Bubble Physics

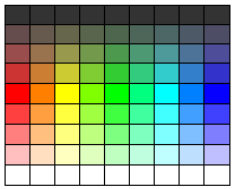
With applications to

airguns and whales

Shuki Ronen

Modeling by Leighton Watson





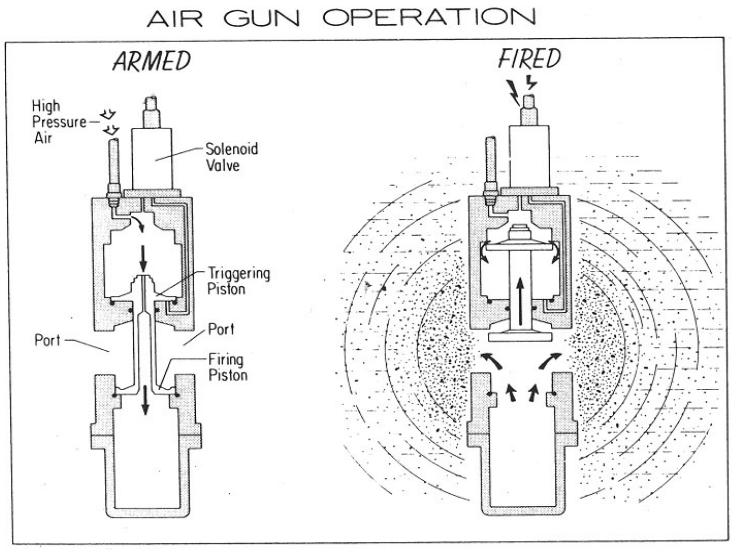
LISS

Sepwww.stanford.edu Totumgeo.com Seismicsources.com

The Air Gun

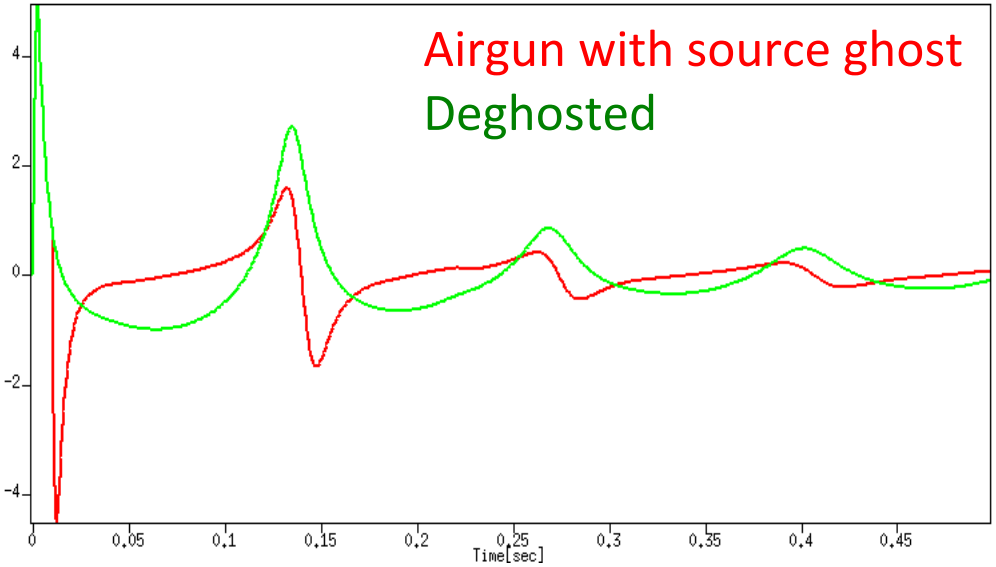


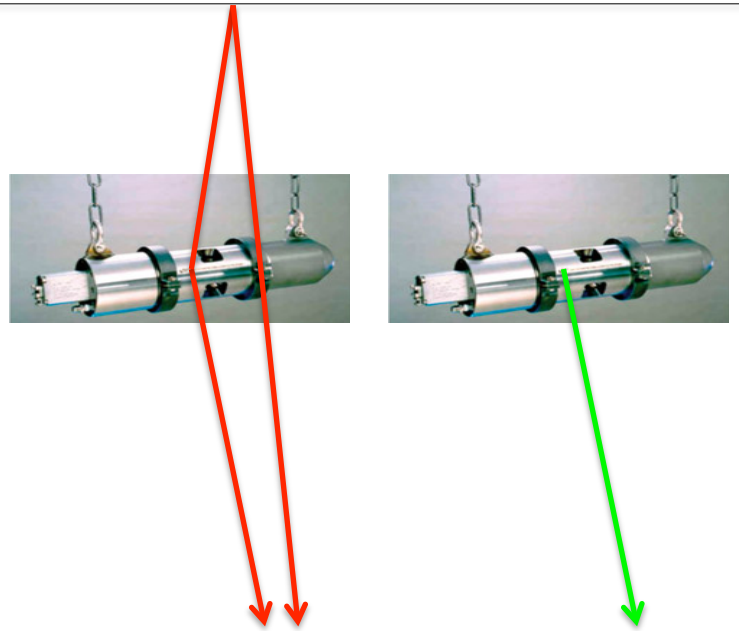
Air gun used for seismic testing before and during discharge.



- The airgun is essentially a controlled bottle of high pressure air that opens suddenly
- It emits a main pulse followed by an oscillating air bubble
- Airguns replaced explosives as the main seismic sources in the 1960-s 1970-s
- Almost all seismic surveys today are done with air-guns. Variations with minor changes: water guns, sleeve-guns, gas-injection (GI) guns are not used much

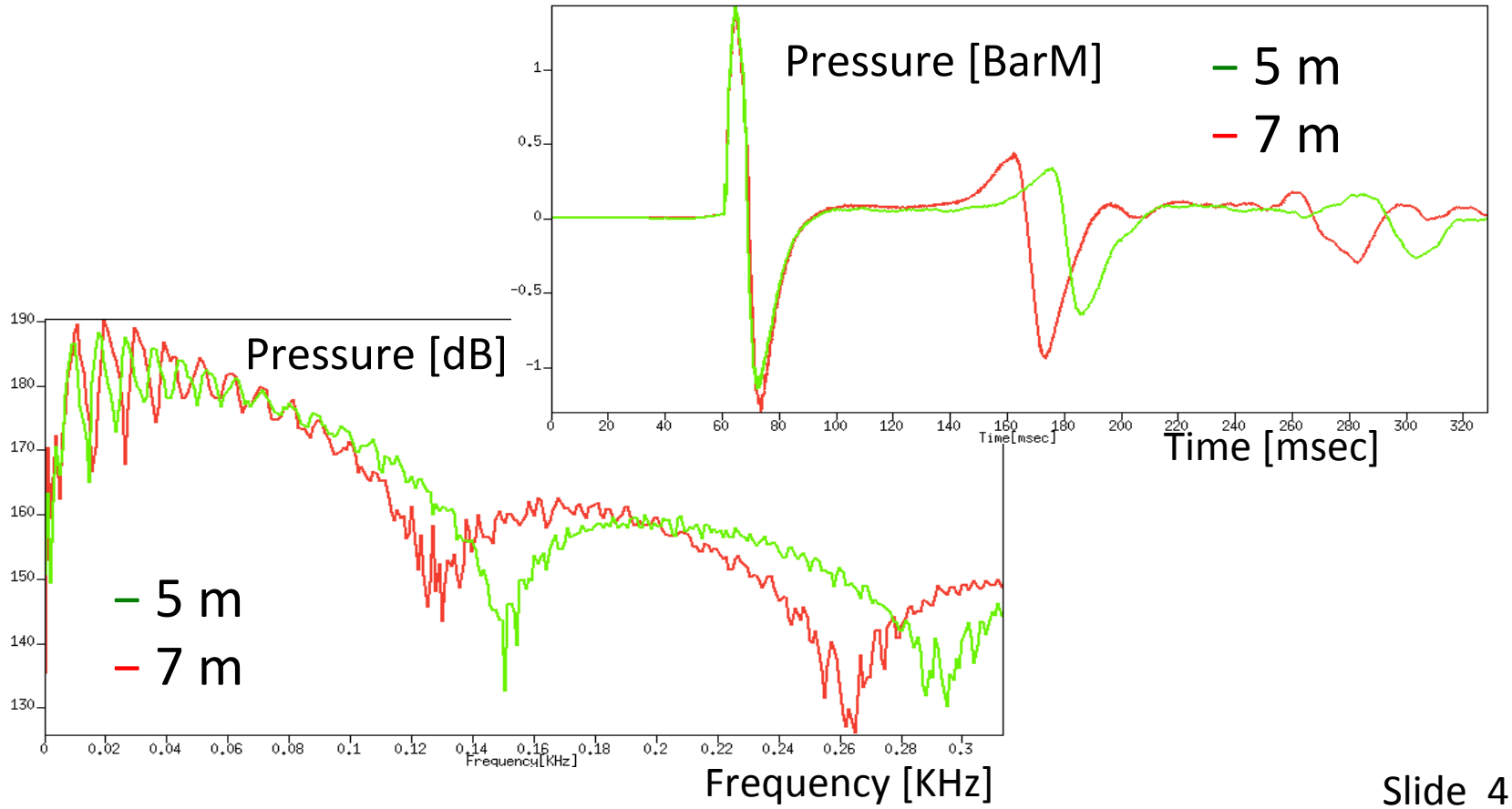
The ghost: echo from the surface





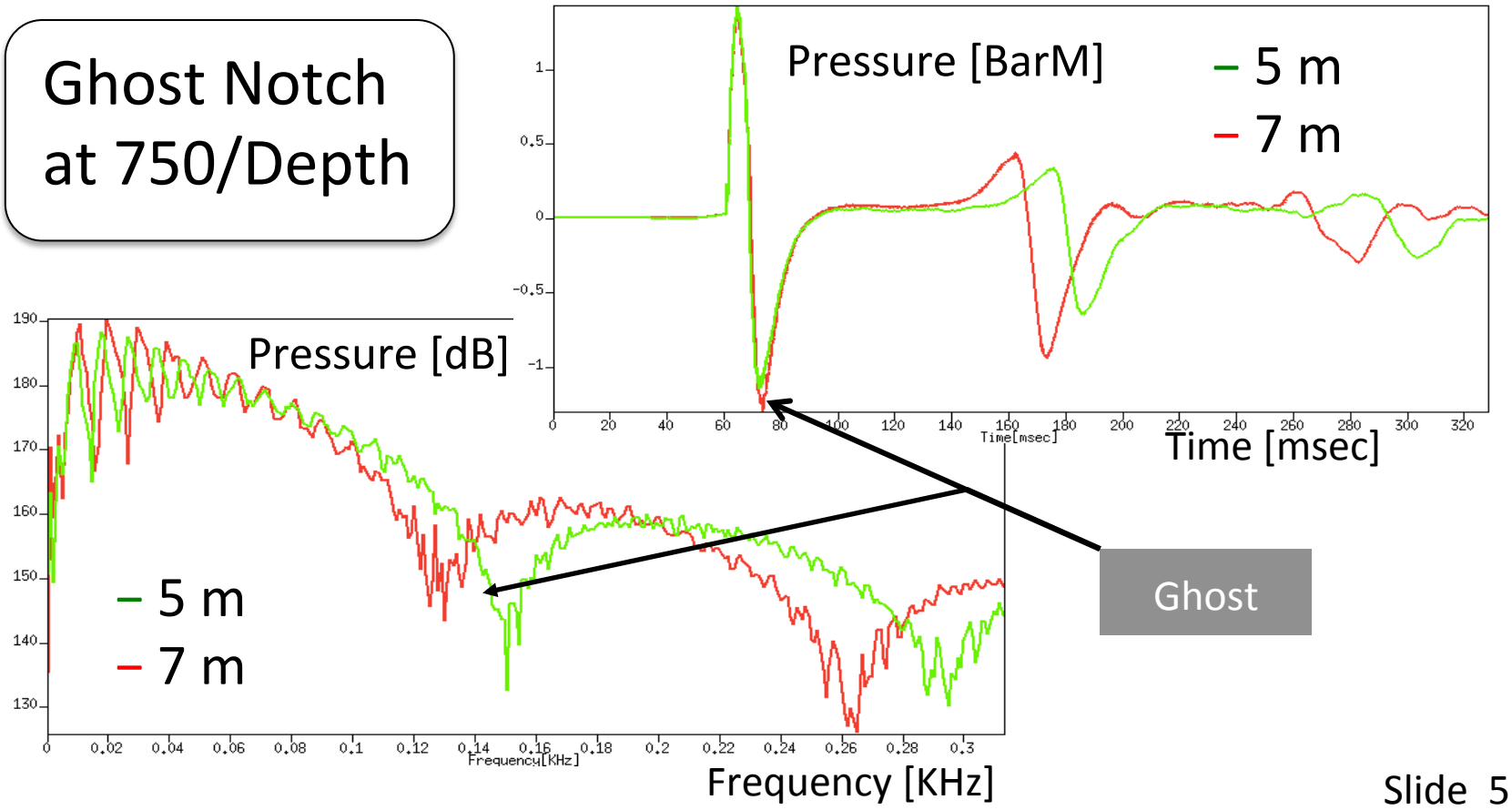
- Ghost(offset): Notches at n × F_{ghost}, n=0,1,2,…
  - $F_{ghost}(0) = 750/D$ vertically
  - $F_{ghost}(\theta) = 750/D/\text{cosine}(\theta)$ at an angle θ

