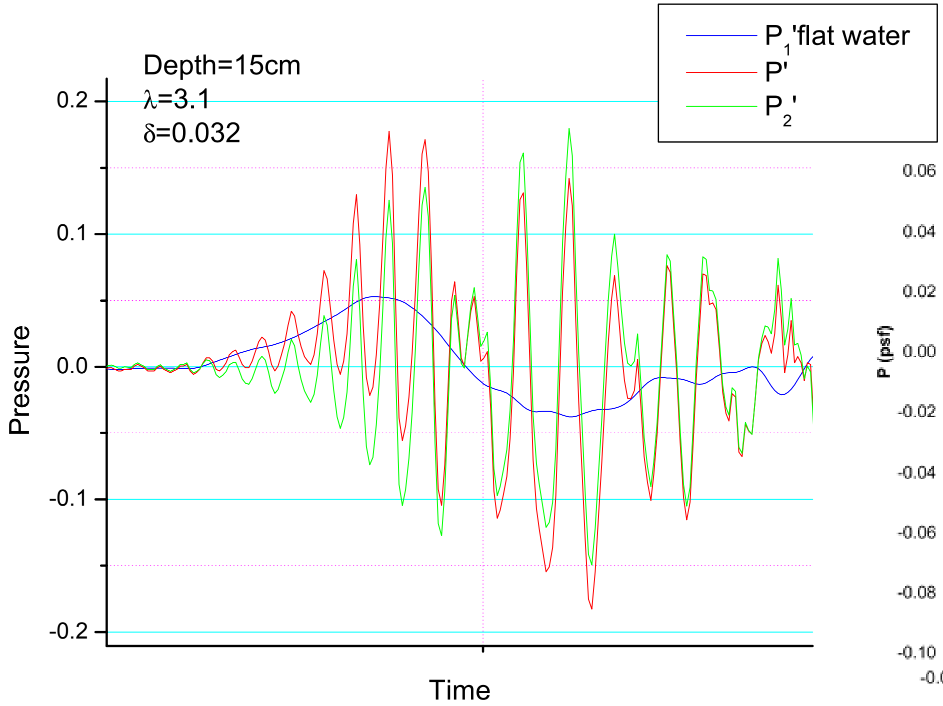


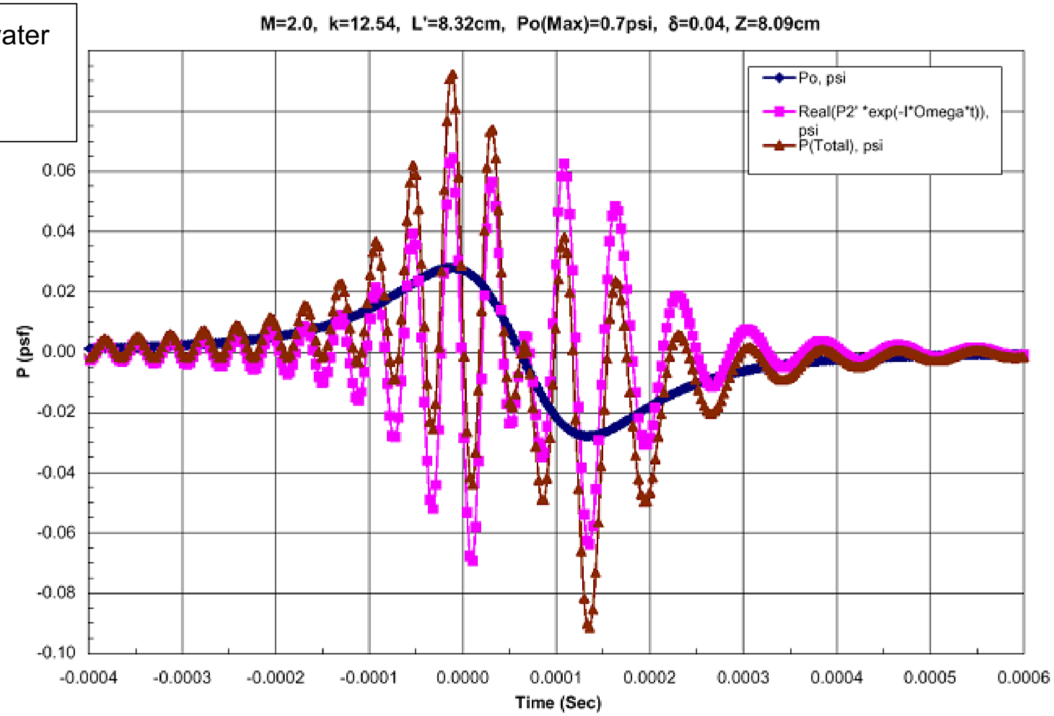
Pressure time traces of P_2' for 4 different depths, data offset .05 psi in y



