UiO **: Department of Informatics**
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Second harmonic imaging in active sonar

Tutorial lecture 8. January 2016,
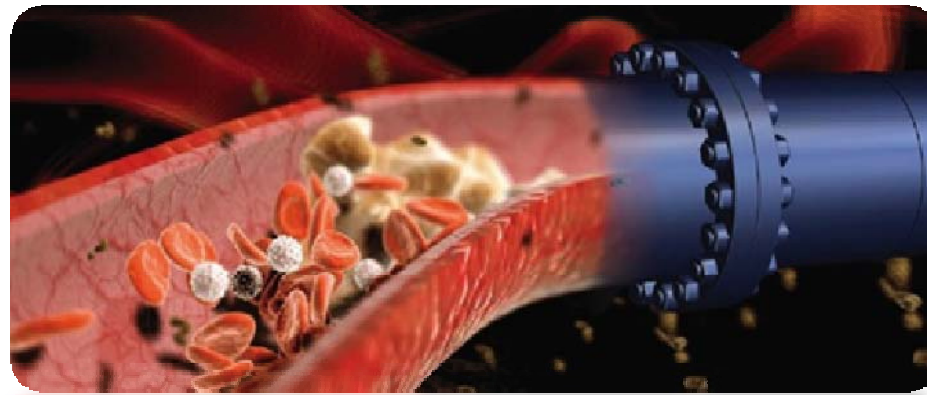**2016 IEEE/OES China Ocean Acoustics Symposium**

Sverre Holm and Fabrice Prieur

COA 2016 中国海洋声学研讨会
IEEE/OES China Ocean Acoustics Symposium
Harbin, China | January 9-11, 2016

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Centre for Innovative Ultrasound Solutions

For health care, maritime, and oil & gas

2015-2023
3 academic, 11 commercial, 4 public partners.
Norwegian Research Council
Centre for research-based innovation (SFI)

The Great Wave off Kanagawa.
Katsushika Hokusai (1760–1849)

Outline

- Wave equation and the two mechanisms for nonlinearity

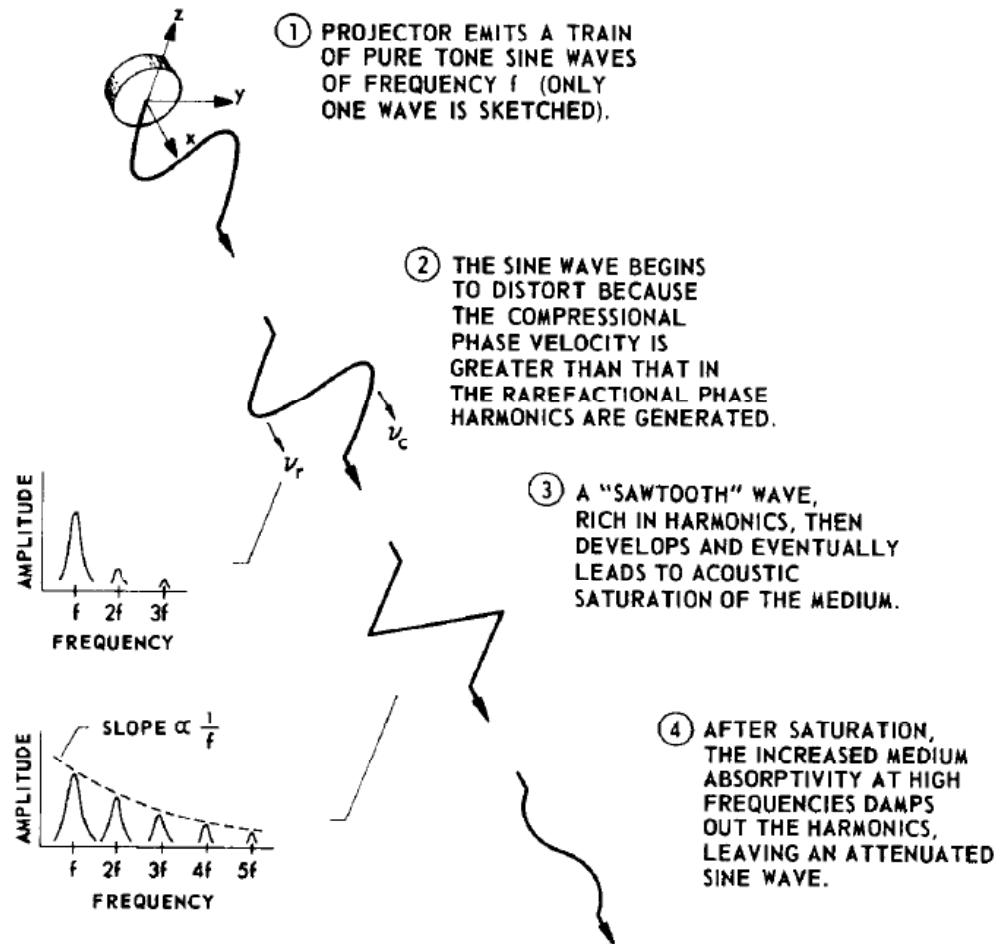- Important applications

- Second harmonic sonar

Feasibility of Second Harmonic Imaging in Active Sonar: Measurements and Simulations

Fabrice Prieur, Sven Peter Näsholm, *Member, IEEE*, Andreas Austeng, *Member, IEEE*, Frank Tichy, and Sverre Holm, *Senior Member, IEEE*

Harmonic generation

① PROJECTOR EMITS A TRAIN OF PURE TONE SINE WAVES OF FREQUENCY f (ONLY ONE WAVE IS SKETCHED).

② THE SINE WAVE BEGINS TO DISTORT BECAUSE THE COMPRESSIONAL PHASE VELOCITY IS GREATER THAN THAT IN THE RAREFACTIONAL PHASE HARMONICS ARE GENERATED.

③ A "SAWTOOTH" WAVE, RICH IN HARMONICS, THEN DEVELOPS AND EVENTUALLY LEADS TO ACOUSTIC SATURATION OF THE MEDIUM.

④ AFTER SATURATION, THE INCREASED MEDIUM ABSORPTIVITY AT HIGH FREQUENCIES DAMPS OUT THE HARMONICS, LEAVING AN ATTENUATED SINE WAVE.