Sample data: Depth effect 7 m and 5 m



Sample data: Depth effect 7 m and 5 m

Ghost Notch at 750/Depth



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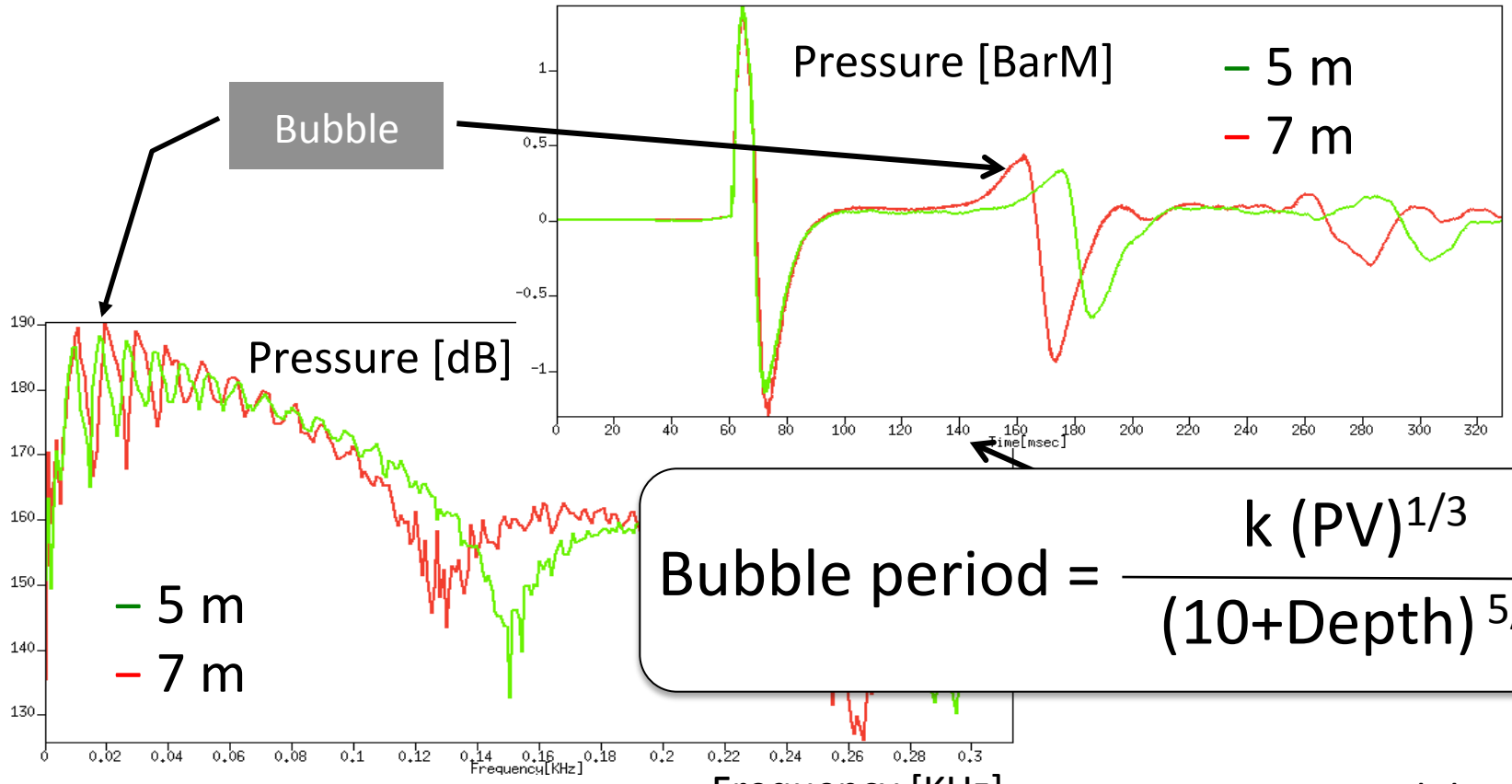


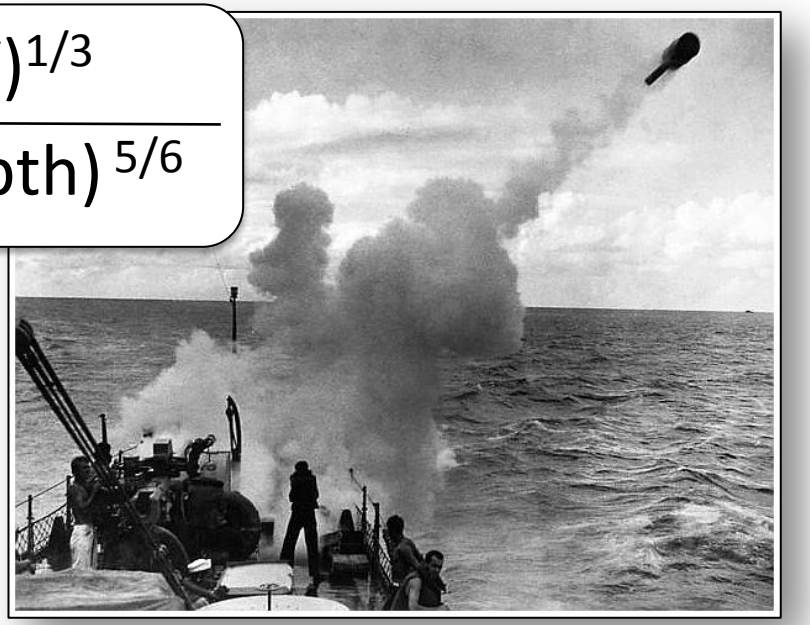
$$\text{Bubble period} = \frac{k\,(PV)^{1/3}}{(10+\text{Depth})^{5/6}}$$

Rayleigh-Willis formula

$$\text{Bubble period} = \frac{k\,(PV)^{1/3}}{(10+\text{Depth})^{5/6}}$$

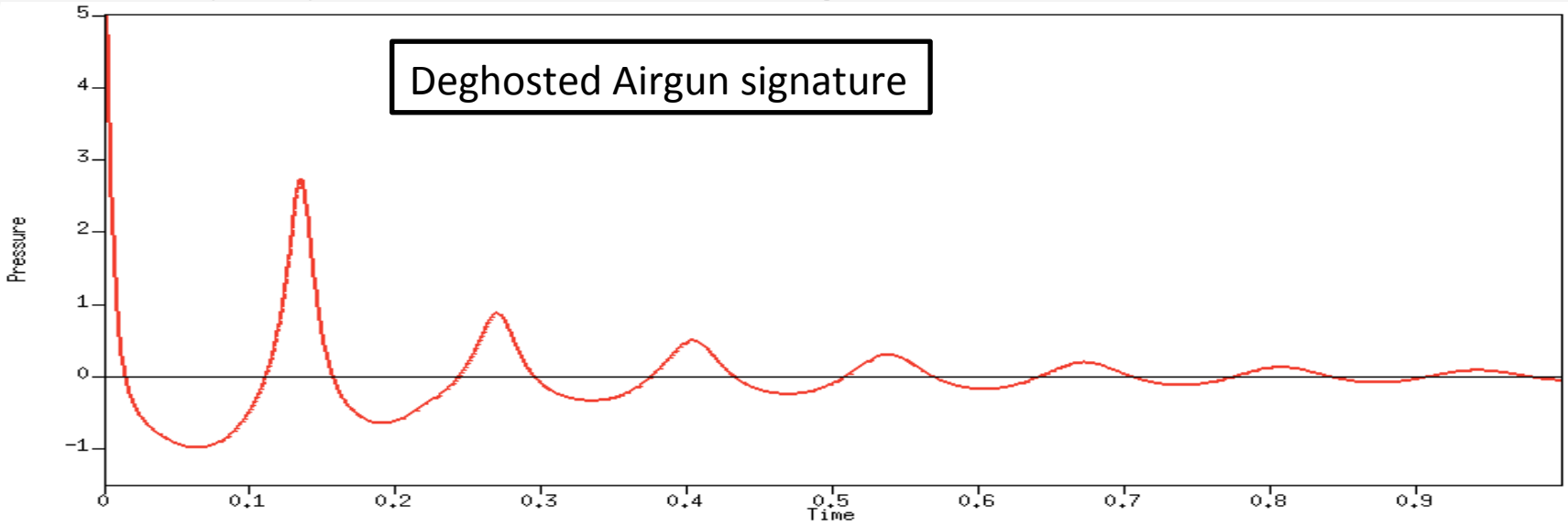


P = Pressure
V = Volume
K = constant

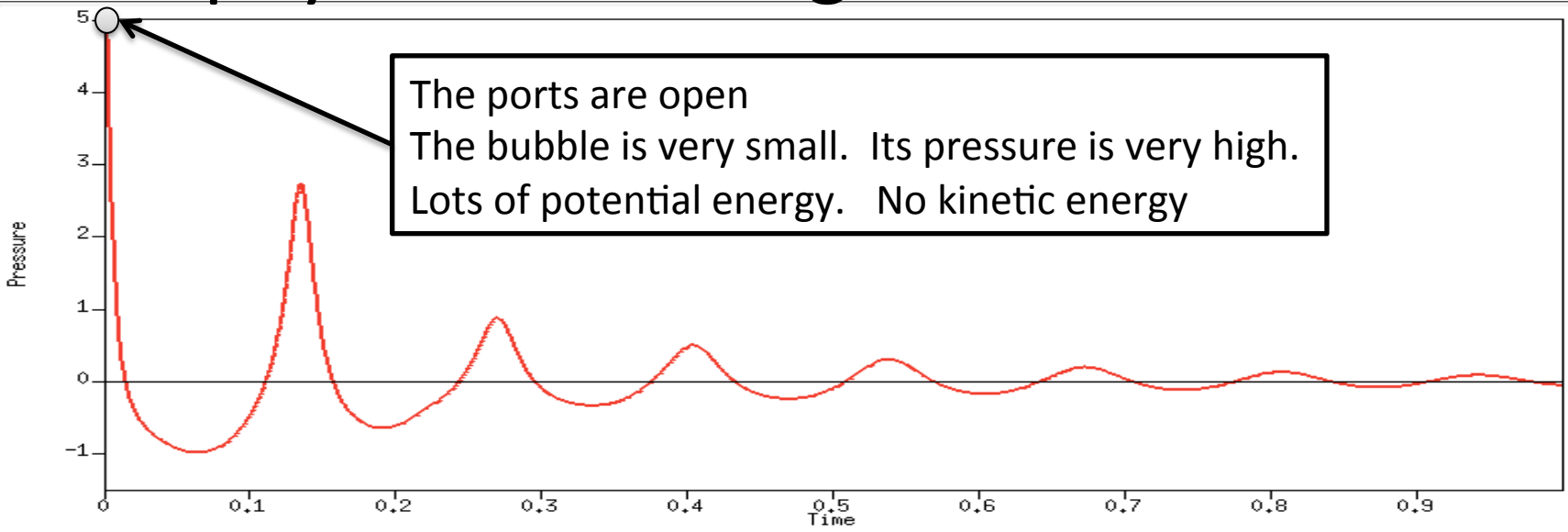


1917 Lord Rayleigh, Steam bubbles in a kettle
1941 P.F. Willis, Underwater explosions
1960- Very useful formula for air gun design

The physics of the airgun bubble



The physics of the airgun bubble



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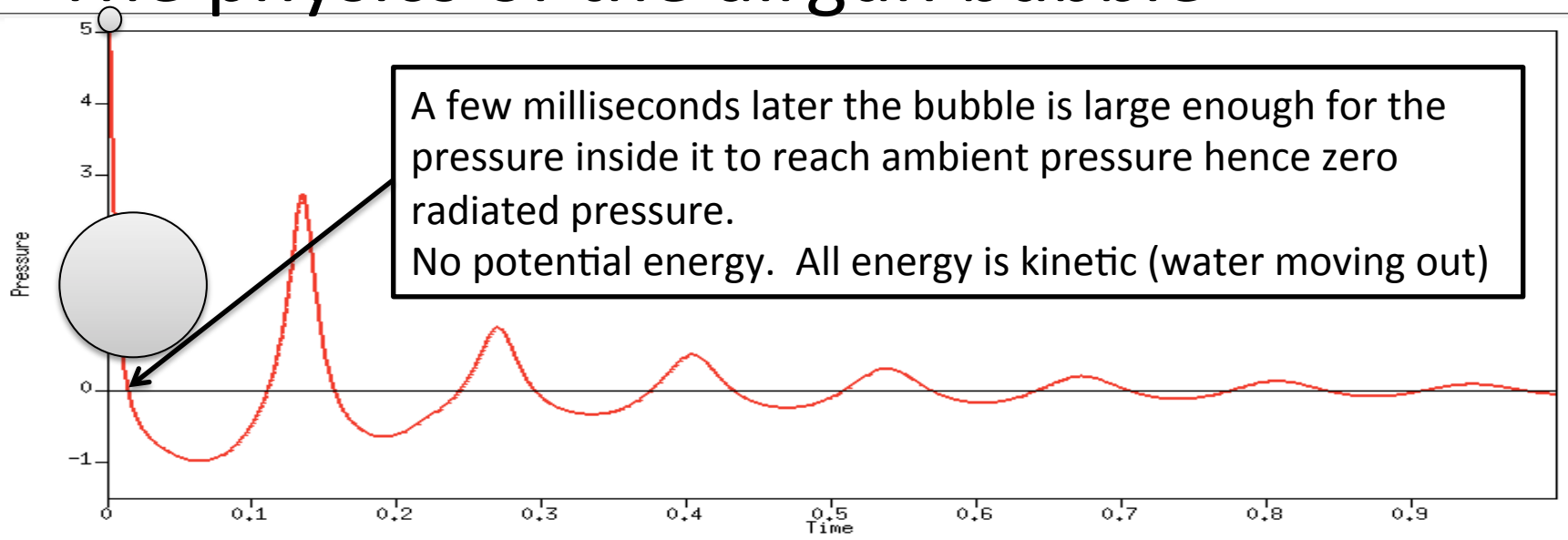
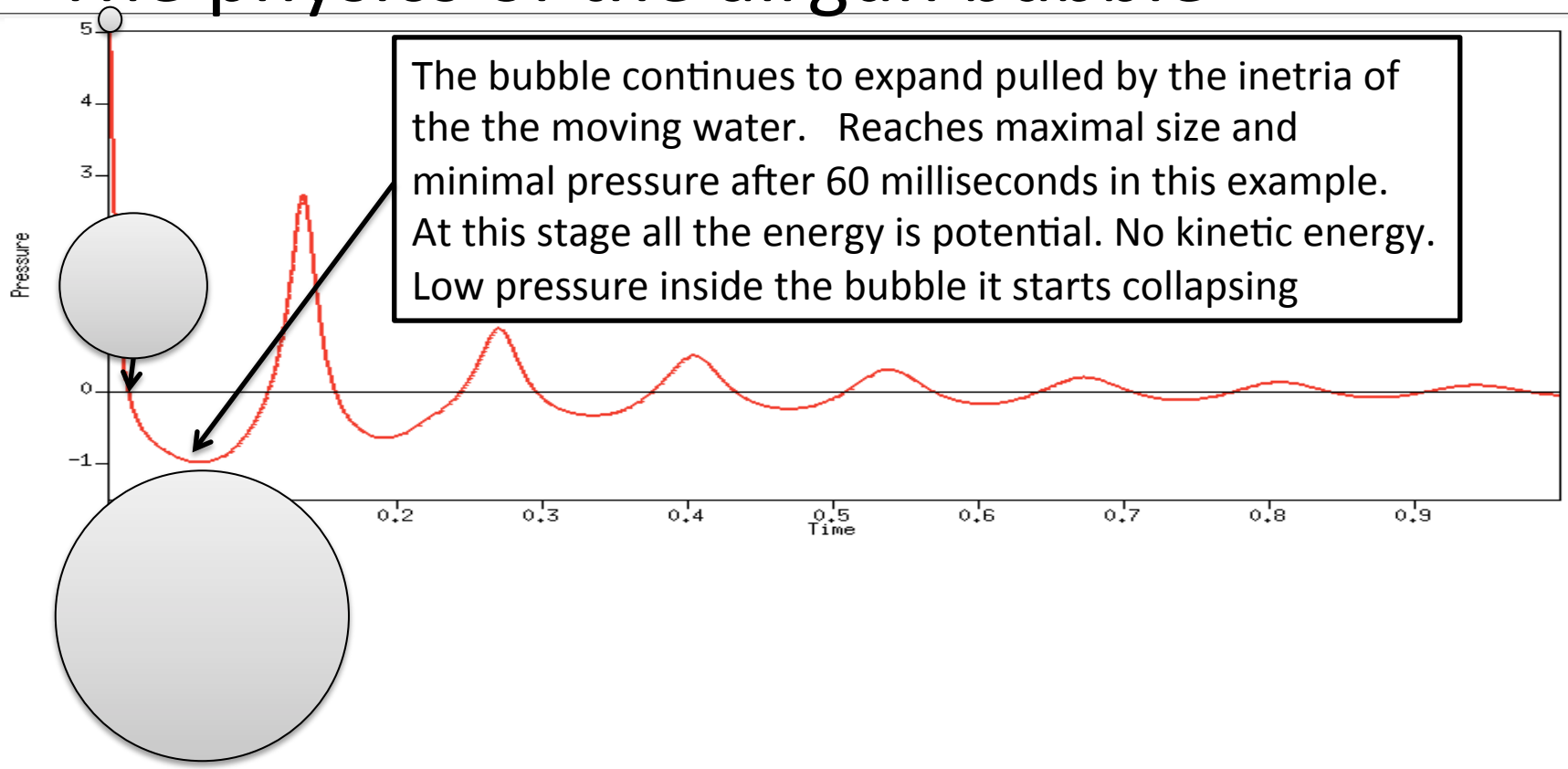
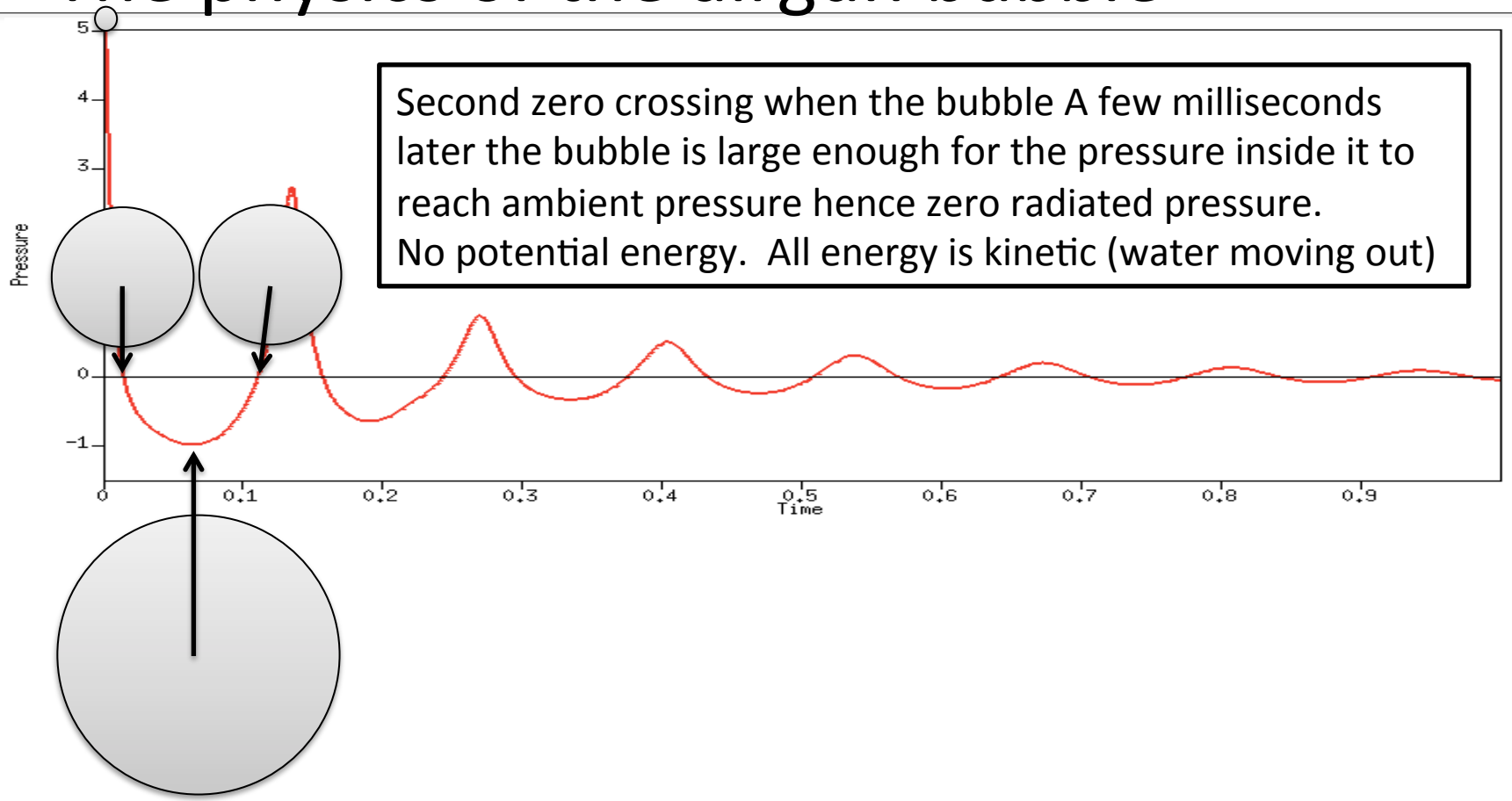