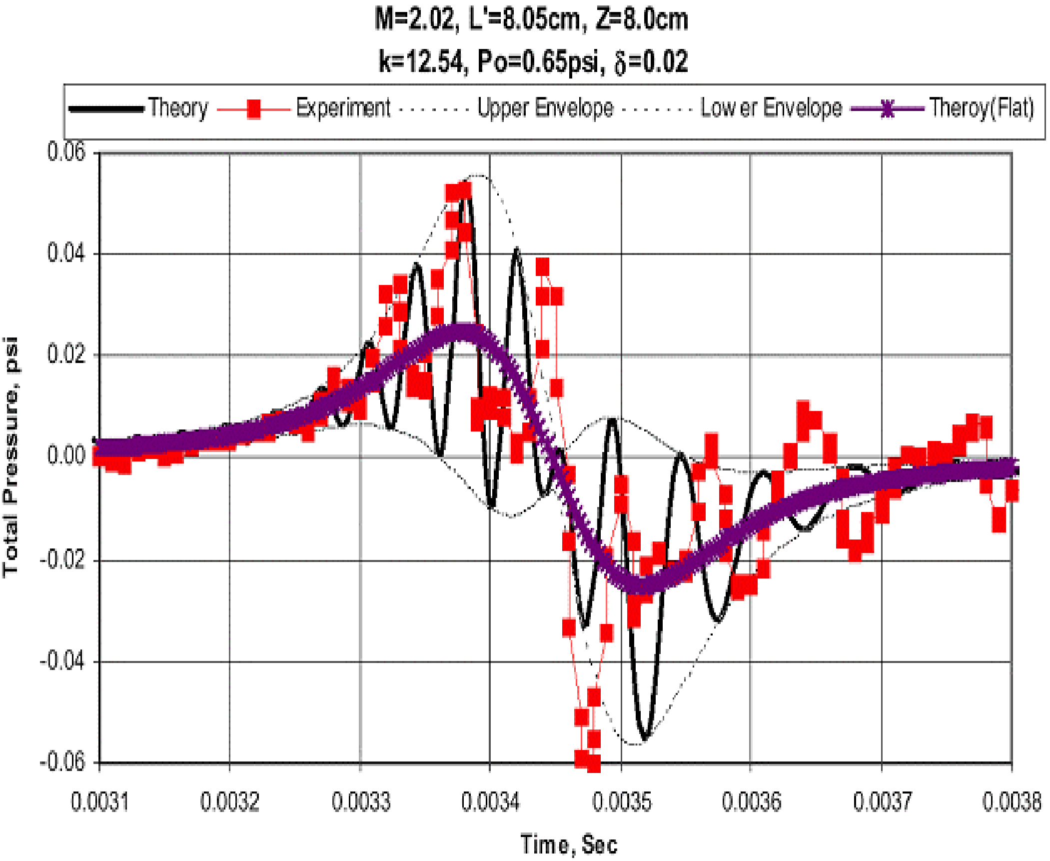
Measured wavy water P_2' attenuation

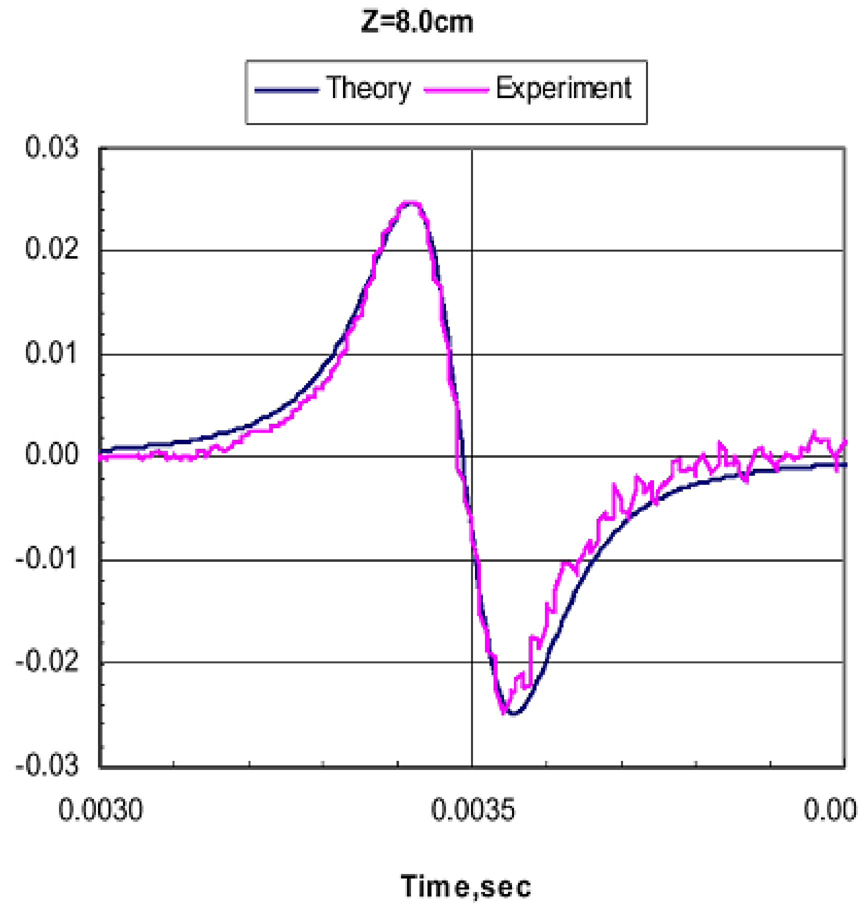
$$|P_2'| \sim \varepsilon\delta / r^{1/2}$$





Qualitative similarity between laboratory and numerical results





Wavy surface

Flat surface

Quantitative comparison of experiment and theory

Conclusions

- The effect of a wavy surface is to produce a packet of wavelets, that at depth overwhelm the Sawyers flat ocean model.
- Sawyers model verified in laboratory to 5 signature depths.
- Good agreement between the Theory, Numerical & Laboratory work Conclusively showing that the theory of Cheng and Lee (2000) is valid at the laboratory scale.

$|P_1| \sim \varepsilon / r^2$ Flat water N-wave attenuation

$P' \sim P_1' + P_2'$ P_2' overwhelms P_1' at ~1 signature depth

$|P_2'| \sim \varepsilon\delta / r^{1/2}$ Wavy water attenuation

- Sonic Boom sound levels in the ocean from supersonic over flight predicted > 120 dB (re 1 μPa) in the 15-25 Hz range.