HARMONIC SPECTRA

- Losses
- Nonlinearity
- Weak nonlinearity

- Muir and Carstensen: Prediction of nonlinear acoustic effects at biomedical frequencies and intensities, Ultrasound in Medicine & Biology, 1980
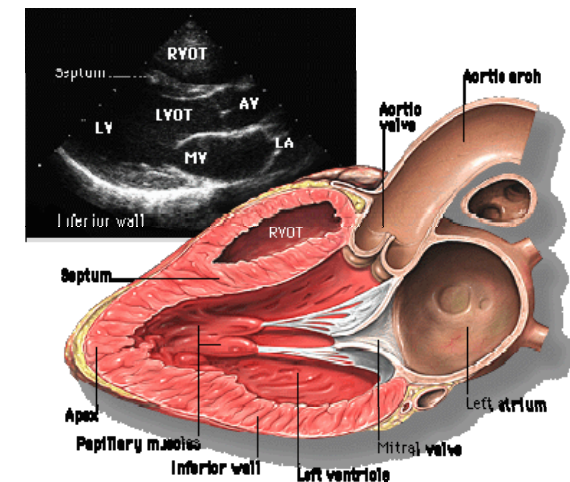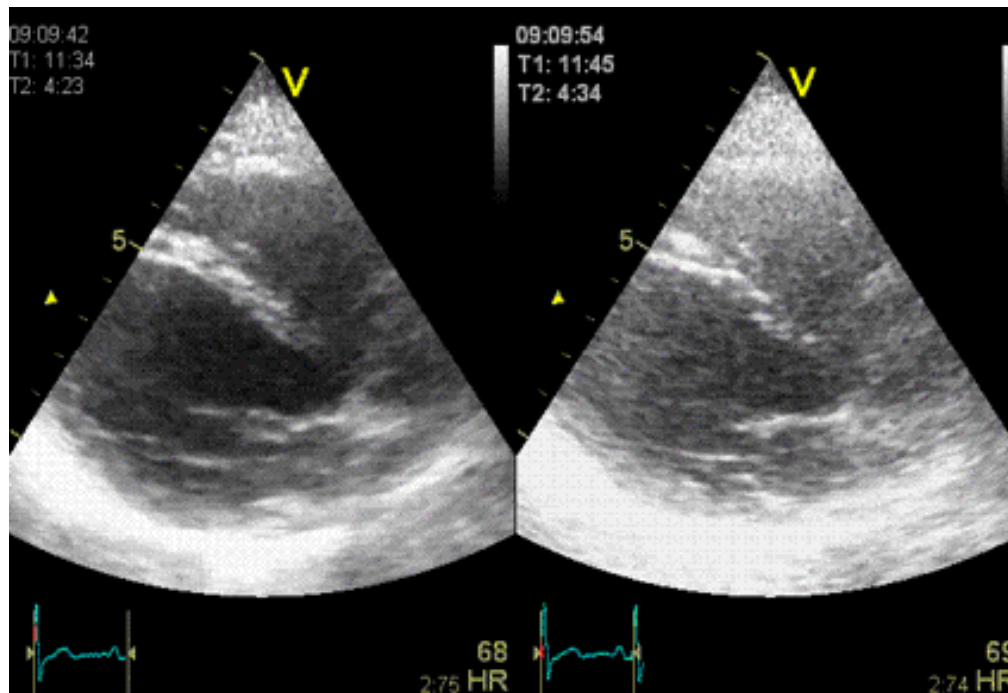
Applications of nonlinear acoustics

Difference frequency:

- Parametric sonar

- Parametric loudspeaker

- Parametric imaging in medical ultrasound

Harmonics:

- Harmonic imaging in medical ultrasound

- Harmonic imaging in sonar

Tissue Harmonic Medical Imaging

- Ultrasound image of a heart (parasternal view) using second harmonic (left) and fundamental (right) signals. (Courtesy of Asbjørn Støylen, NTNU, Trondheim, Norway
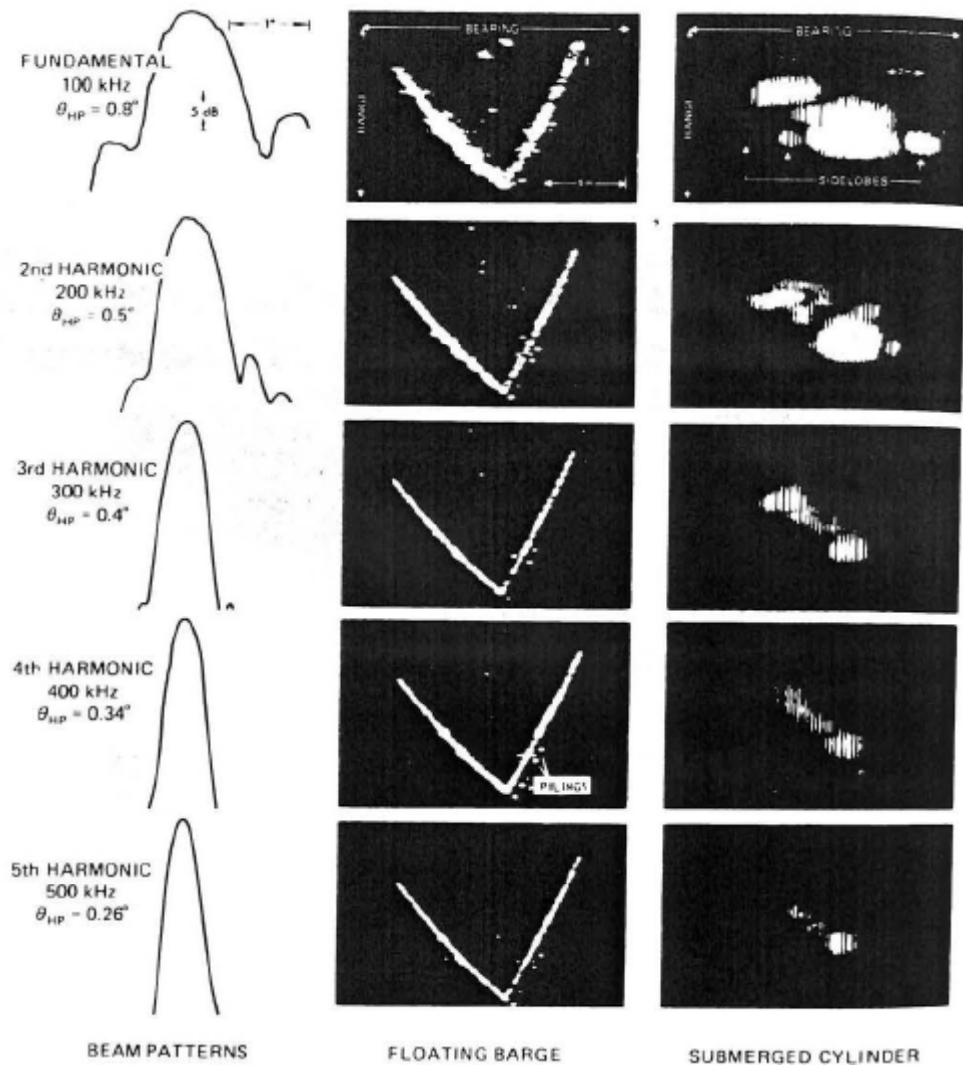
Muir 1980
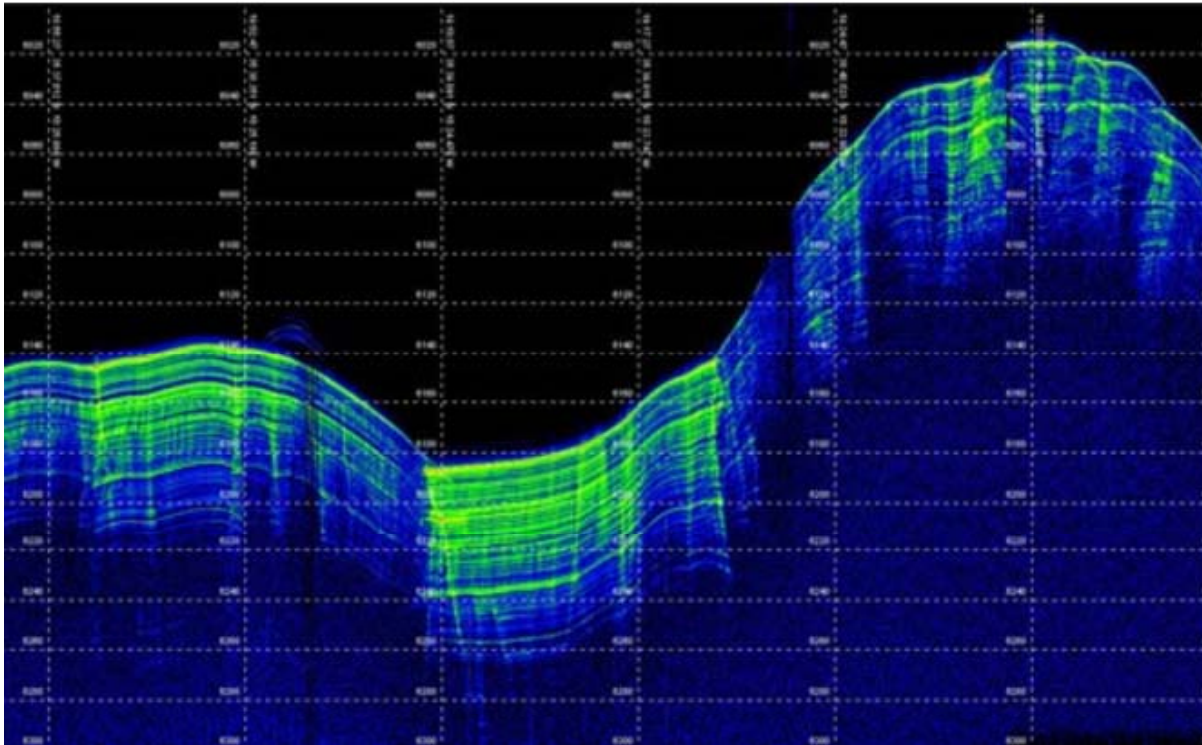
NONLINEAR EFFECTS IN ACOUSTIC IMAGING

Thomas G. Muir

Applied Research Laboratories
The University of Texas at Au
Austin, Texas 78712

Range – bearing display
 @ 100 m range

4th harmonic: fair reprentation
of cylinder target

FUNDAMENTAL
100 kHz
$\theta_{HP} = 0.8°$

2nd HARMONIC
200 kHz
$\theta_{HP} = 0.5°$

3rd HARMONIC
300 kHz
$\theta_{HP} = 0.4°$

4th HARMONIC
400 kHz
$\theta_{HP} = 0.34°$

5th HARMONIC
500 kHz
$\theta_{HP} = 0.26°$

BEAM PATTERNS

FLOATING BARGE
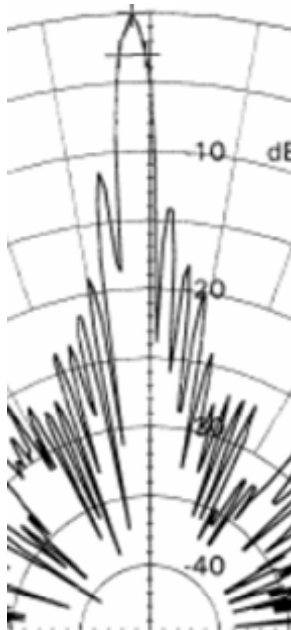
SUBMERGED CYLINDER

Parametric sub-bottom profiler

TOPAS parametric sonar.
Water depth >4600 m, penetration depth 60-90 m.
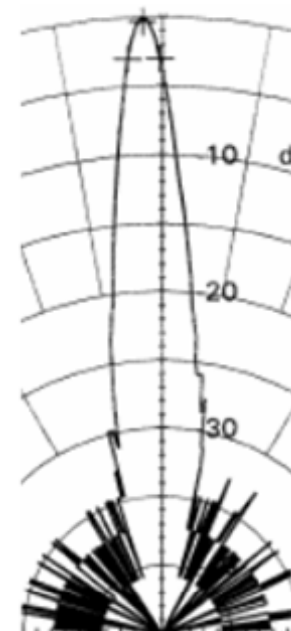Courtesy of Kongsberg Maritime, Norway