The physics of the airgun bubble

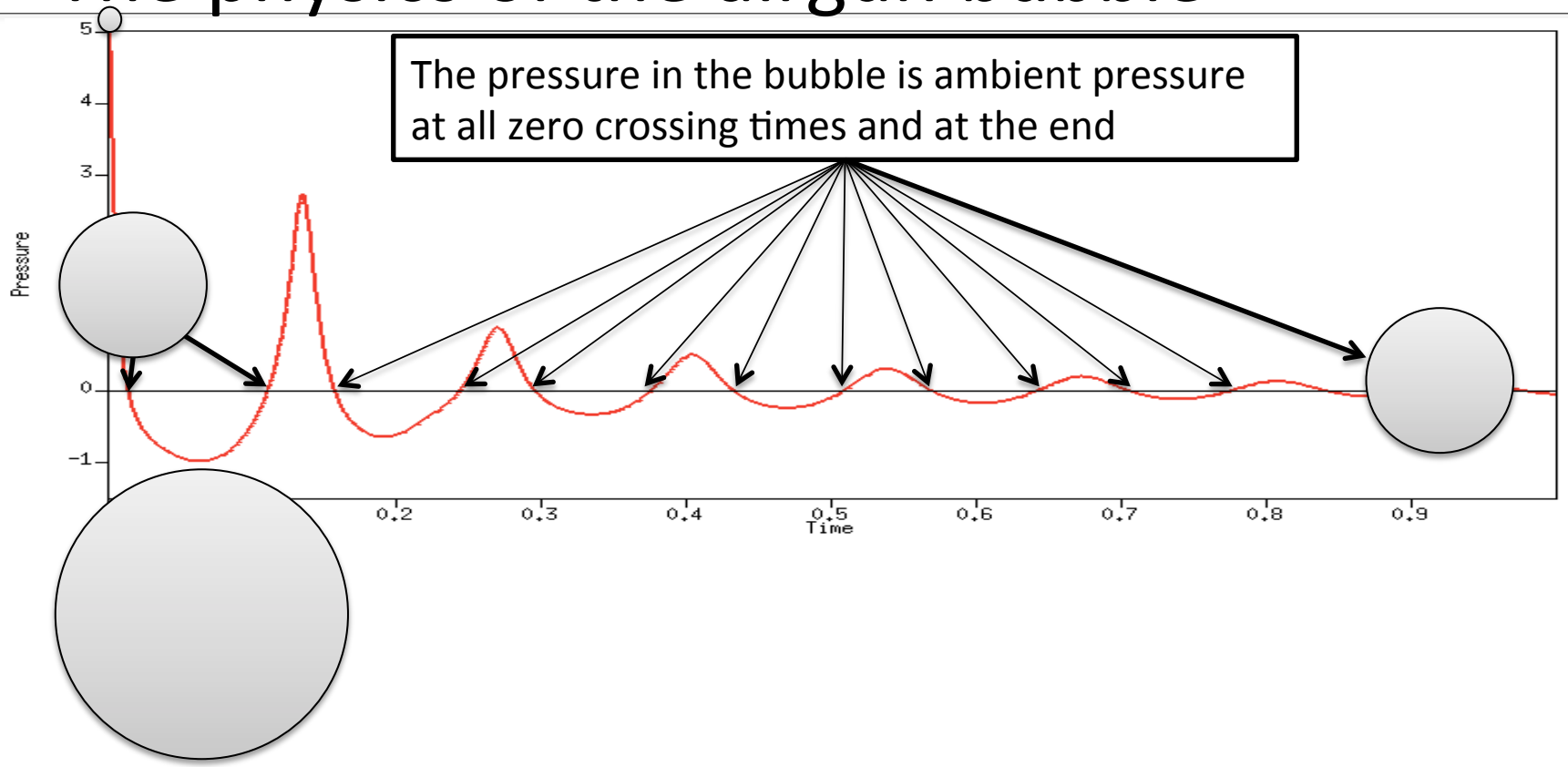


The bubble continues to expand pulled by the inetria of the the moving water. Reaches maximal size and minimal pressure after 60 milliseconds in this example. At this stage all the energy is potential. No kinetic energy. Low pressure inside the bubble it starts collapsing