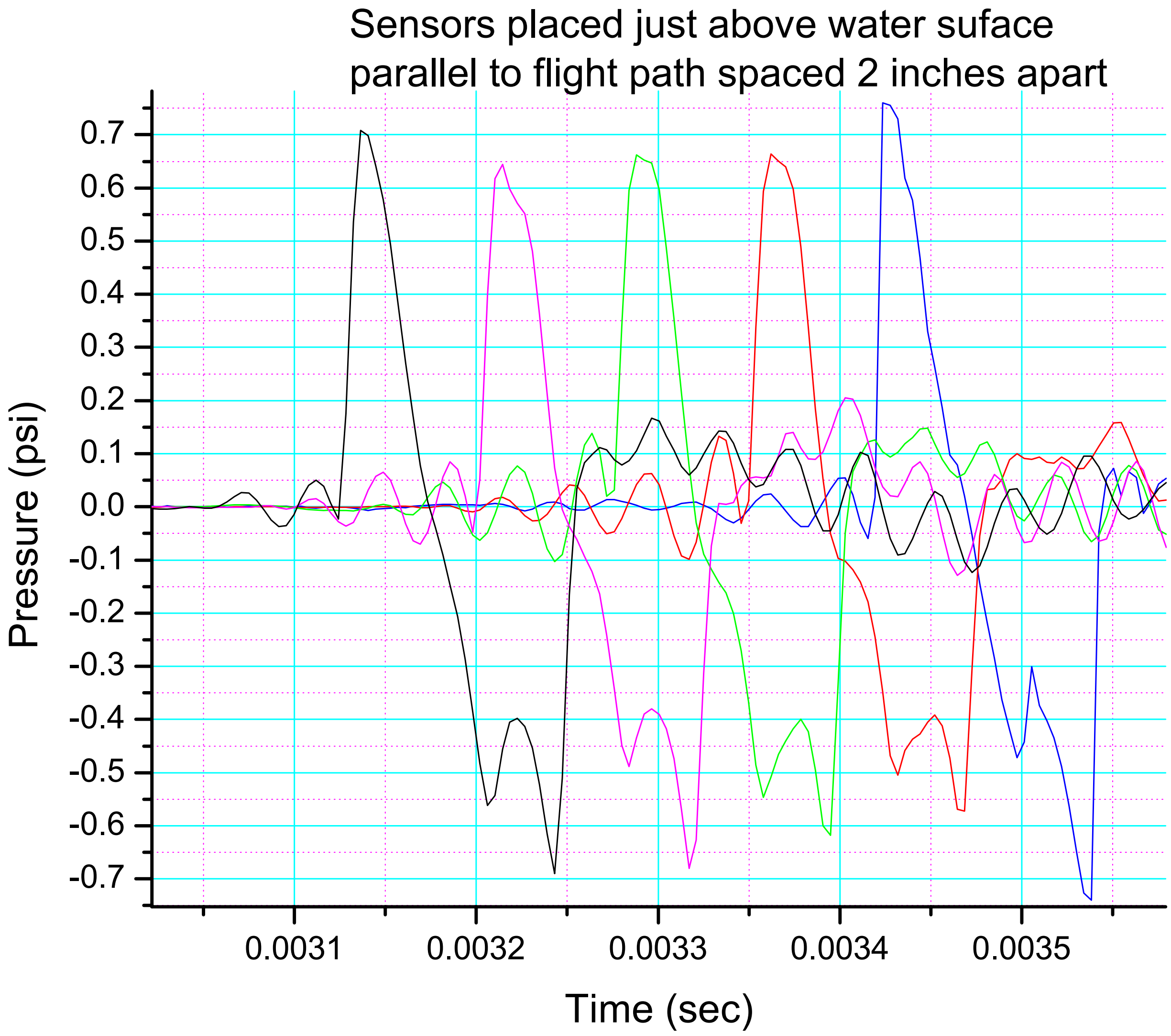
References

- Cheng, H.K. and Lee, C.J. (2000) "Sonic Boom Noise penetration Under Wavy Ocean: Part I Theory", Univ. Southern California Dept. Aero. Mech. Engineering, USC AME Report 11-112000; web page http://www-bcf.usc.edu/~hkcheng

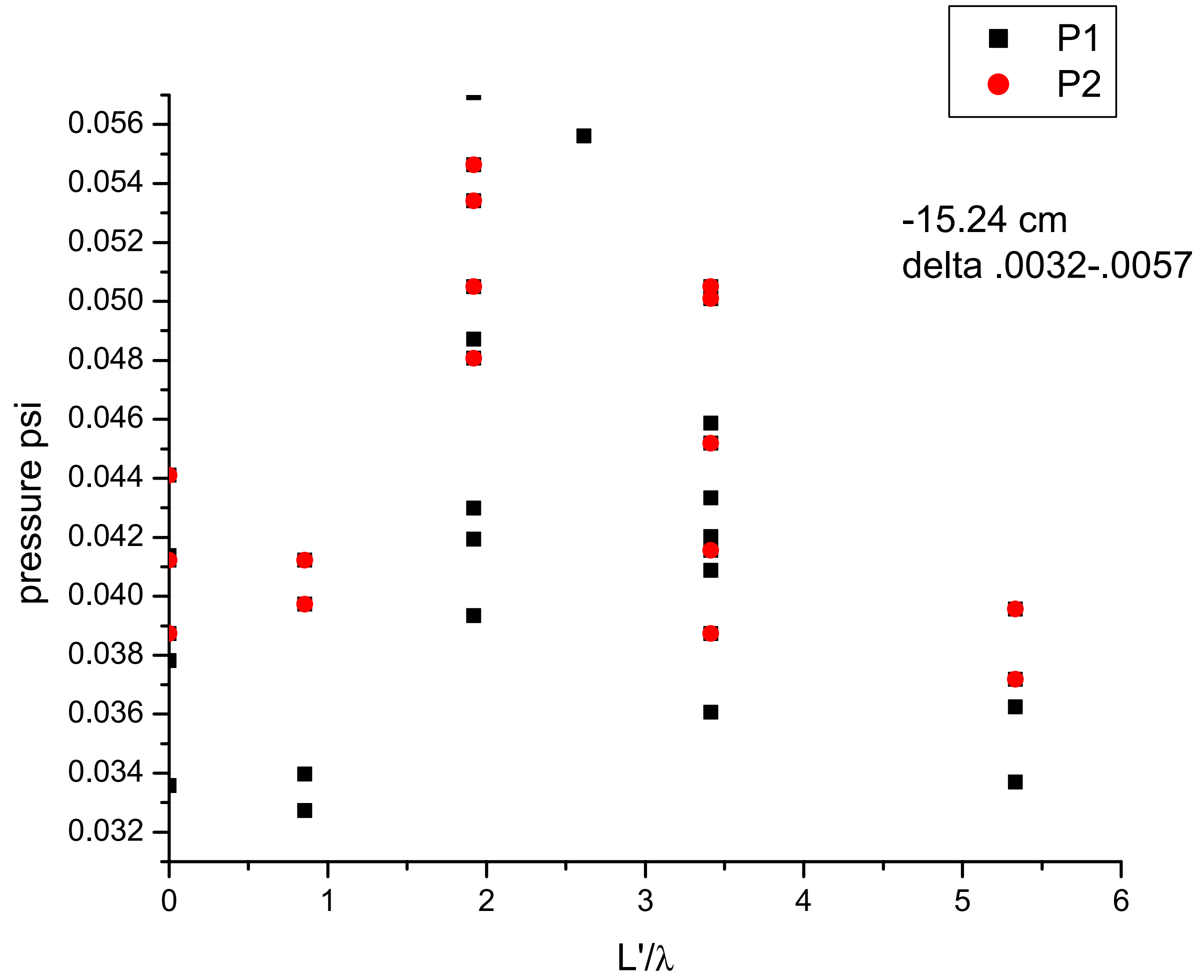
- Cheng, H.K., Lee, C.J. and Edwards, J.R. (2001) "Sonic Boom Noise Penetration Under a Wavy Ocean: Part II. Examples and Extensions", Univ. Southern Calif. Dept. Aero Mech. Engineering, USC AME Report 4-4-2001; web page http://ax.losangeles.af.mil/axf/comments/comments.html