Primary and secondary beamprofiles
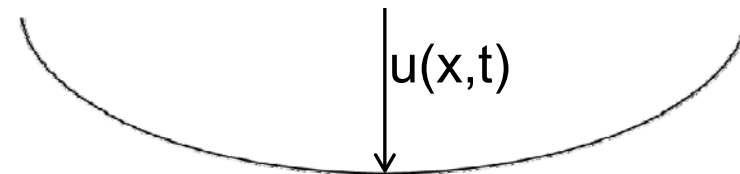
Primary: 40 kHz

Secondary: 4 kHz

Conventional sonar would have required
5-10 times larger aperture

Lossless wave equation

- ## Think of u as the displacement of a string

$$\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial t^2}$$

u(x,t)

- ## Left: Positive second derivative if u(x) is smaller than its neighbors

- ## Right: Then acceleration is upwards

Lossless wave equation

$$\nabla^2 p - \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} = 0$$

- Laplacian, second derivative in space:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

- c_0 = speed of sound (at zero frequency)
- p = pressure

Add some losses

$$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \tau \frac{\partial}{\partial t}\nabla^2 p = 0$$

- τ, viscosity/bulk modulus (solid)

- Small loss approximation: $\nabla^2 p \approx \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2}$
- So lossy wave equation is often written

$$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \frac{\delta}{c_0^4}\frac{\partial^3 p}{\partial t^3} = 0, \quad \delta = \tau c_0^2$$
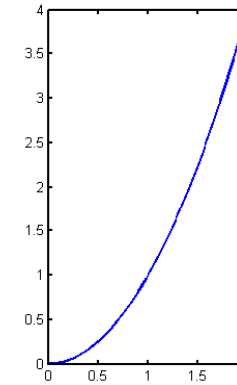
Losses in a fluid, gas in particular

$$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \frac{\delta}{c_0^4}\frac{\partial^3 p}{\partial t^3} = 0$$

- Loss: $\delta = \delta_{me} + \delta_{th} = \frac{1}{\rho_0}\left(\zeta + \frac{4}{3}\eta\right) + \frac{\kappa}{\rho_0}\left(\frac{1}{c_v} - \frac{1}{c_p}\right)$
- Mechanical:
  - ζ, η - shear and bulk viscosity coefficients
- Thermal:
  - $\cdot$ - thermal conductivity
  - c_v , c_p - heat capacity at constant volume/pressure.
- Loss terms are additive at low frequencies

Then add nonlinearity

$$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \frac{\delta}{c_0^4}\frac{\partial^3 p}{\partial t^3} = -\frac{\beta}{\rho_0 c_0^4}\frac{\partial^2 p^2}{\partial t^2}$$

- Nonlinearity coefficient: $\beta = 1 + \dfrac{B}{2A}$

- Nonlinearity parameter: B/A
- Westervelt equation

Observations

- Mechanical and thermal losses

$$\delta = \delta_{me} + \delta_{th} = \frac{1}{\rho_0}\left(\zeta + \frac{4}{3}\eta\right) + \frac{\kappa}{\rho_0}\left(\frac{1}{c_v} - \frac{1}{c_p}\right)$$

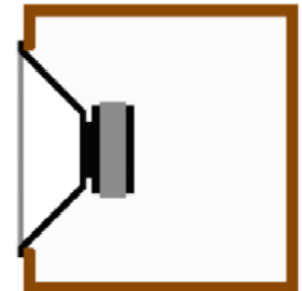- Also two contributions to nonlinearity

$$\beta = 1 + \frac{B}{2A}$$

Nonlinearity (1)

- Convection: The '1' in β=1+B/2A

- The collective movement of ensembles of molecules within fluids

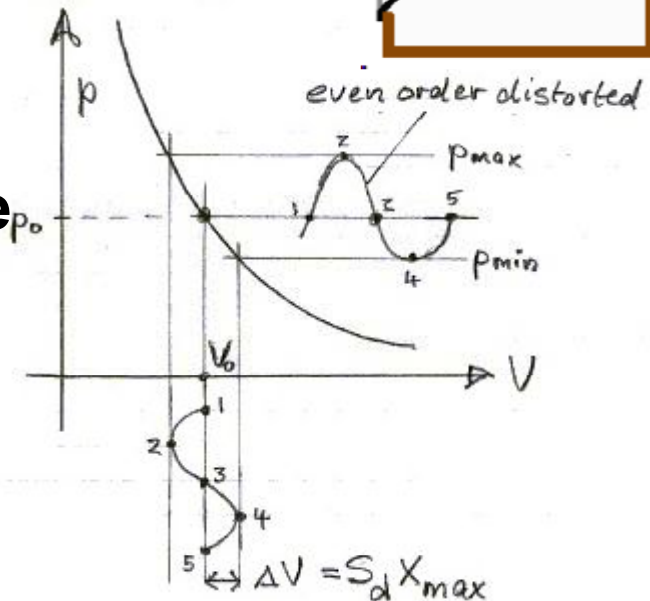- Propagation velocity is $c = c_0 \pm u$ due to particle velocity, u:
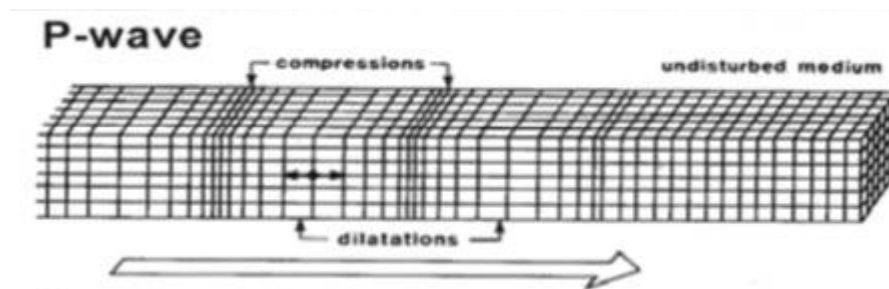
Nonlinearity (2)

– B/2A term: Pressure – density relation

– Gas law, adiabatic (no heat transfer) $pV^{\gamma}=C$

– γ is the adiabatic exponent, $\gamma = 1.4$ for air

Closed enclosure subwoofer:

– A loudspeaker affects the **volume**

– Our ears sense the **pressure**

– Small box & high-power

– Siegfrid Linkwitz, www.linkwitzlab.com

State equation for gas (gas law)

$$\frac{p}{p_0} = \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

- Taylor series for pressure variation:

$$p - p_0 = A\frac{\rho - \rho_0}{\rho_0} + \frac{B}{2!}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \cdots$$