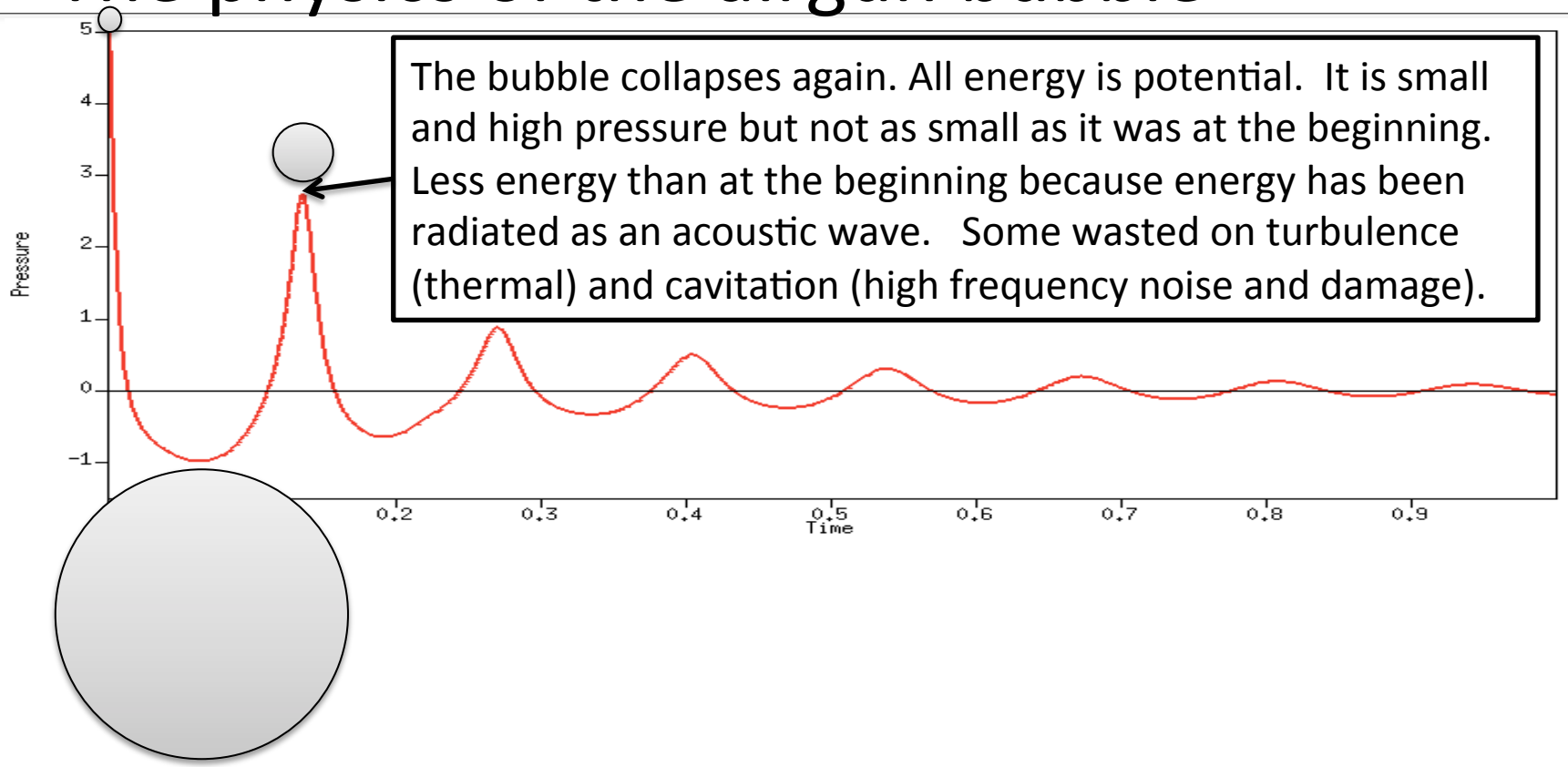
The physics of the airgun bubble



The physics of the airgun bubble

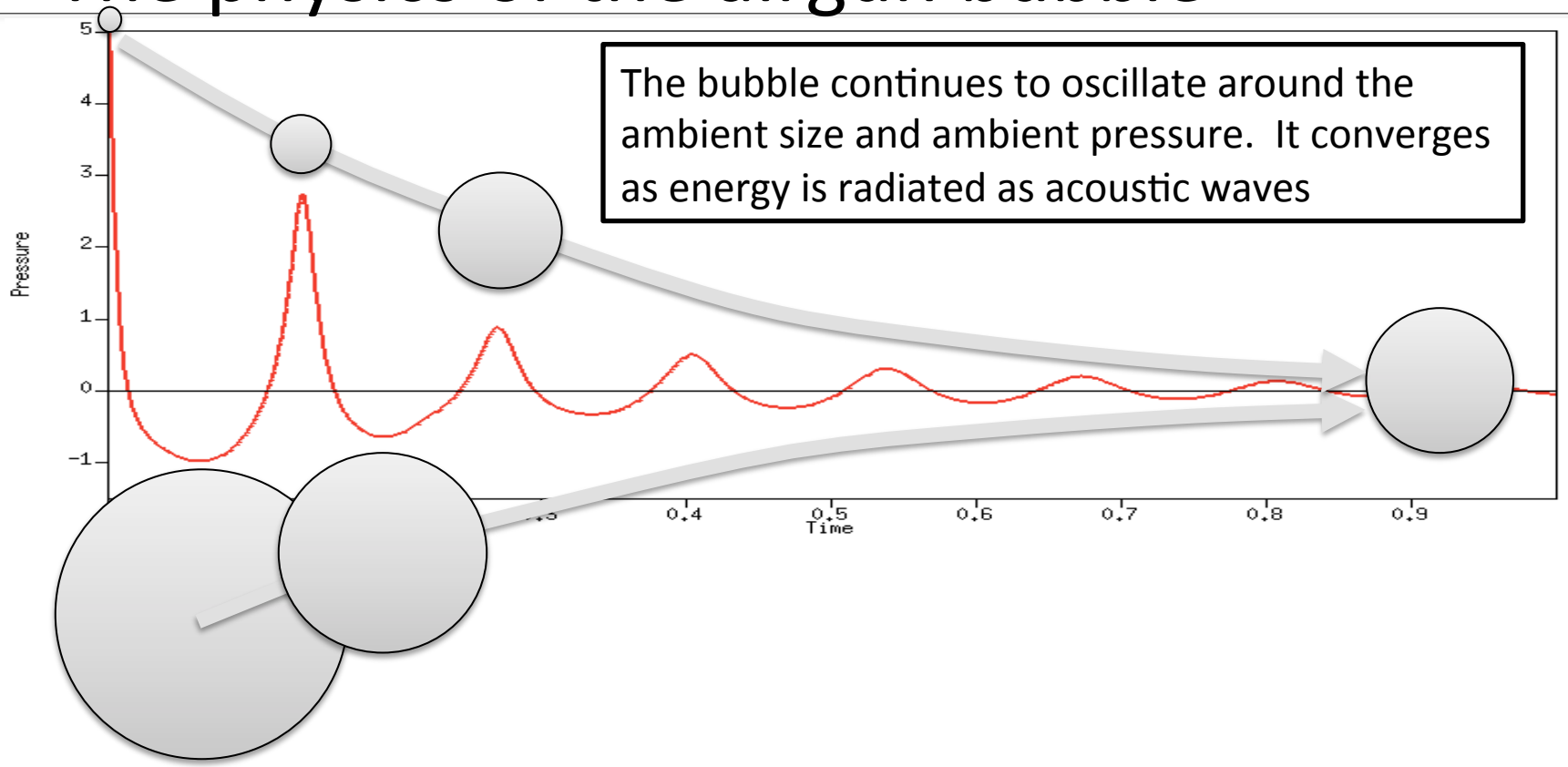


The physics of the airgun bubble

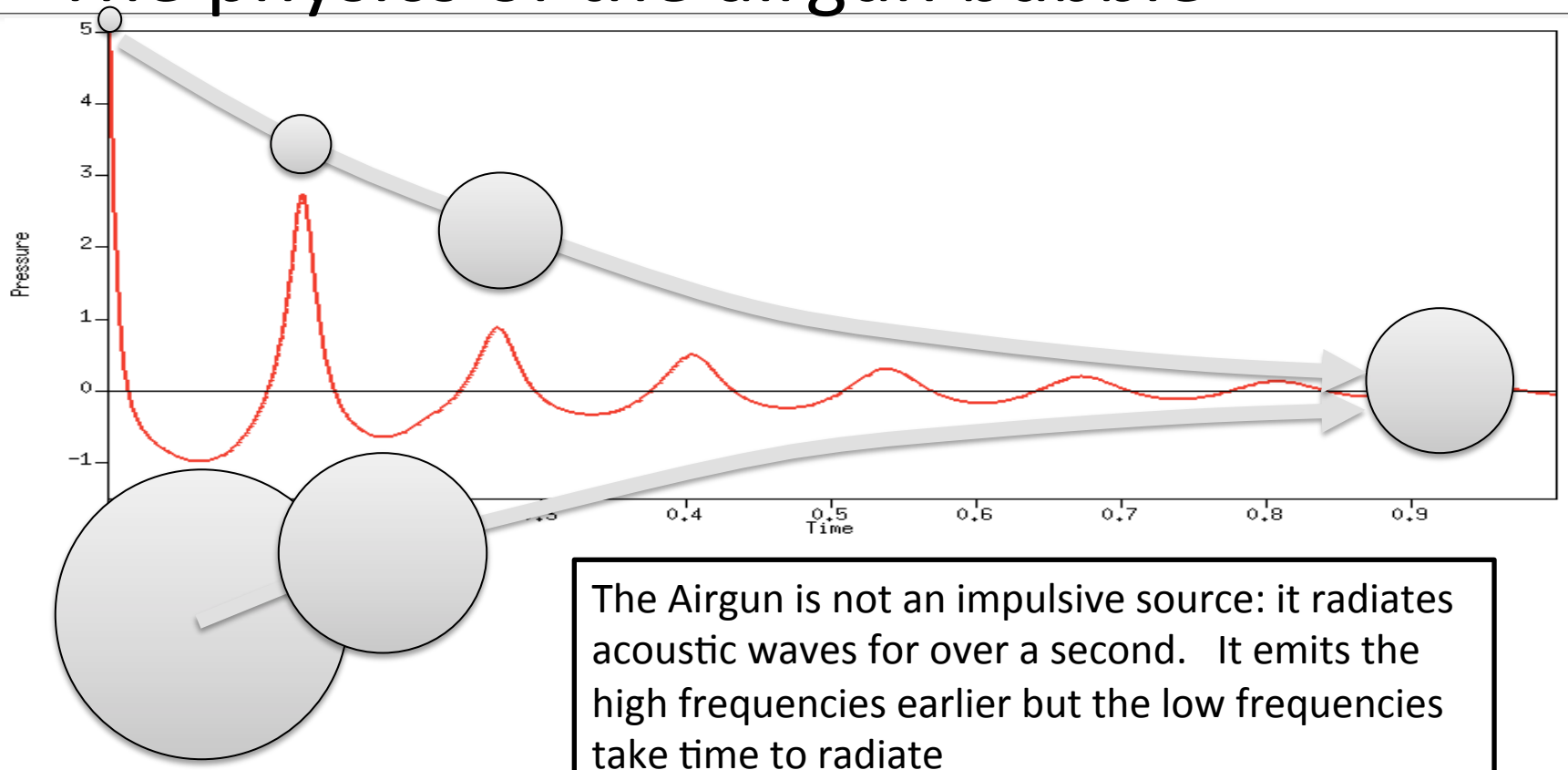


The bubble collapses again. All energy is potential. It is small and high pressure but not as small as it was at the beginning. Less energy than at the beginning because energy has been radiated as an acoustic wave. Some wasted on turbulence (thermal) and cavitation (high frequency noise and damage).

The physics of the airgun bubble



The physics of the airgun bubble



The Airgun is not an impulsive source: it radiates acoustic waves for over a second. It emits the high frequencies earlier but the low frequencies take time to radiate

Numerical modeling (Leighton Watson)

- Bubble radius and pressure from the Rayleigh equation $$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{2S}{\rho_\infty R} = \frac{p - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p} + F(t)$$
- Volume from Adiabatha equation PV^γ = Constant
- Temperature from ideal gas equation PV=nRT
- Far field signature

$$\Delta p(t, r) = \rho_\infty \left[\frac{\ddot{V}(t - r/c)}{4\pi r} - \frac{\dot{V}^2(t - r/c)}{32\pi^2 r^4} \right]$$

Rayleigh equation

Surface tension

Acoustic radiation

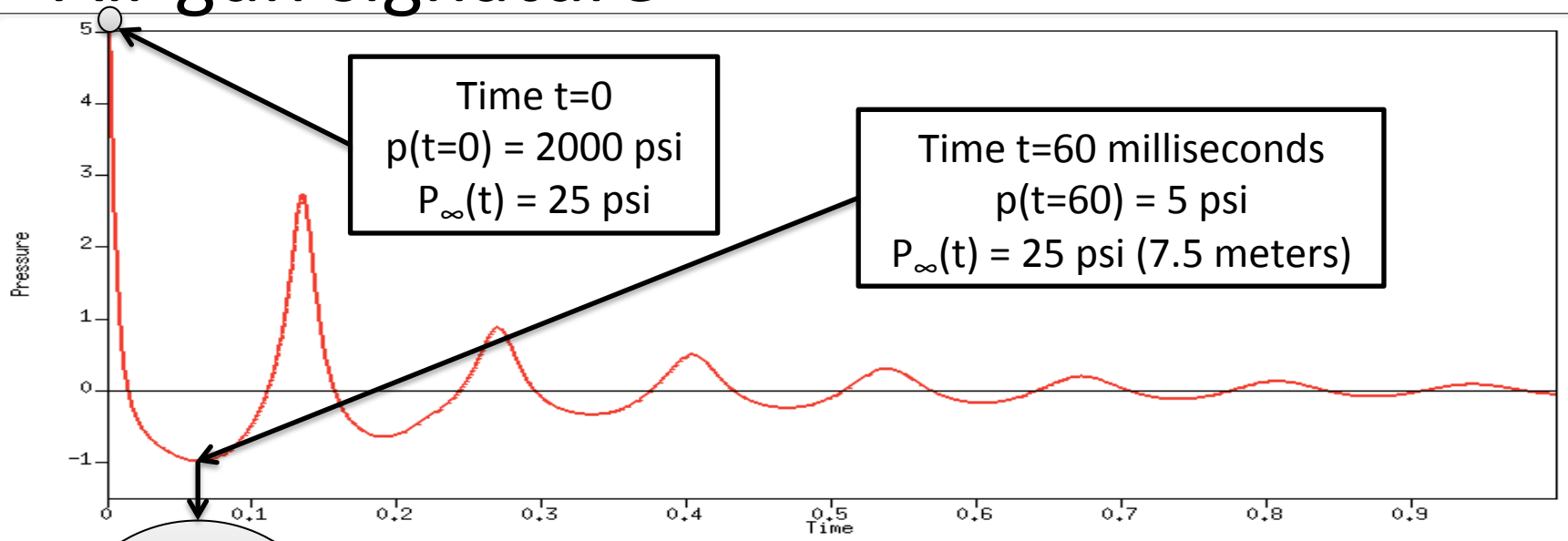
$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{2S}{\rho_\infty R} = \frac{p - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p} + F(t)$$

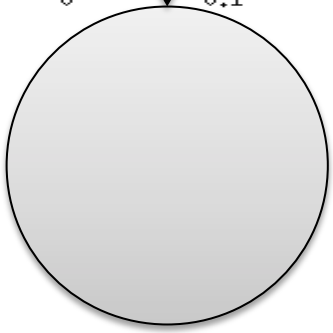
Inertial terms

Pressure

Force

Air gun signature





$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{2S}{\rho_\infty R} = \frac{p - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p} + F(t)$$

No surface tension *S=0* and no force *F(t) = 0*

Air Gun Modeling

Inertial terms

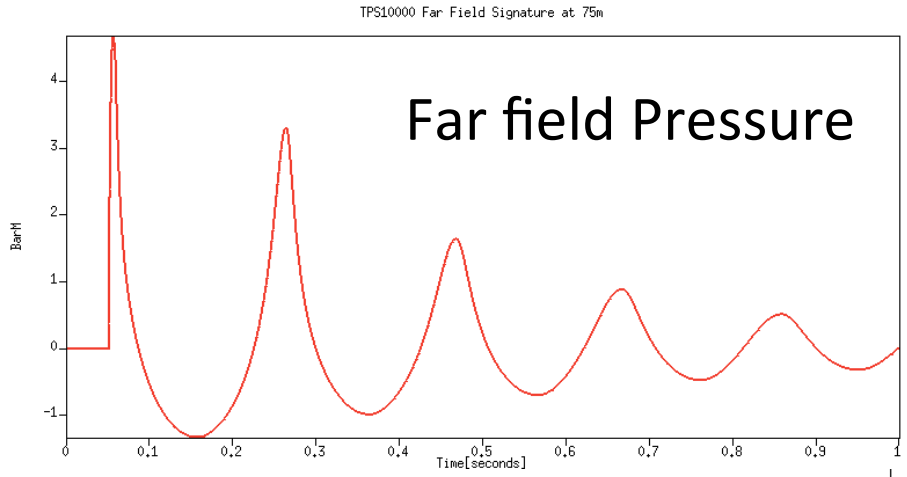
Pressure

Acoustic radiation

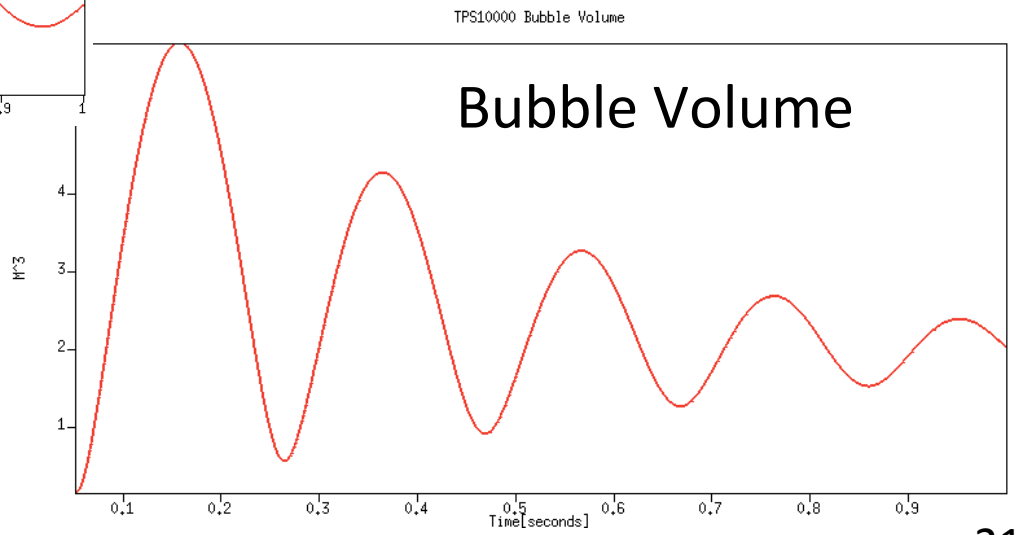
$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{2S}{\rho_\infty R} = \frac{p - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p} + F(t)$$

- No surface tension
- No Force—homogeneous equation
- Initially high pressure inside the bubble. Much larger than ambient