- Fincham, A. and Maxworthy, T. (2001) "An Experimental Study of Sonic Boom penetration Under a Wavy Air-Water Interface" Univ. Southern Calif. Dept. Aero. Mech. Engineering, USC AME Report (-11-2001; web page same as Cheng, Lee and Edwards (2001)

- Cheng, H.K. (2001) Draft "Final Report of Experimental and Theoretical Investigations on Ocean Sonic Boom propagation", by HKC Research under Parsons Engineering Science Subcontract 738249, 3000-02; web page same as Fincham and Maxworthy (2001),

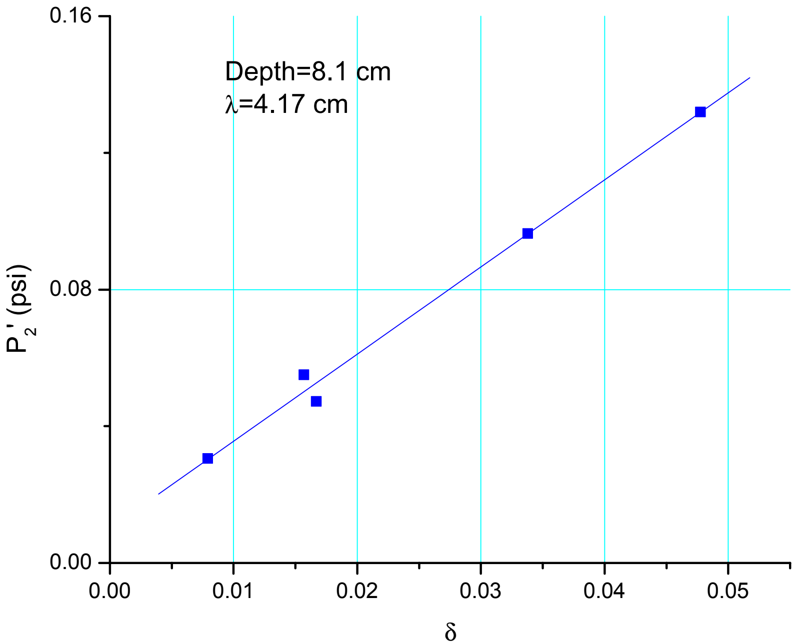


Pressure signals from 5 piezotrons in the air just above the air-water interface

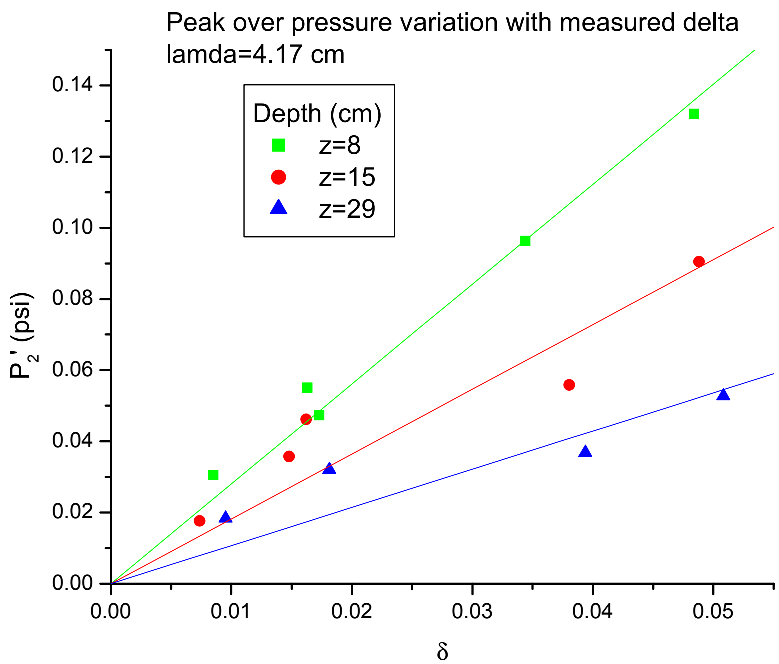


Preliminary peak measured pressure for probes at 2 different stream wise positions vs. λ/L′ based on older data acquisition and laboratory setup