- Combined: A=$\rho_0\gamma$, B=$\rho_0\gamma(\gamma-1)$ and **B/A = γ-1**

- A nonlinear spring: replaces Hooke's law
  – Similar approach for fluids

Nonlinearity parameter B/A

Material	B/A = γ-1
Blood	6.1
Brain	6.6
Fat	10
Liver	6.8
Muscle	7.4
Water	5.2

$\beta = 1 + B/2A$ is nonlinearity coefficient

- Wikipedia

Sound speed under nonlinearity

Speed of sound, *c,* varies with particle displacement, *u*, or pressure *p:*

$$\frac{dx}{dt} = c(t) = c_0 + (1 + \frac{B}{2A})u(t) = c_0 + (1 + \frac{B}{2A})\frac{p(t)}{\rho_0 c_0}$$

- *p₁(t)* = pressure = *p₀* + *p(t)*
  - *p₀* = static pressure
  - *p(t)* = applied pressure variation (= "signal")

Nonlinearity and plane wave

- A plane wave in water,
- Initial amplitude: 2 MPa = 20 atm
- Frequency of 3.5 MHz
- Propagates for 100 mm.
- Starts to deform immediately,
- Peak-to-peak amplitude and power decrease only slowly, following the exponential attenuation of water.
- Beyond 35 mm, however, a shock wave has formed, and the amplitude decreases rapidly.
- By 100 mm, the amplitude has halved, and 80% of the beam's power has been lost.
- Generated by the "Bergen code" written at the University of Bergen in Norway.
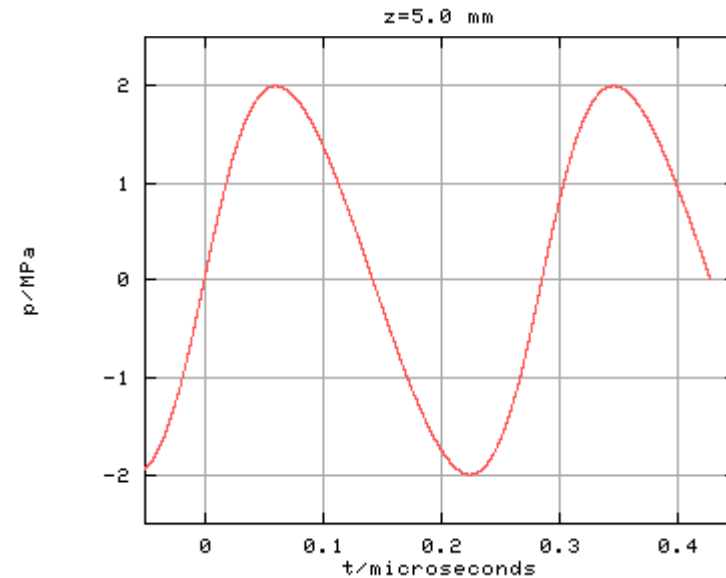
1 MHz pulse shape and harmonics measured in water tank in our lab
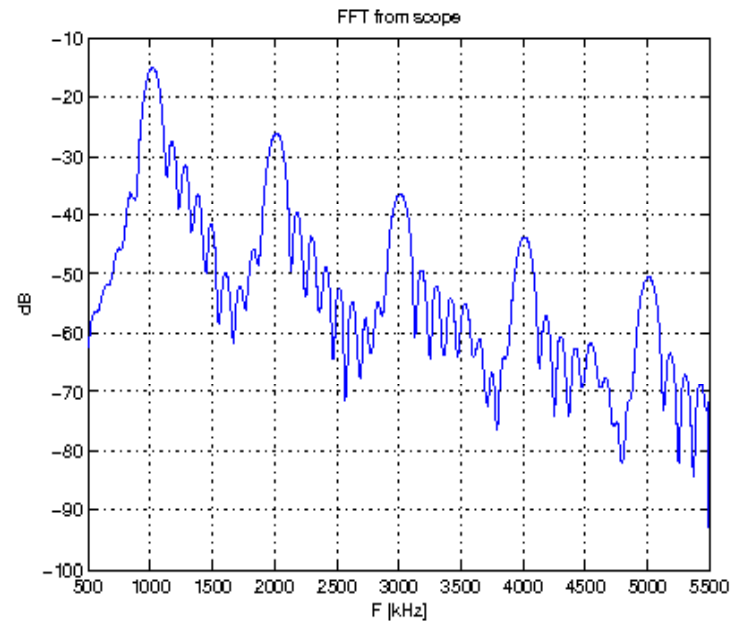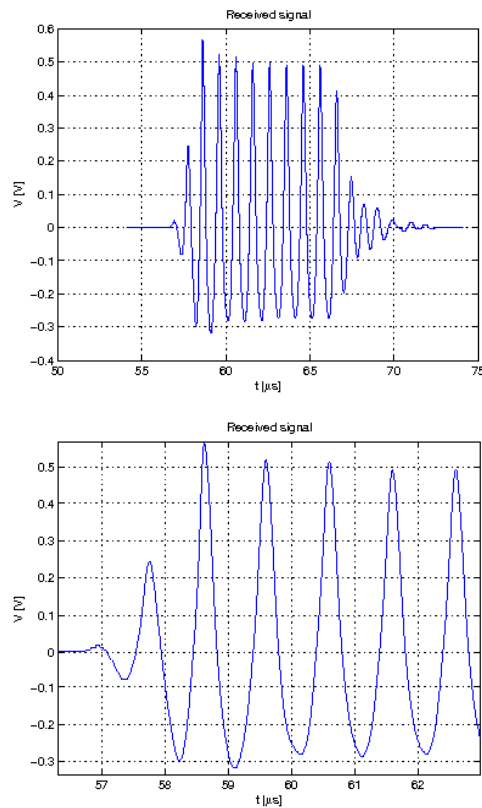
Fabrice Prieur, Sept. 2009

Harmonic & intermodulation distortion

Transmit f_1 and f_2

1. Harmonic distortion: $2f_1$, $2f_2$, $3f_1$, $3f_2$, ...

2. Intermodulation distortion: f_1-f_2, f_1+f_2, $2f_1-f_2$, ...

Main applications of nonlinearity

1. Harmonic imaging, medical ultrasound:

   – Transmit f: generate 2f, (3f, 4f, ...)