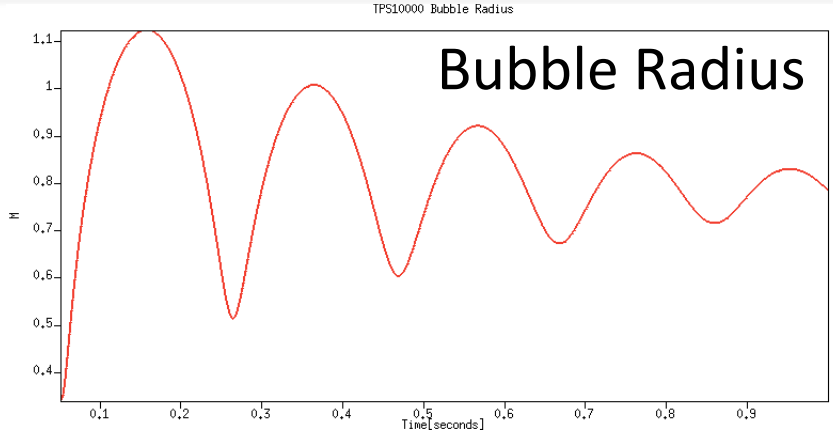
Integrate the far field signature twice



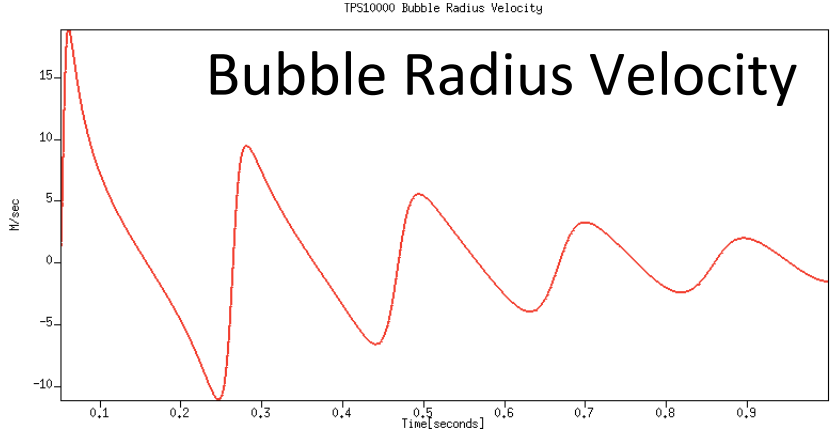
$$\Delta p(t,r) = \rho_\infty \left[\frac{\ddot{V}(t - r/c)}{4\pi r} - \right.$$

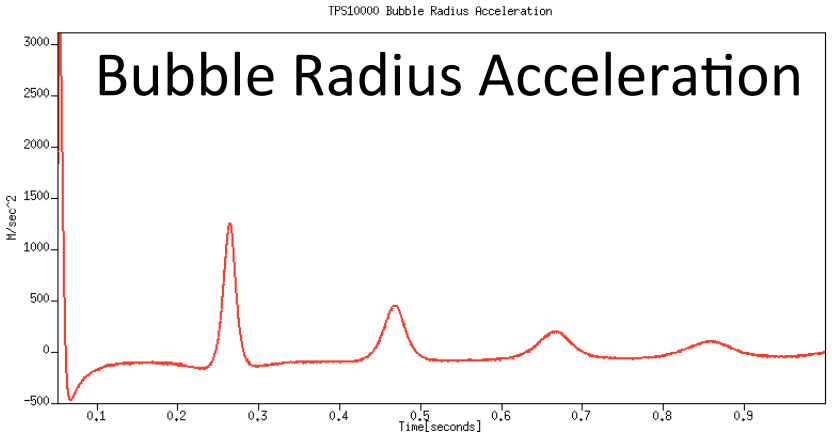


Bubble radius calculated from the volume

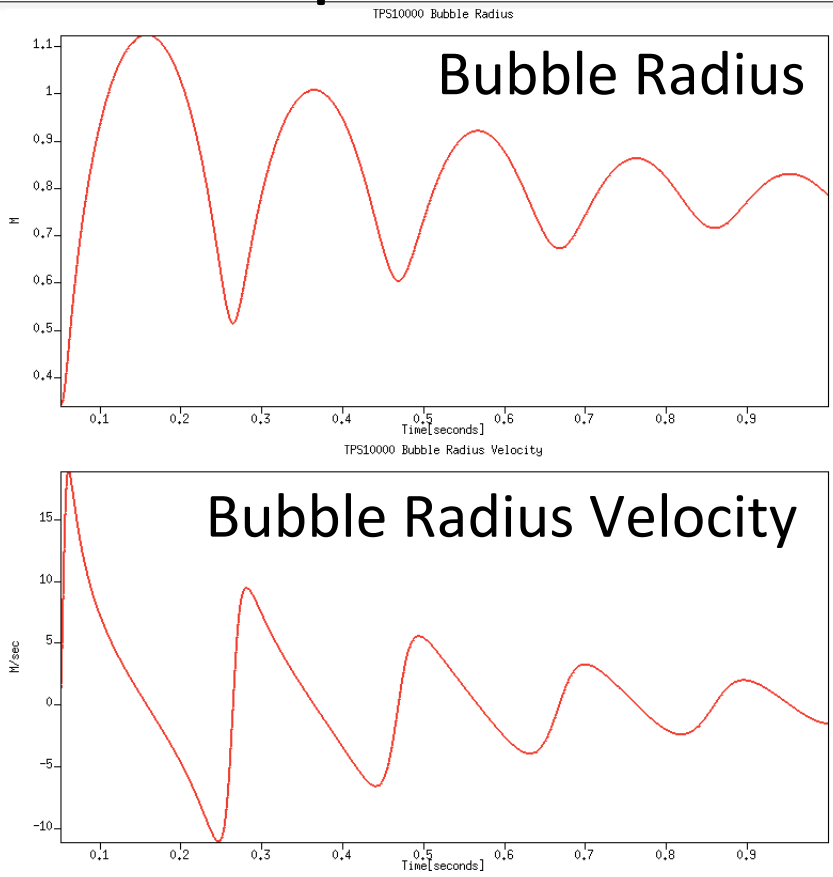


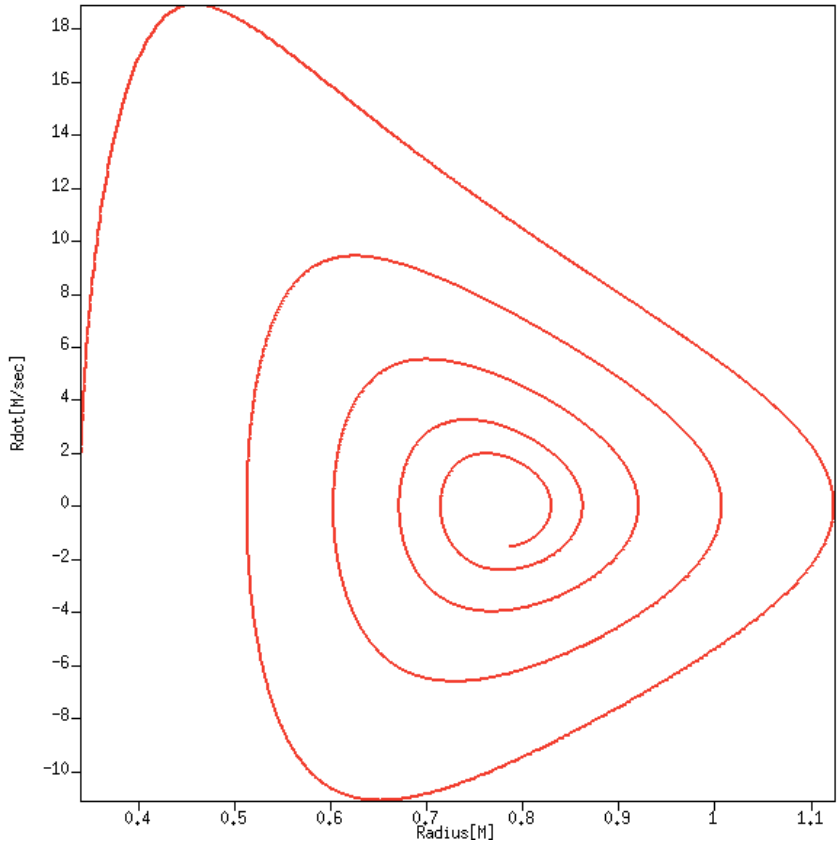
Volume = $4\pi/3\ R^3$





Cross-plot Radius and velocity





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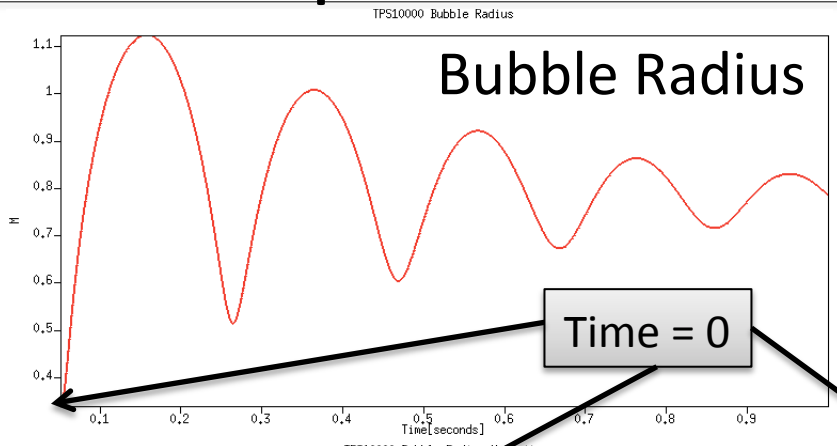
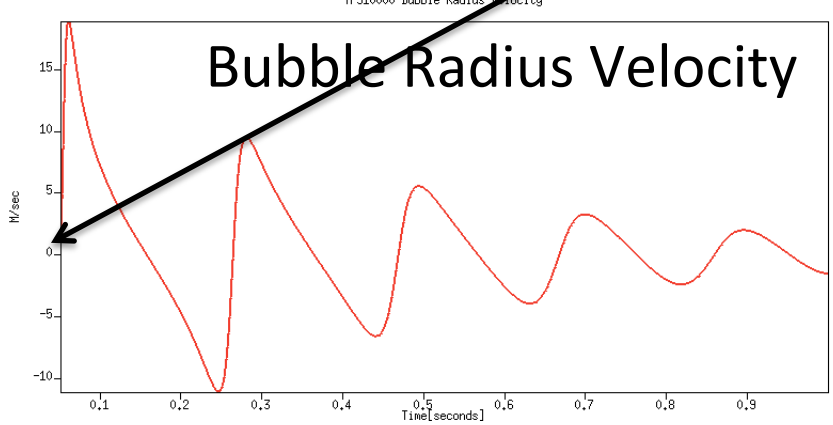
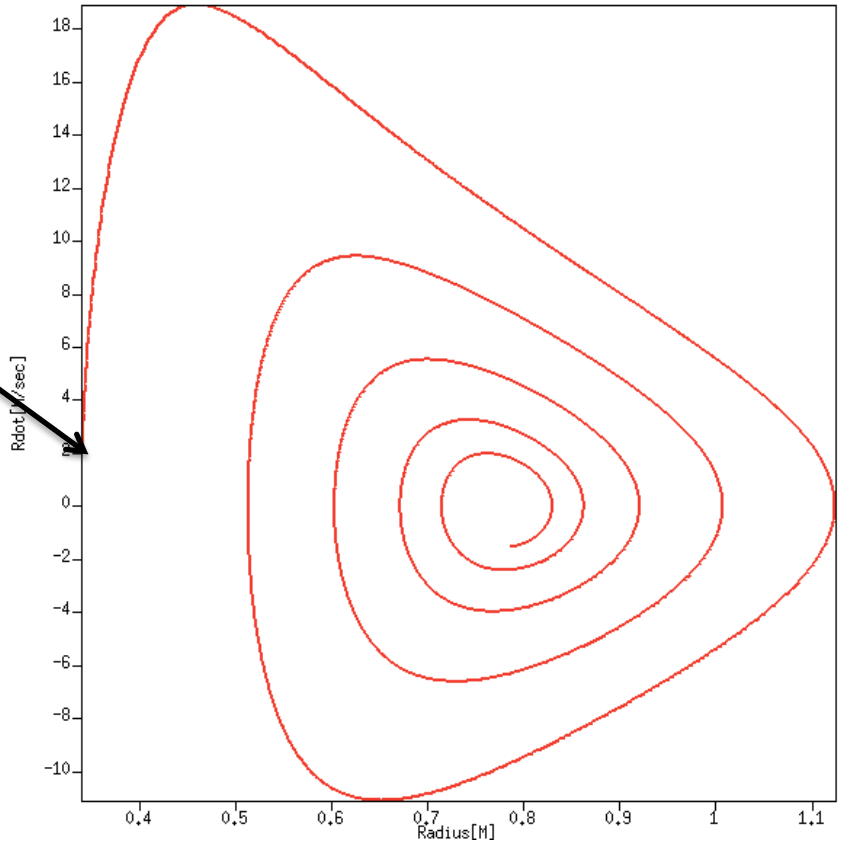
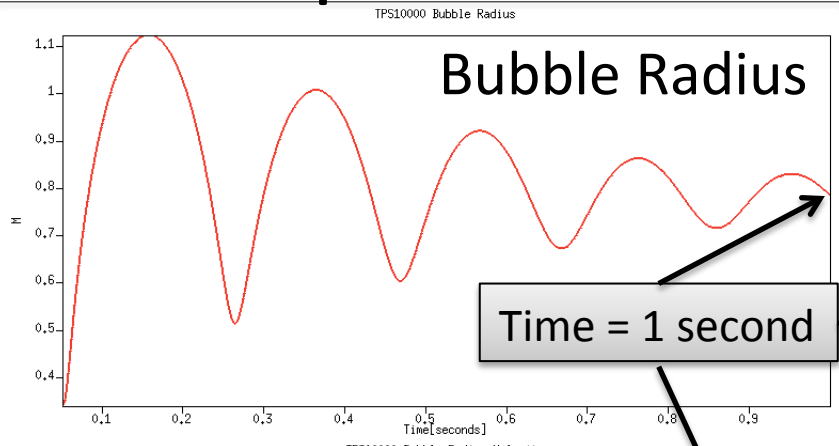