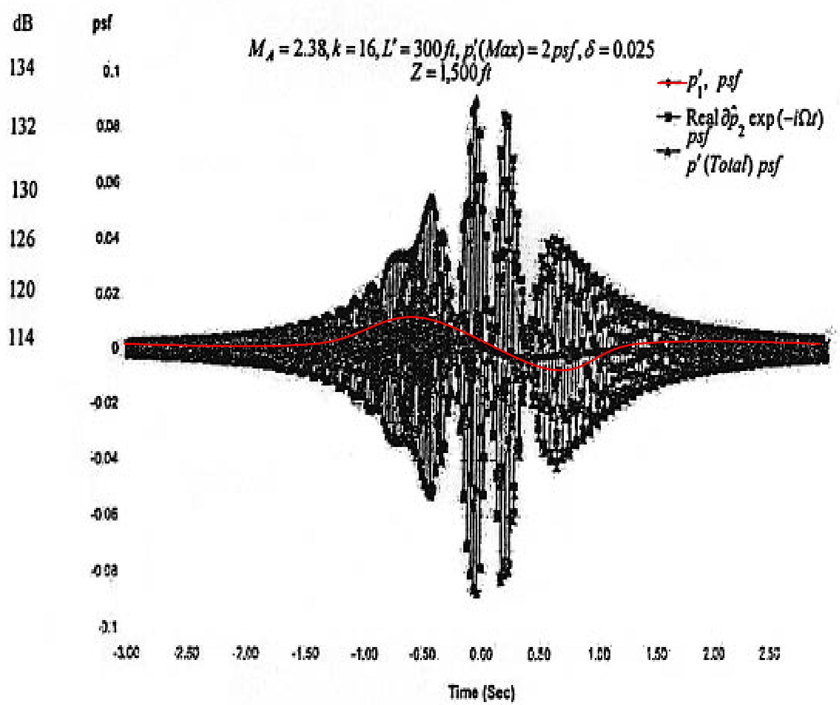
Importance of the wave height δ

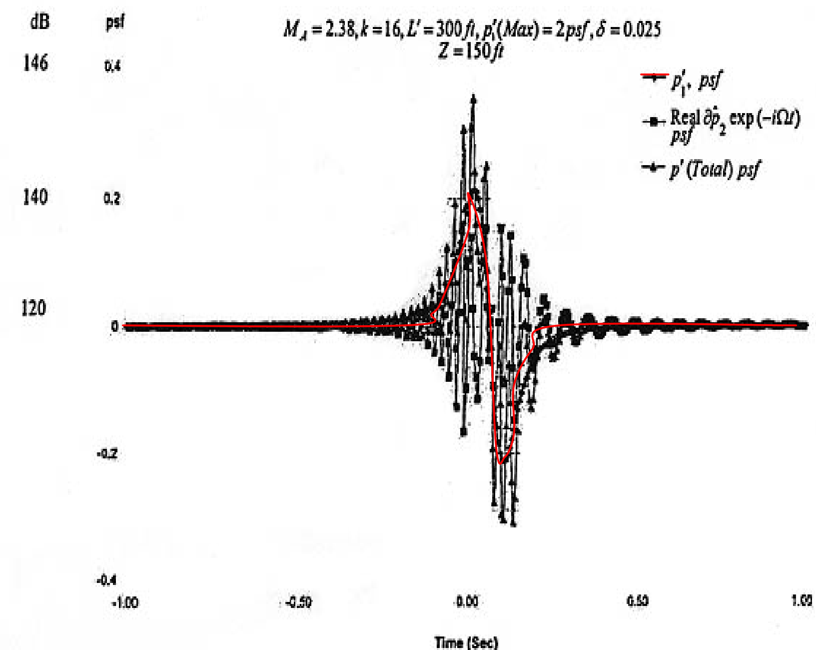


Linear dependence of P_2' on measured δ for shallow depths

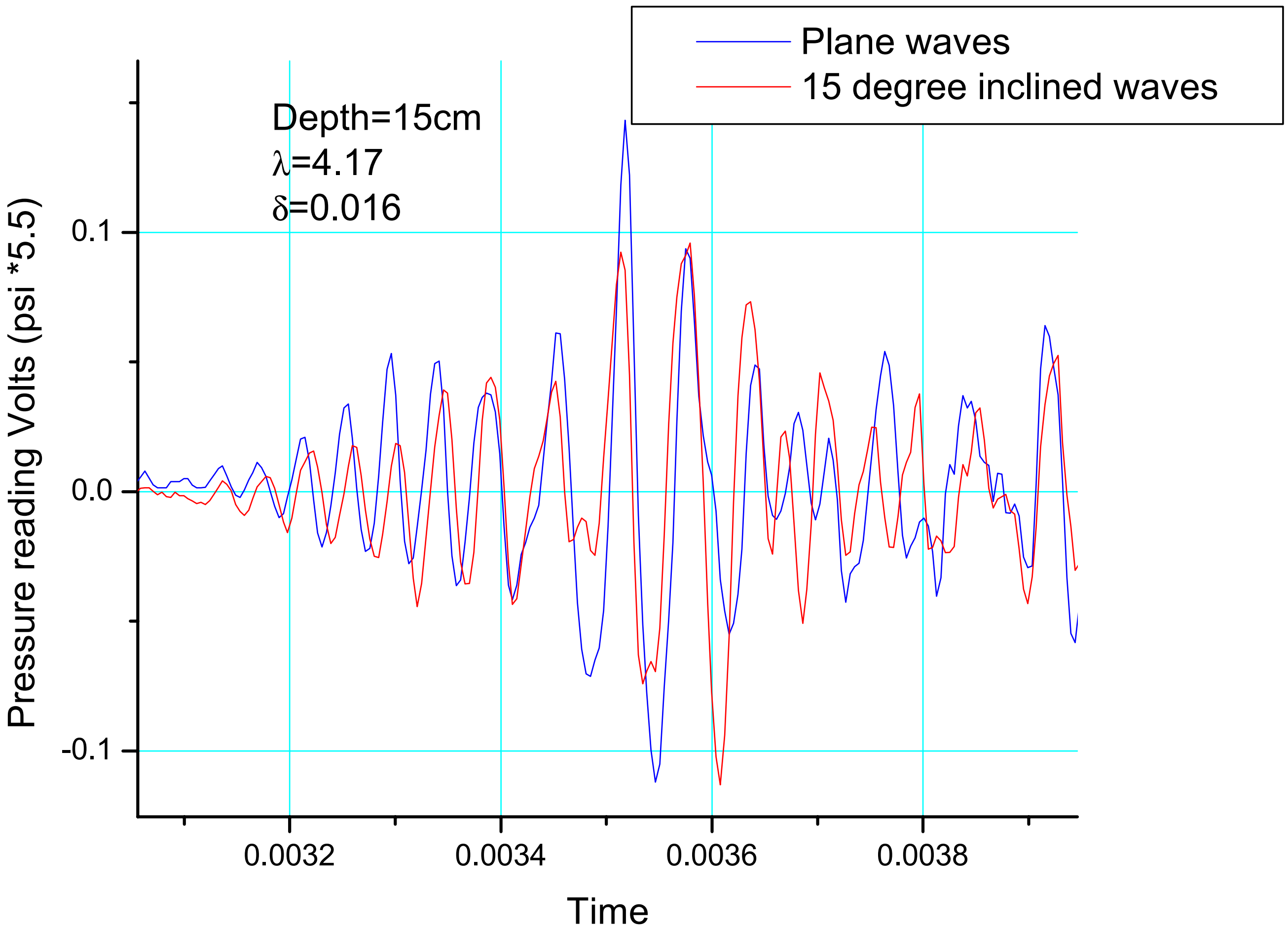


P_2' verses δ for different depths


$M_A = 2.38, k = 16, L' = 300\,ft, p_1'(Max) = 2\,psf, \delta = 0.025$
$Z = 1{,}500\,ft$
dB
psf
134
132
130
126
120
114
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
p_1', psf
Real $\partial\hat{p}_2 \exp(-i\Omega t)$ psf
p' (Total) psf
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
Time (Sec)


$M_A = 2.38, k = 16, L' = 300\,ft, p_1'(Max) = 2\,psf, \delta = 0.025$
$Z = 150\,ft$
dB
psf
146
140
120
0.4
0.2
0
-0.2
-0.4
p_1', psf
Real $\partial\hat{p}_2 \exp(-i\Omega t)$ psf
p' (Total) psf
-1.00
-0.50
0.00
0.50
1.00
Time (Sec)