2. Parametric sound source, parametric sonar:

   – Transmit f_1 and f_2: Use difference frequency f_1-f_2

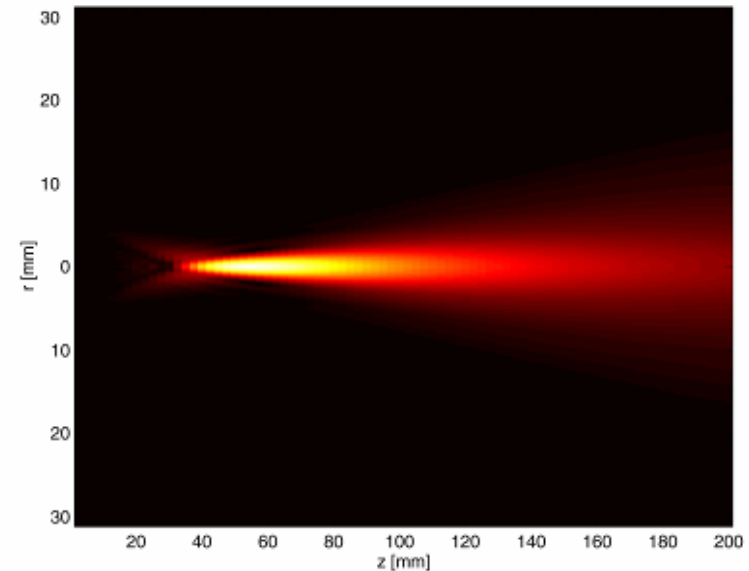   – Narrow beam at primary frequencies also at difference frequency

1 Harmonic imaging
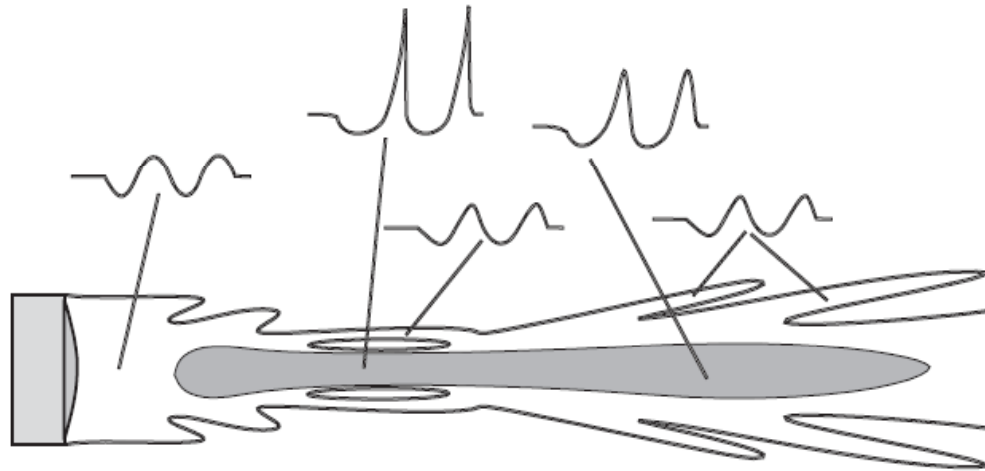
Circular symmetric (1-D) simulation
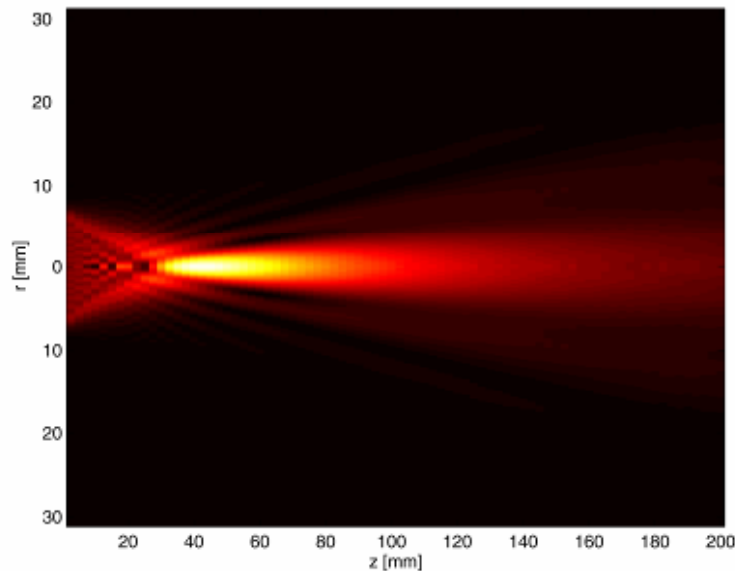
1. harmonic: **2. harmonic:**

15 mm aperturte, focus 60 mm, f=2.275 MHz

J.F.Synnevåg UIO, Burgers equation (Christopher & Parker k-space)

1. Harmonic imaging, ultrasound

Whittingham, Medical diagnostic applications and sources, Progress Biophys & Molecular Biology, 2007

- Positive effect on images:
  - 2. harmonic beam is narrower => better resolution
  - Is not generated in sidelobes of 1. harmonic beam => lower sidelobes
  - Is generated inside medium => avoids some of the reverberations from chest wall
- Negative effect:
  - 2. harmonic attenuates faster => less penetration