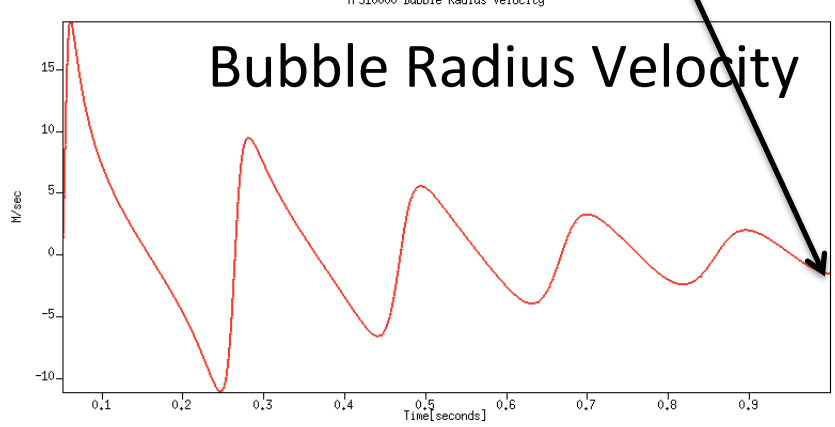
Time = 0



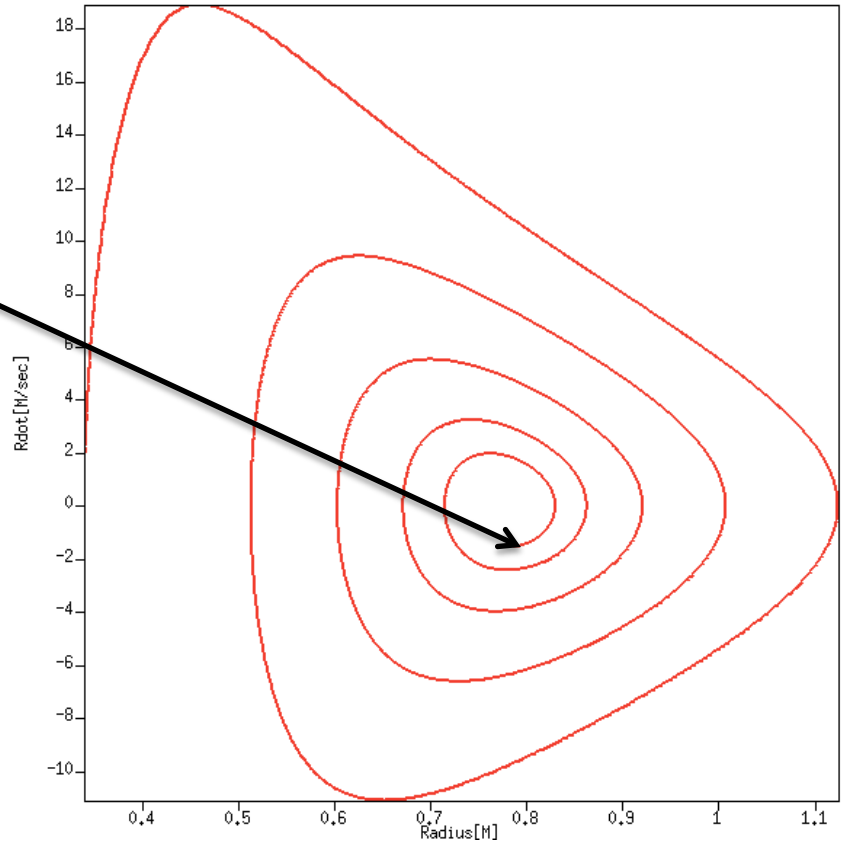


Cross-plot Radius and velocity





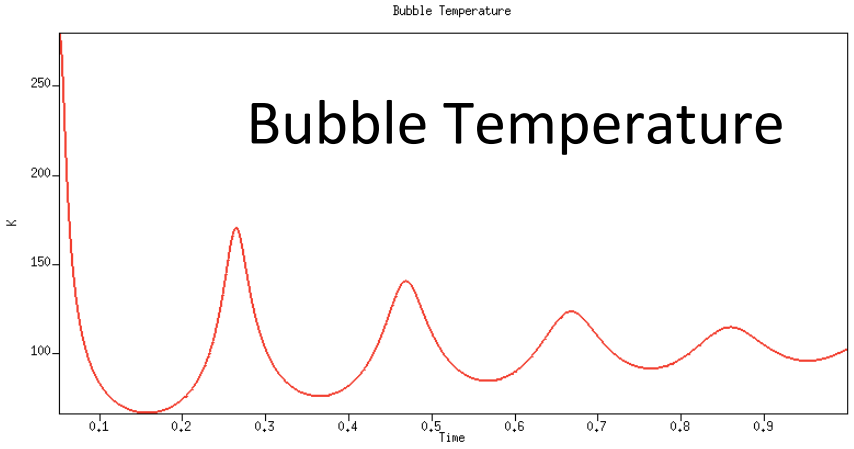
Time = 1 second

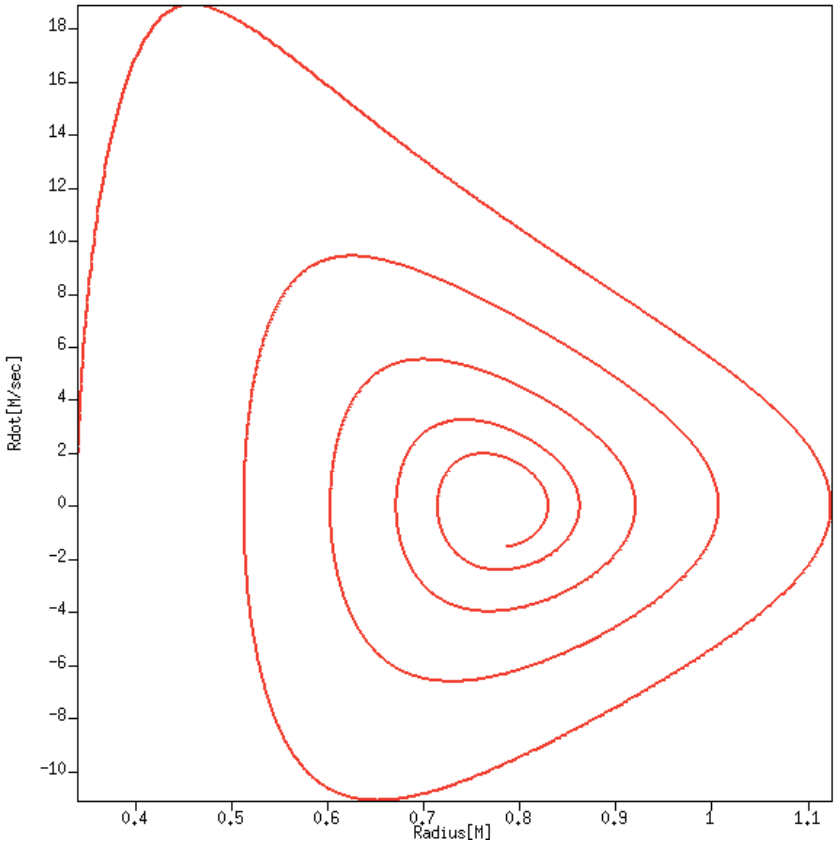


Radiating adiabatic oscillator

Energy:

- Kinetic proportional to Velocity^2
- Potential proportional to $(R-R_\infty)^2$
- Thermal proportional to Temperature
- Radiated as acoustic wave





Zero Kinetic Energy: R dot = 0

Energy:

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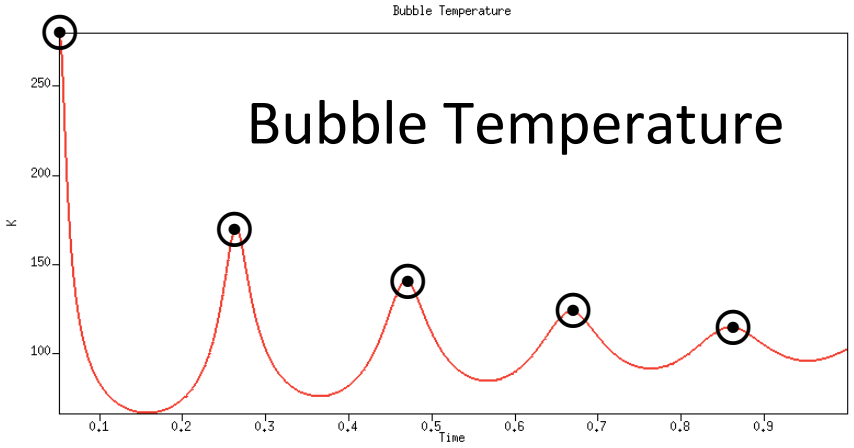

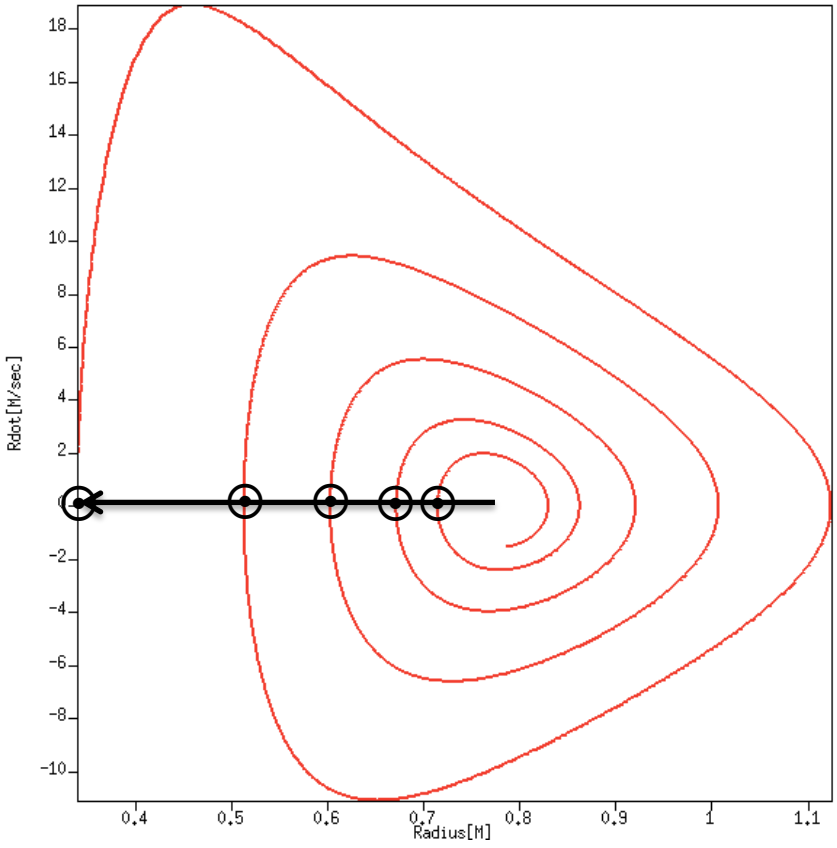

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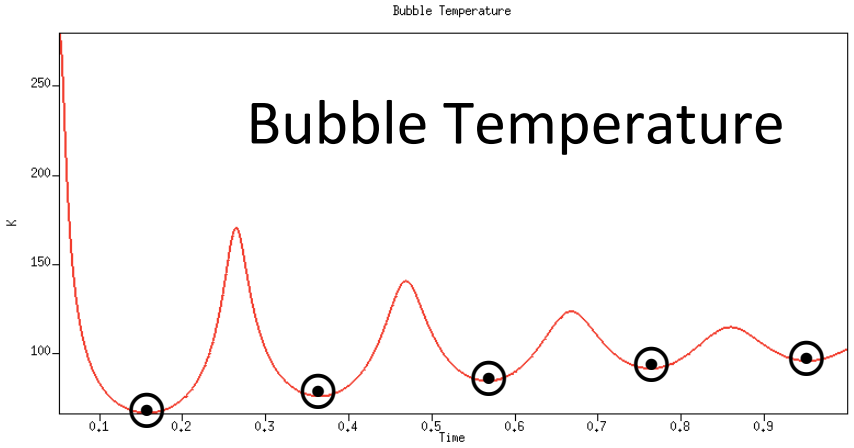
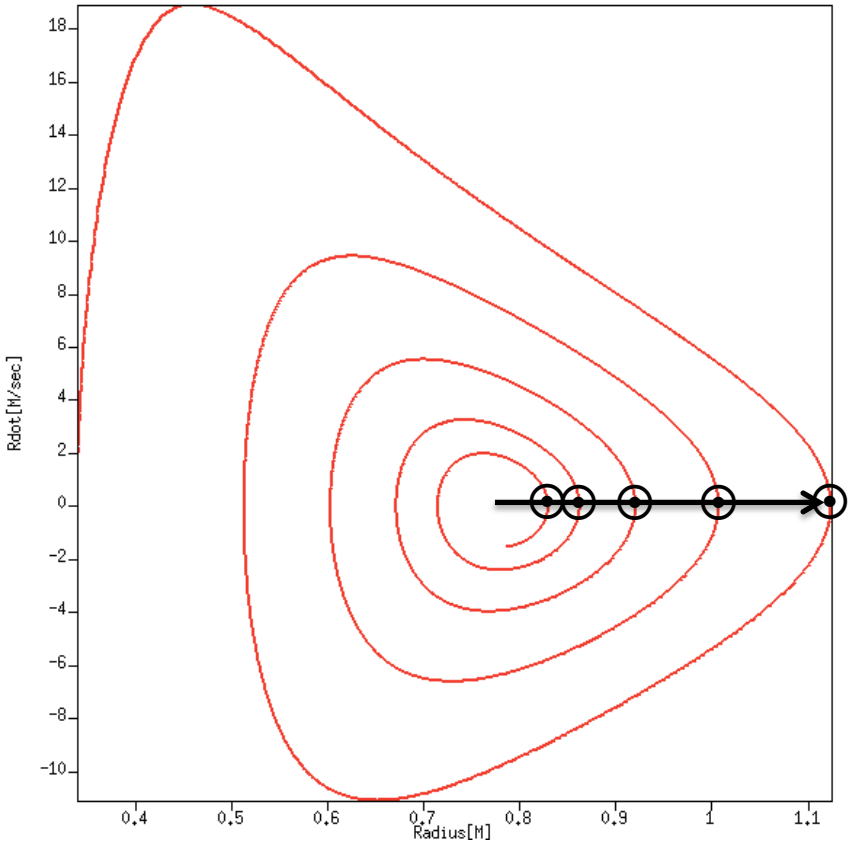
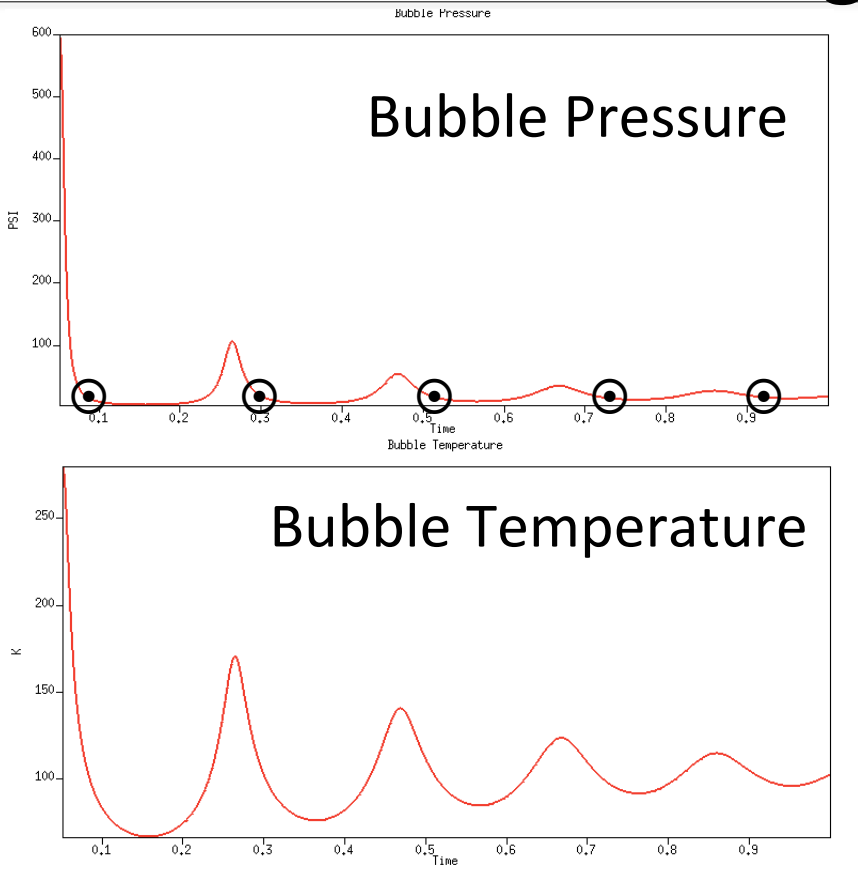
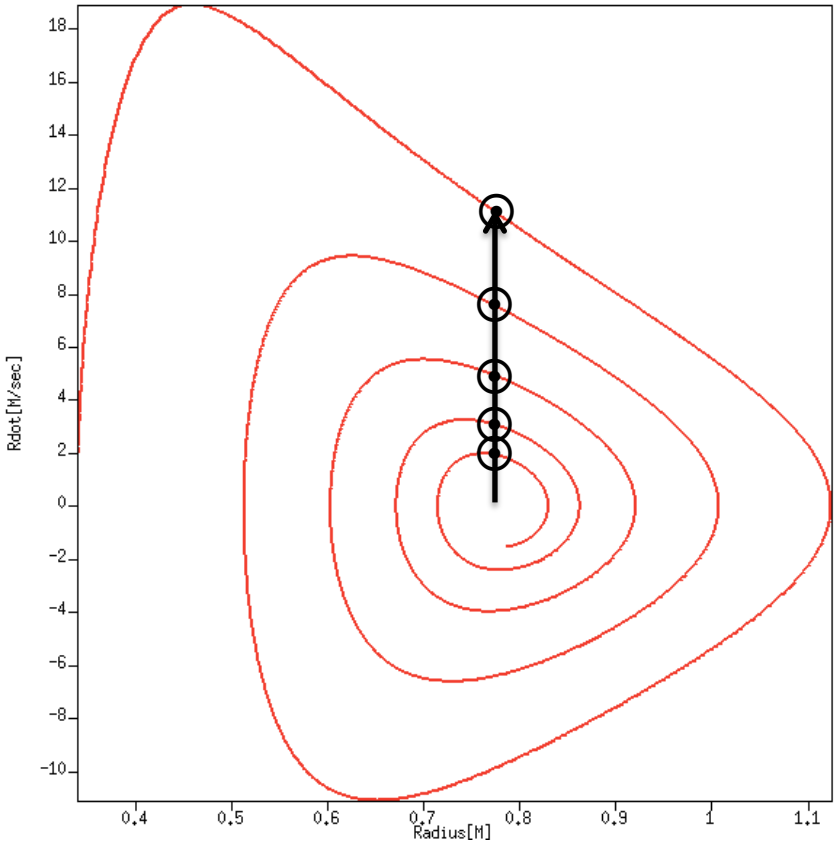