$dB(re\ 1\mu Pa)$



Effects of inclined surface wave trains

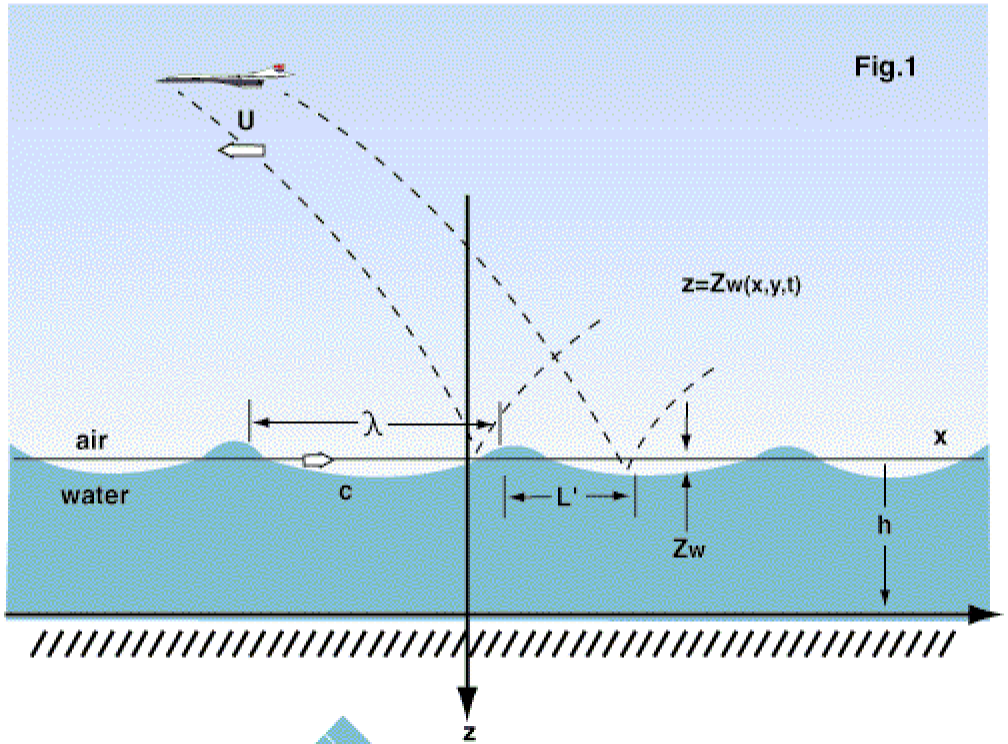


Fig.1