Liver, 1. harmonic vs 2. harmonic
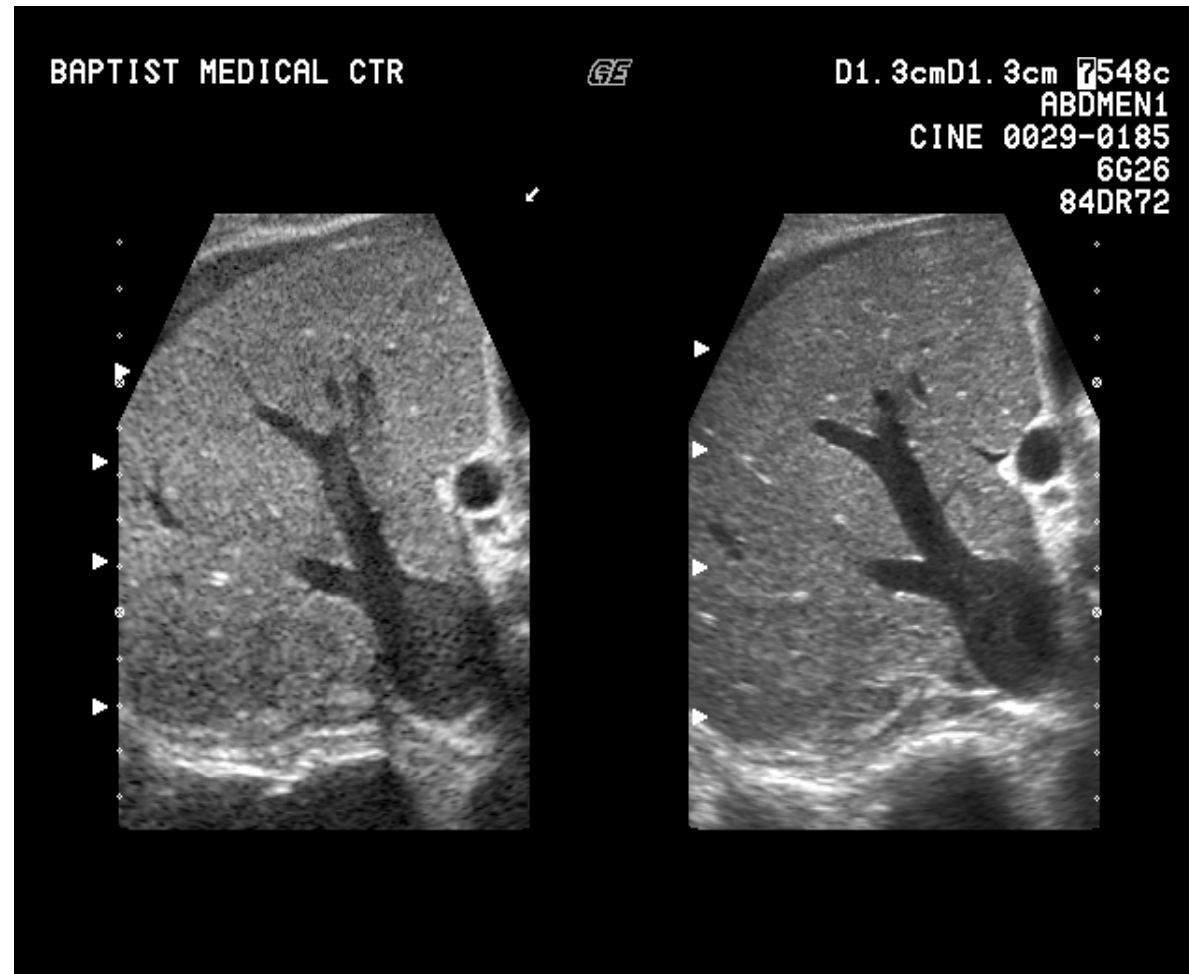
2. Parametric imaging

2a. Parametric audio sound source

- Non-linear interaction
- Holosonics: Audio Spotlight
  - http://www.holosonics.com/

Parametric Audio Source

- Primary frequencies 50-70 kHz
- Transmission of a single sinusoid: simple

- Ex: transmission of two sinusoids: 1 and 1.3 kHz
  - Send 50, 51 and 51.3 kHz
  - Nonlinarity creates 1 and 1.3 kHz: OK
  - It also gives intermodulation products at 0.3 kHz + harmonics ++
  - Result: Up to 50% distortion with broadband audio

- Predistortion to cancel the undesired intermodulation

2b Parametric medical imaging

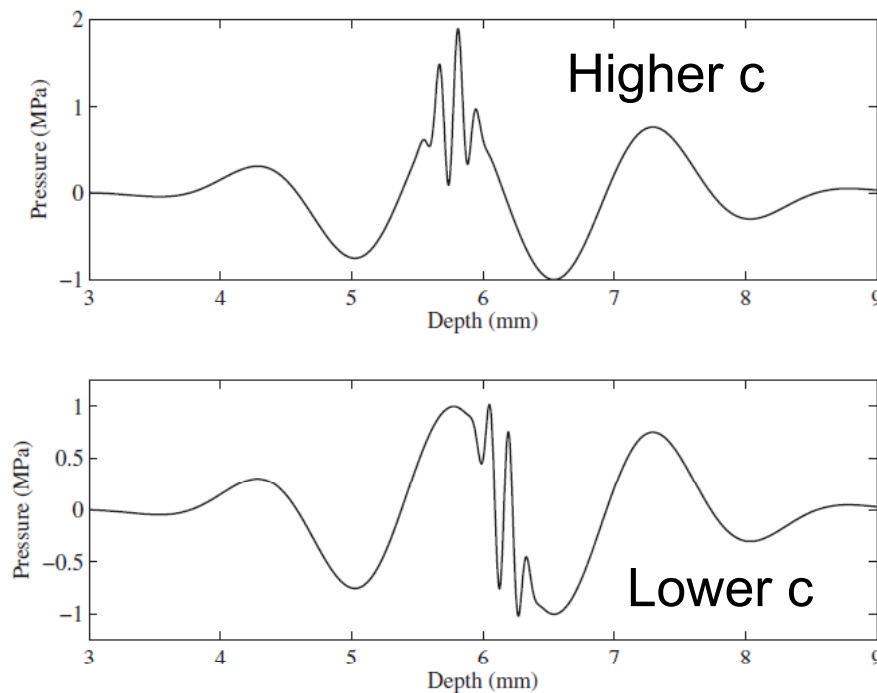# SURF: Second order UltRasound Field
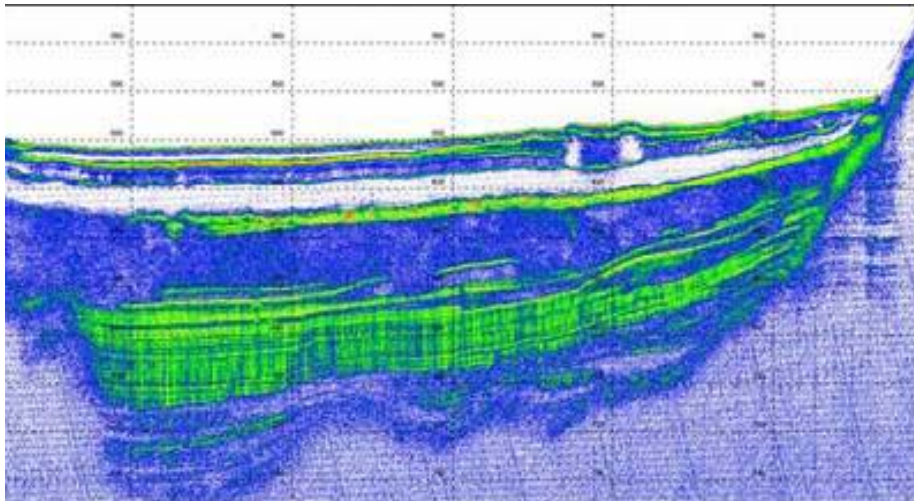

Higher c

Lower c

FIG. 1. Example of SURF transmit pulse complexes. The HF imaging pulse is placed on the positive pressure peak of the LF manipulation pulse (upper panel) and at the maximal negative spatial pressure gradient of the LF manipulation pulse (lower panel).