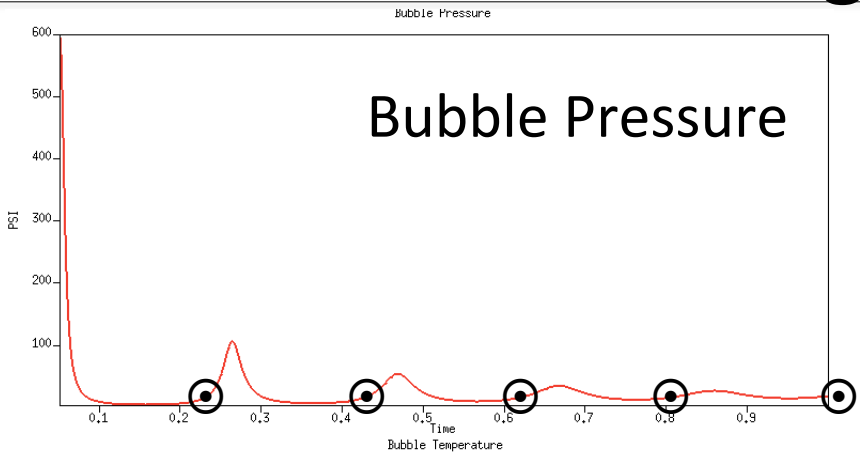


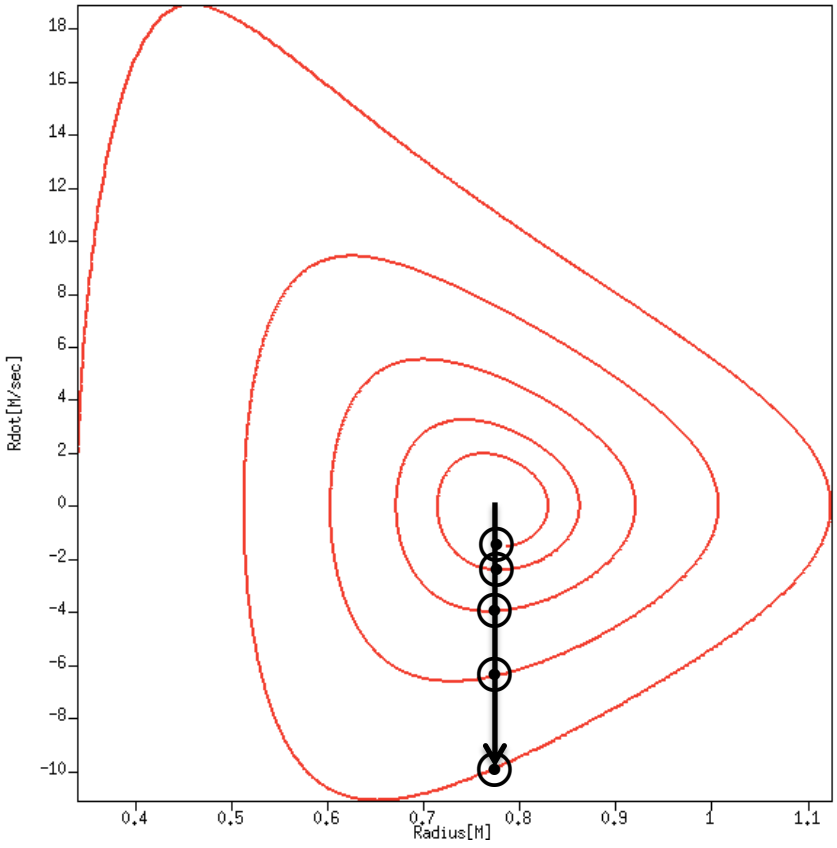
Zero Potential Energy: $R = R_\infty$





Zero Potential Energy





Modeling Fin Whale low frequency calls

Modeling code by Leighton Watson

Whale tag data from Stanford University and UCSB

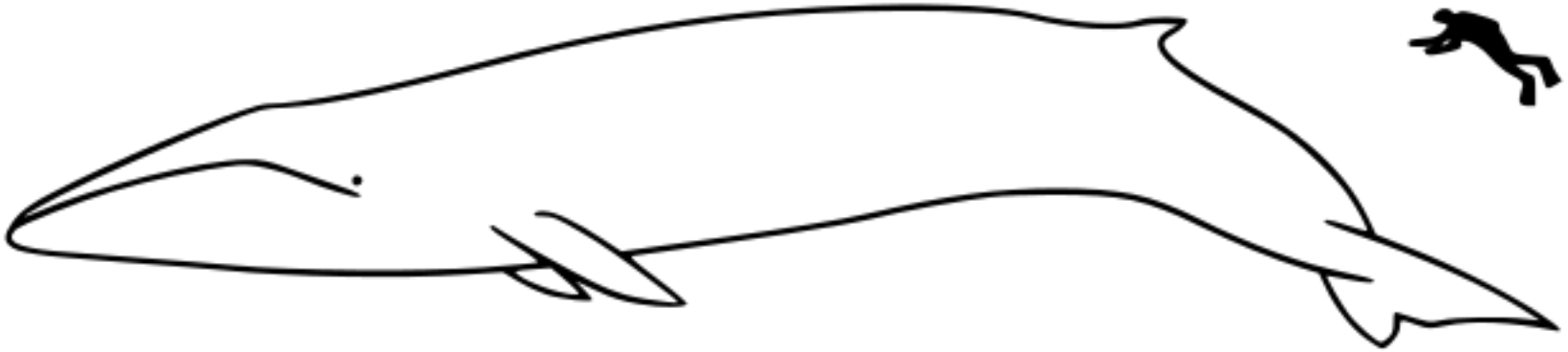
Under work by Watson, Ronen, Dunham, Goldbogen, Southall

Fin whales



The second largest whale (after the Blue whale)
27m long, 100 tons (Blue whale: 30m, 180 tons)

Fin Whales



Moans up to 186 dB re uPaM (Blue whale up to 188 dB)
(According to https://en.wikipedia.org/wiki/Whale_vocalization)
The biologists we talked to did not know the mechanism

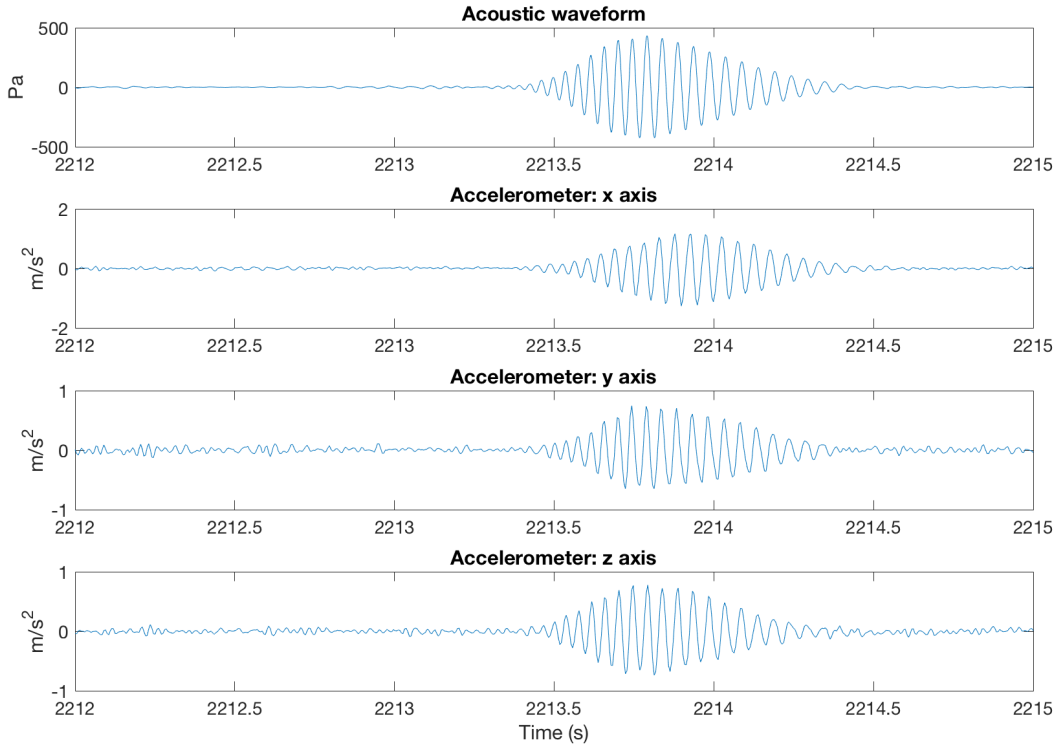
Tagging a whale



The tag is deployed on the whale skin

- A Hydrophone
- 3-C accelerometer
- GPS
- Depth sensor
- …

Data from a tag on a Fin whale

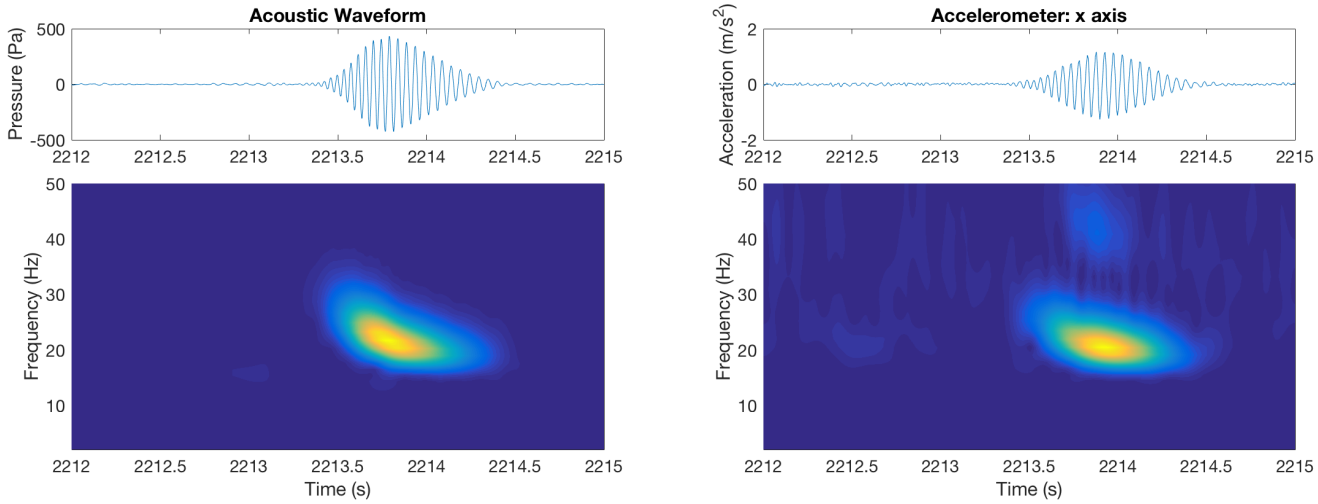


Goldbogen et al, 2014

Using accelerometers to determine the calling behavior of tagged baleen whales

This tag was deployed over the lungs

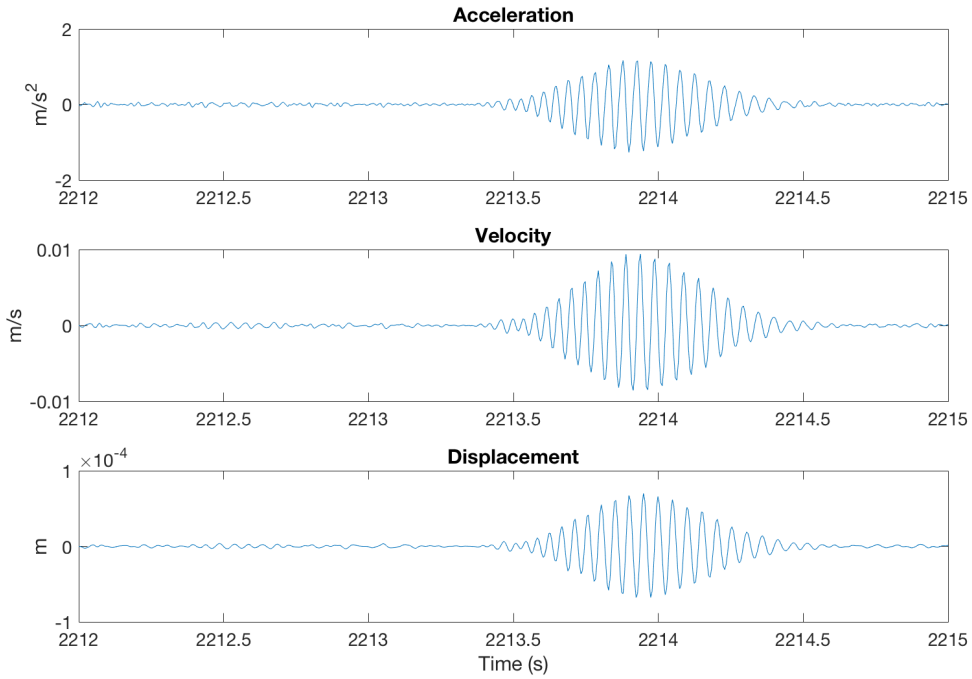
Data from a tag on a Fin whale (CWT)



Continuous Wavelet Transform (CWT)

The whale is sweeping down from 30Hz to 15 Hz

Tag data processing: time integration



Acceleration data

Integrate once to get Velocity

… twice to get Displacement

Fin whale lung

Each lung 2 meter long
About 2/3 meters diameter

Cluster of 2 lungs

Fin whale Total Lung Capacity

TLC = 1300 Litres

Piscitelli et al, 2014. A Review of Lung Morphology and Mechanics

Chapter 12).