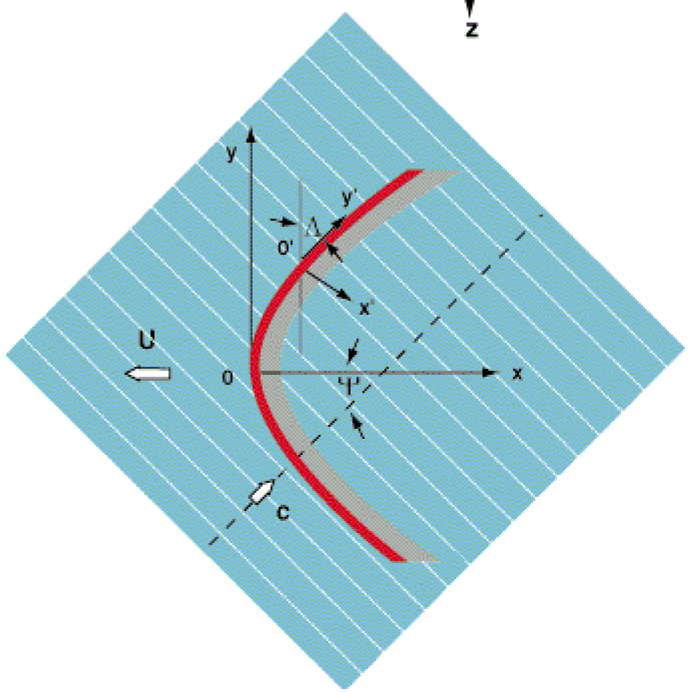
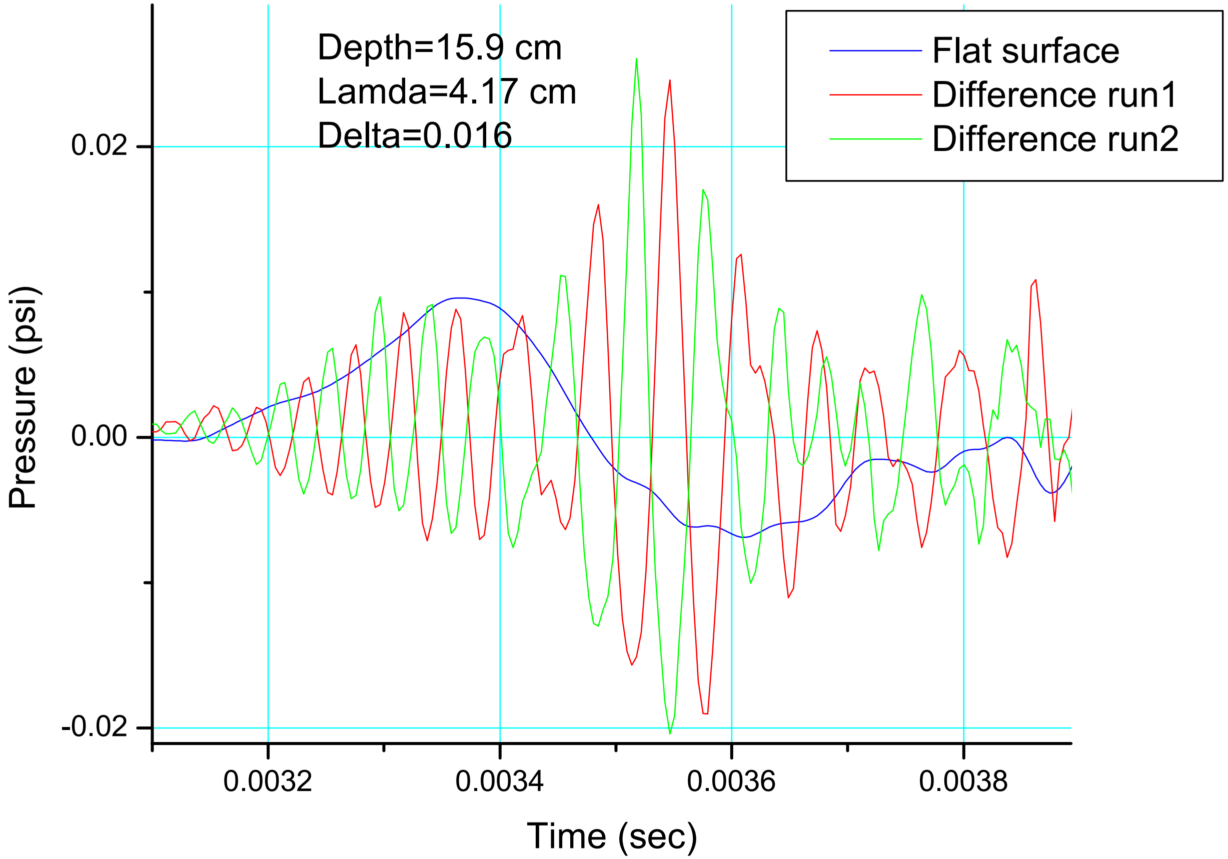
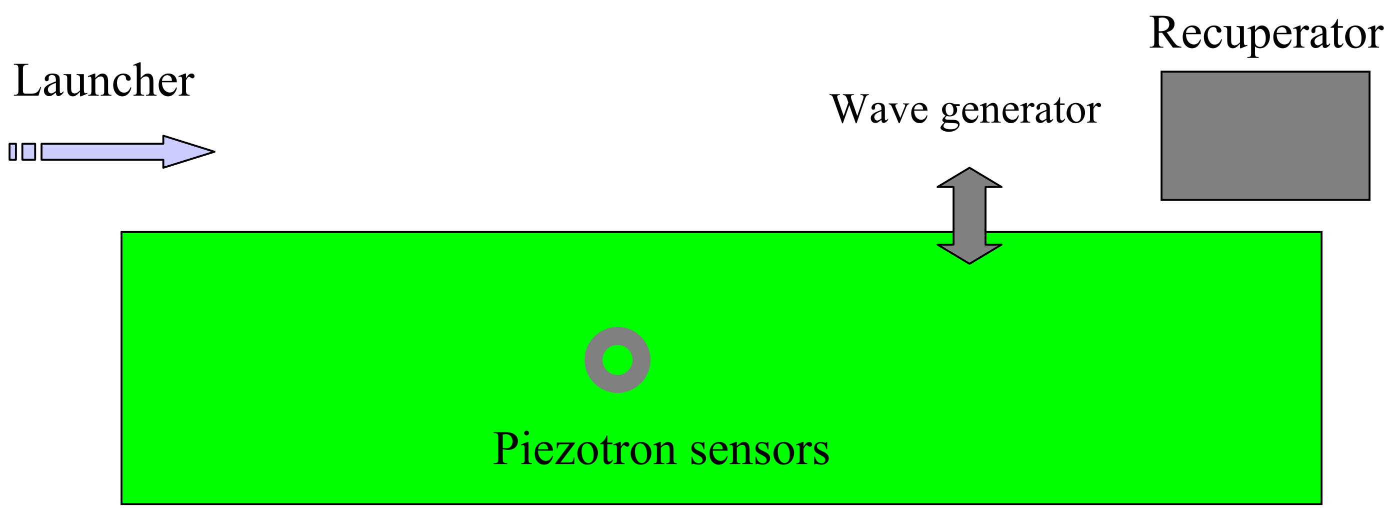