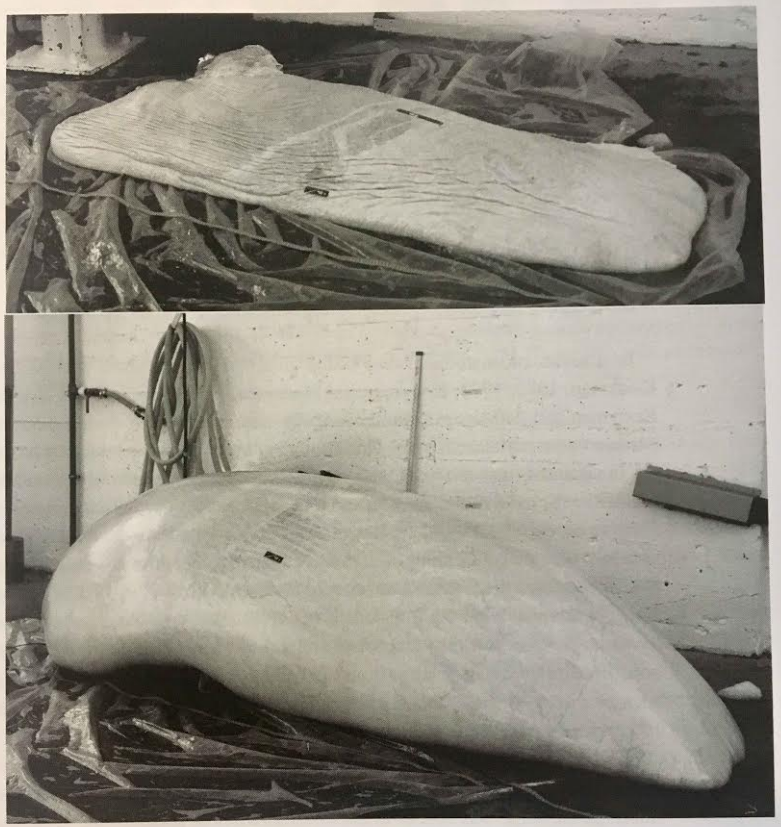


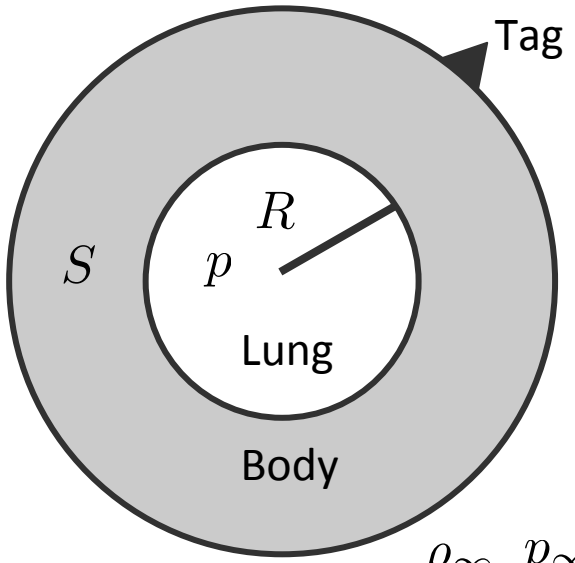
Figure 3.1 Deflated and inflated lung of a fin whale, *Balaenoptera physalus*. Such observations of lungs on a whaling vessel probably led Scholander to the hypothesis of lung collapse at depth as a mechanism for the prevention of decompression sickness in deep-diving marine mammals. Photographs with permission and courtesy from W. Vogl and M. Piscitelli.

Modeling a whale

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{2S}{\rho_\infty R} = \frac{p - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p} + F(t)$$

Surface tension

Force



$\rho_\infty \quad p_\infty \quad c_\infty$

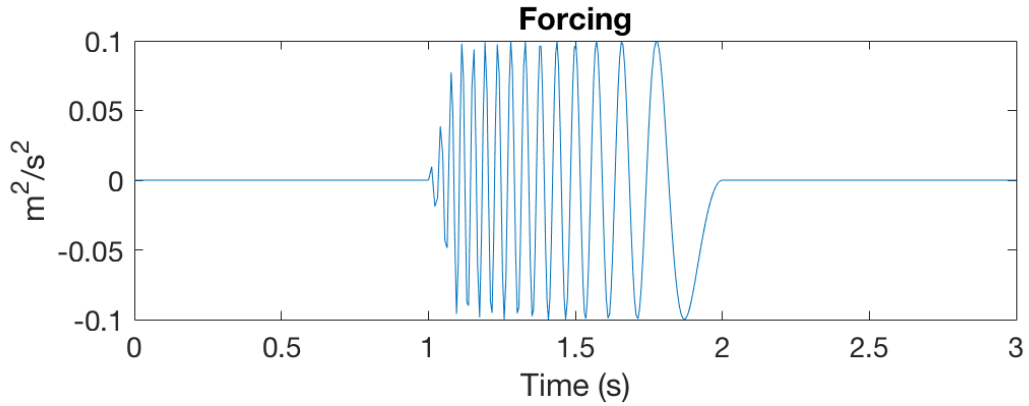
Whale terms

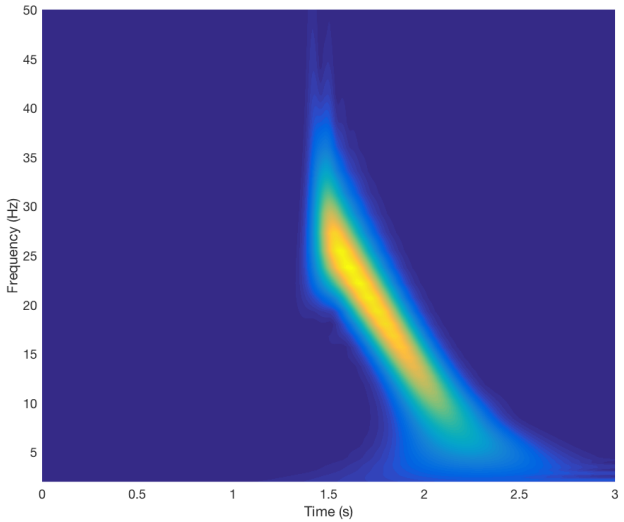
- Surface tension of whale body
- Start with equilibrium $p(0) = p_\infty$
- Force from muscles that excite oscillation

Quick check: Guess a Force term

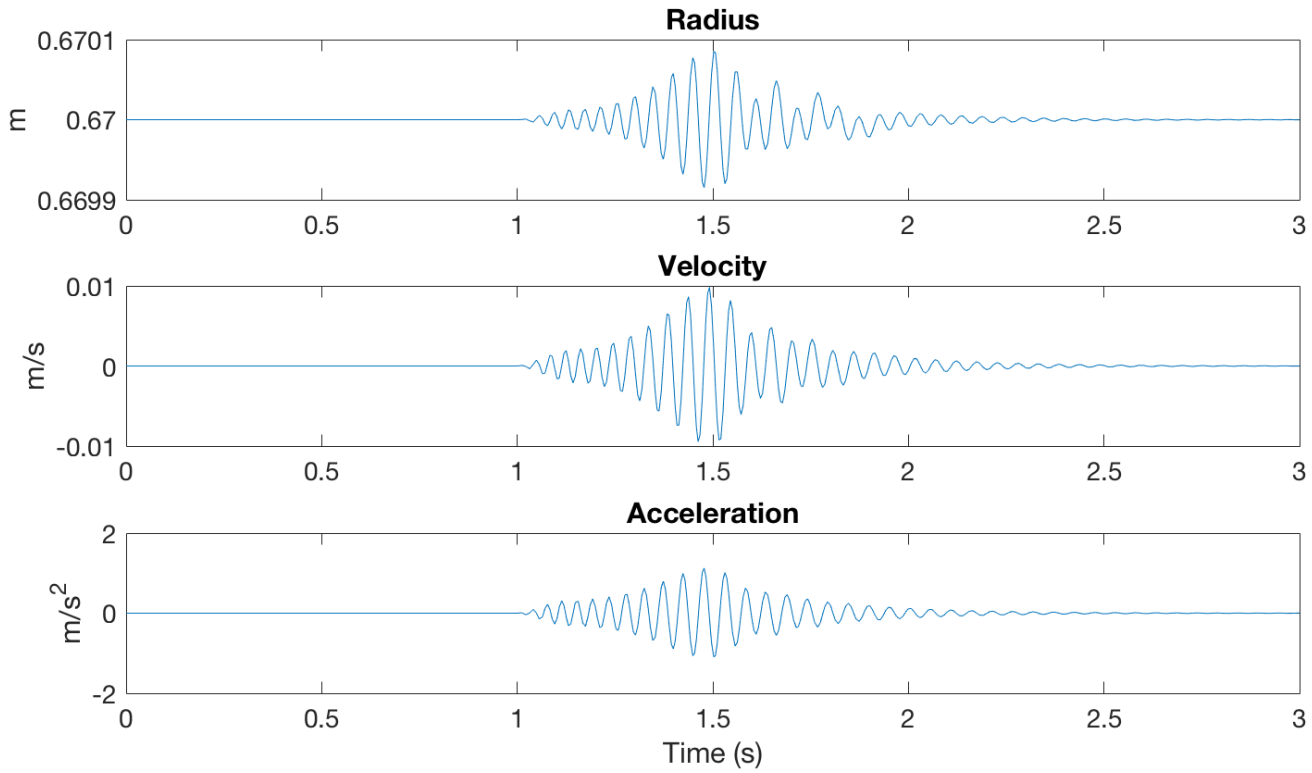
$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{2S}{\rho_\infty R} = \frac{p - p_\infty}{\rho_\infty} + \frac{R}{\rho_\infty c_\infty}\dot{p} + F(t)$$

Forcing

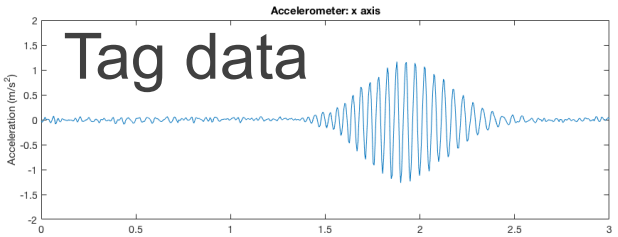


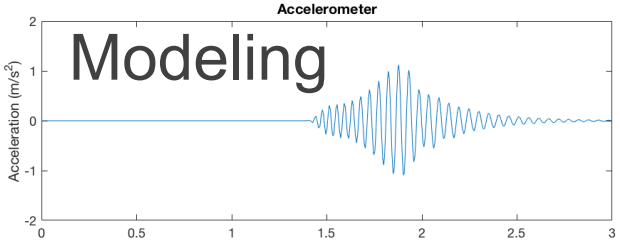


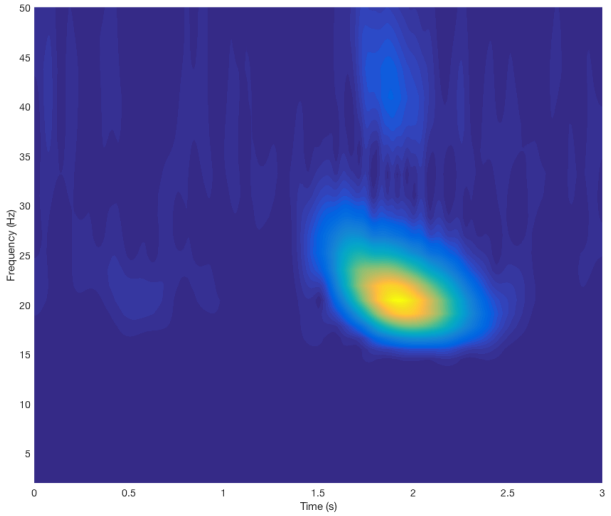
Modeling results

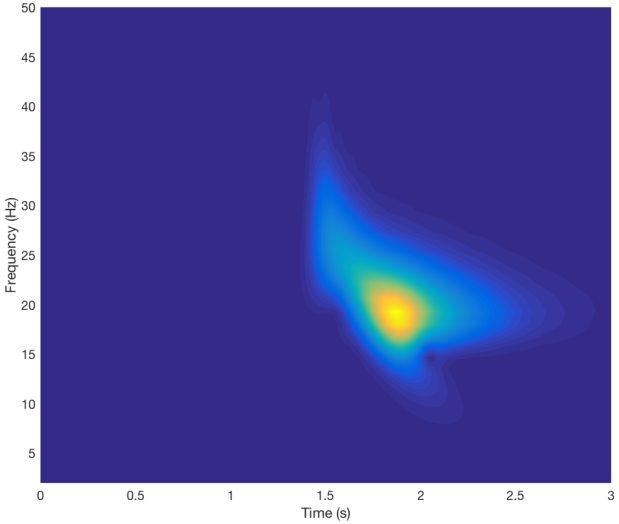


Compare modeling to tag data









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Summary

- Whale moans are forced oscillation of their lungs
  - They learned to use generalized Rayleigh-Willis
  - They select their depth optimally for bubble and ghost
- We can follow them with modified air gun modeling
  - Add surface tension to simulate the whale body
  - Add force to simulate the whale muscles
  - Whale moan modeling: starting from equilibrium
  - Air gun modeling: starting from high initial pressure

On going work

- Check with biologists and biophysicists co-authors—do they have the muscle and the nerve control (30-15 Hz sweep)
- Do they always down sweep or can they use up/down/other FM signal to communicate information?
- Invert for the force (model green function impulse response and then shaping filter to deconvolve the data by the green function)

Sometimes there are harmonics

http://marinebio.org/oceans/sounds-of-the-sea/

"**Northeast Pacific blue whale call**
Northeastern Pacific blue whale calls are perhaps the best known blue whale call to date. They generally consist of two parts, A and B. The A call is a series of pulses (on the order of 1.5 pulses/s) which often exhibits side-banding and the B call is a long FM moan.
Click here (338 kb, 10x) to hear the northeastern blue whale call."