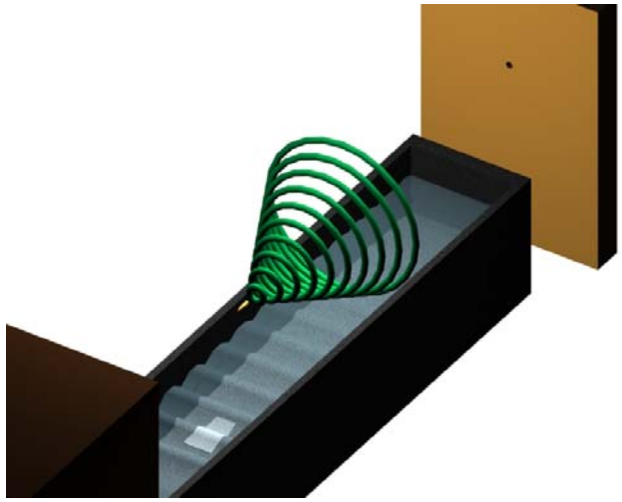
Fig.2

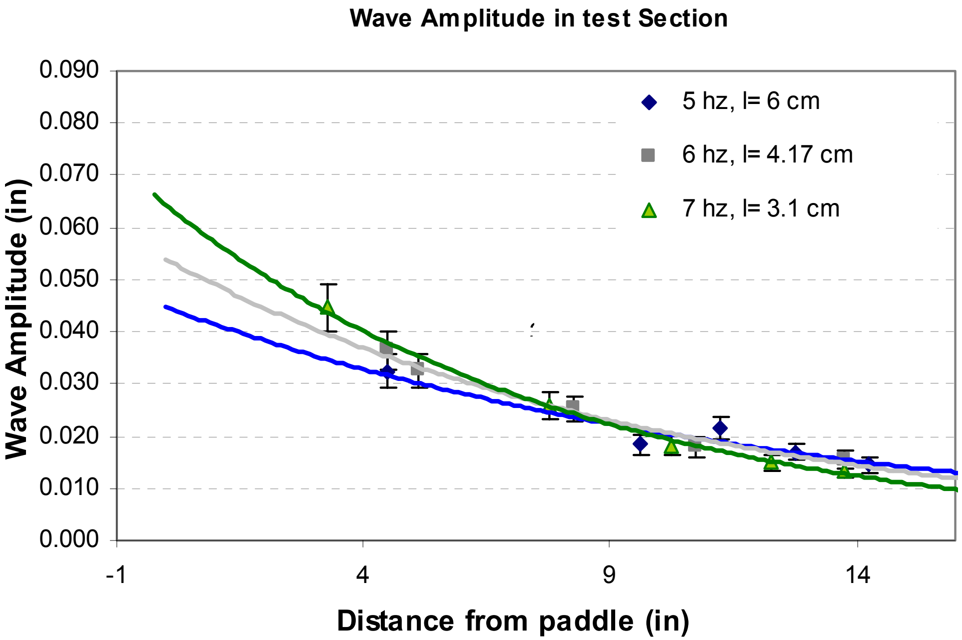


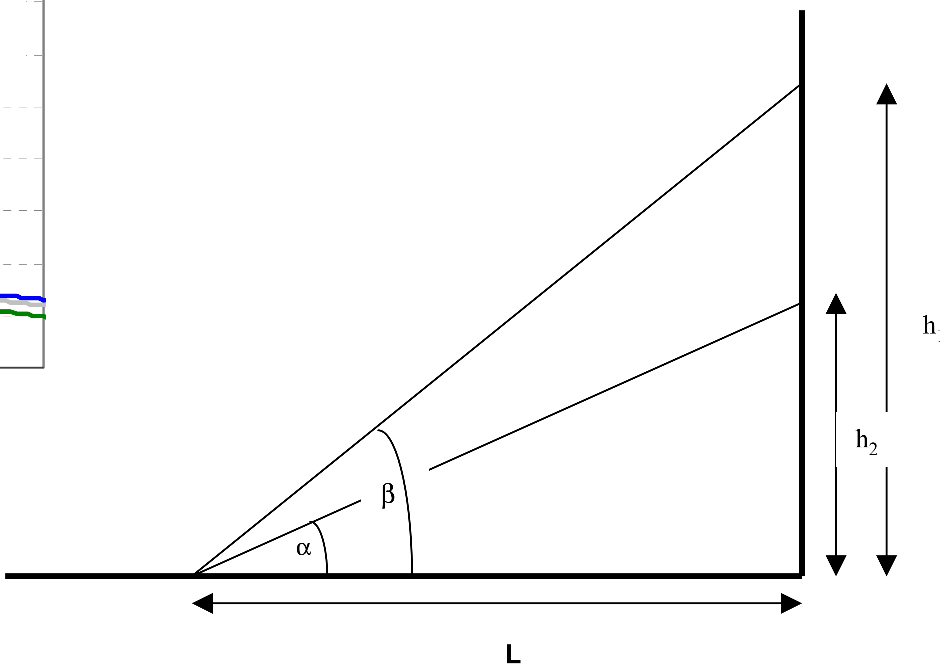
Two different ensembles of the same experiment showing the difference in phase that permits a better resolution of the wave packet envelope

Experimental setup





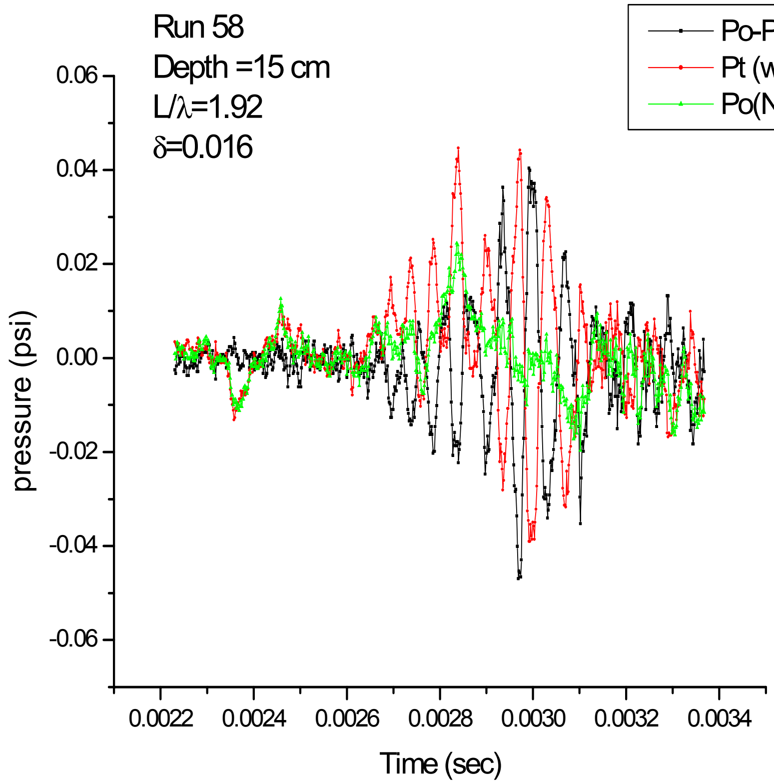




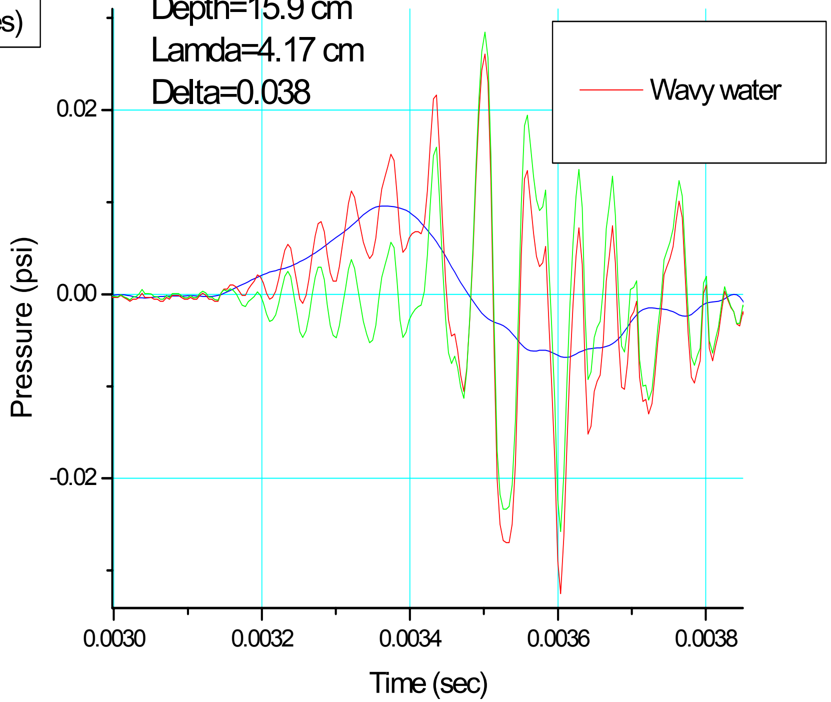
$$A=\delta\lambda/2\pi,$$

$$2\delta=\tan^{-1}(h_1/L)-\tan^{-1}(h_2/L).$$

Optical wave height gauge geometry



Old data



New data

Improvements in data quality