- Hansen, Måsøy, Angelsen, Utilizing dual frequency band transmit pulse complexes in medical ultrasound imaging. *J. Acoustical Society of Am*. 2010

- The HF pulses are used for image reconstruction, whereas the LF pulses are used to manipulate the nonlinear elastic properties of the medium observed by the HF imaging pulses.

- Reverberation suppresion through Dual Band Imaging + Multiple transmissions and Delay Corrected Subtraction

2c. Parametric sonar

- Topas: Kongsberg Defense & Aerospace
- Parametric sub-bottom profilers
- Low frequency sound generation due to non-linear interaction in the water column from two high intensity sound beams at higher frequencies.
- The resulting signal has a high relative bandwidth (~80%), narrow beam profile
- Penetration ~100 m, 150 ms

KONGSBERG Sub-Bottom Profilers: The full range
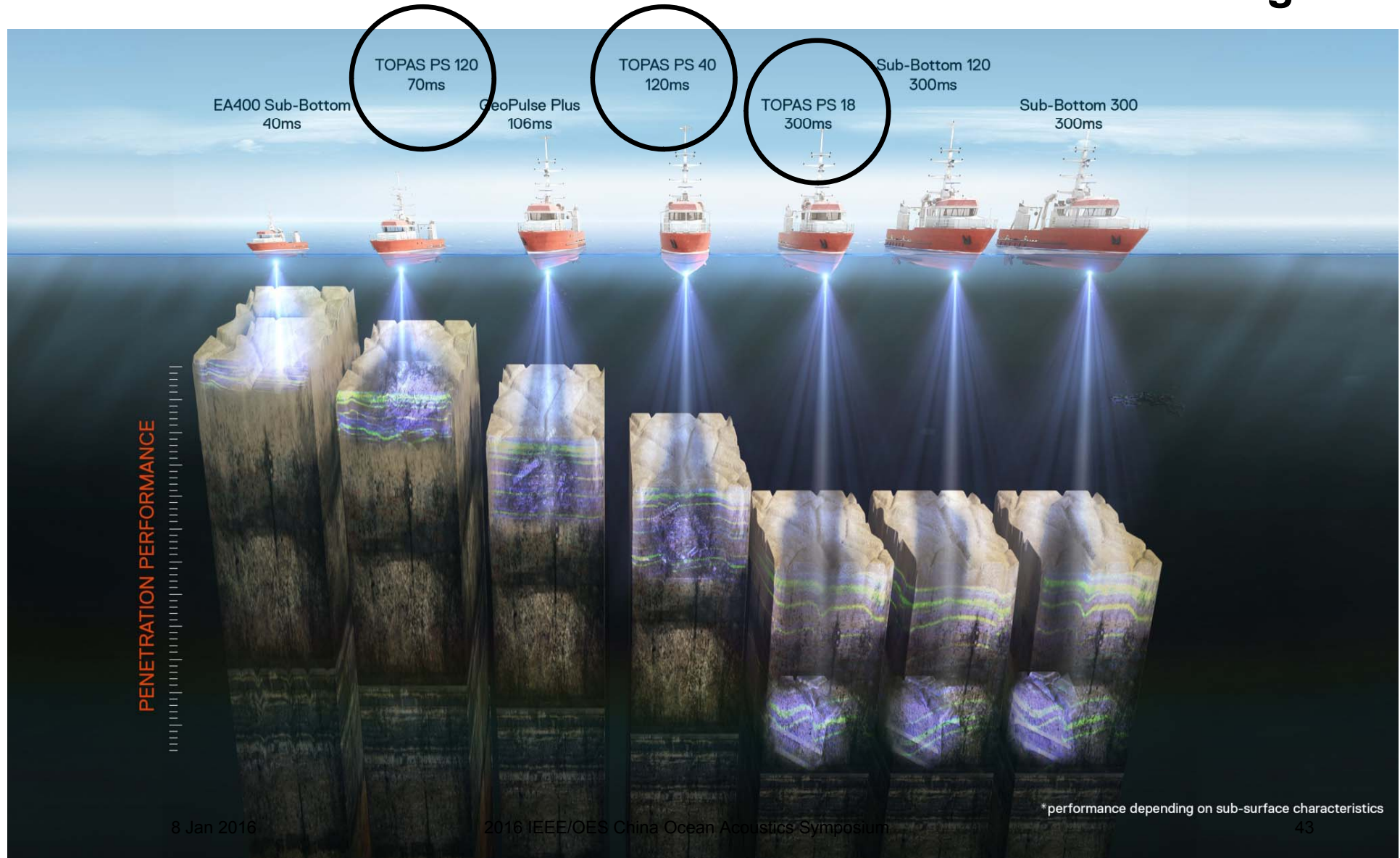
Topas: Parametric profilers

|	PS 18	PS 40	PS 120
Secondary frequency	0.5-6 kHz	1-10 kHz	2-30 kHz
Primary frequencies	15-21 kHz	35-45 kHz	70-100 kHz
Source levels	Secondary: 208 Primary: 242	Secondary: 206 Primary: 240	Secondary: 202 Primary: 238
Water depth	> 10m	5 to > 1000 m	3 to > 400 m
Hor. resolution	<5 x 5 deg	< 4 x 6 deg	< 4 x 6 deg
Signatures	CW, Chirp, Ricker		

TOPAS PS 18 – 650 meters depth (faults)

Mediterranean
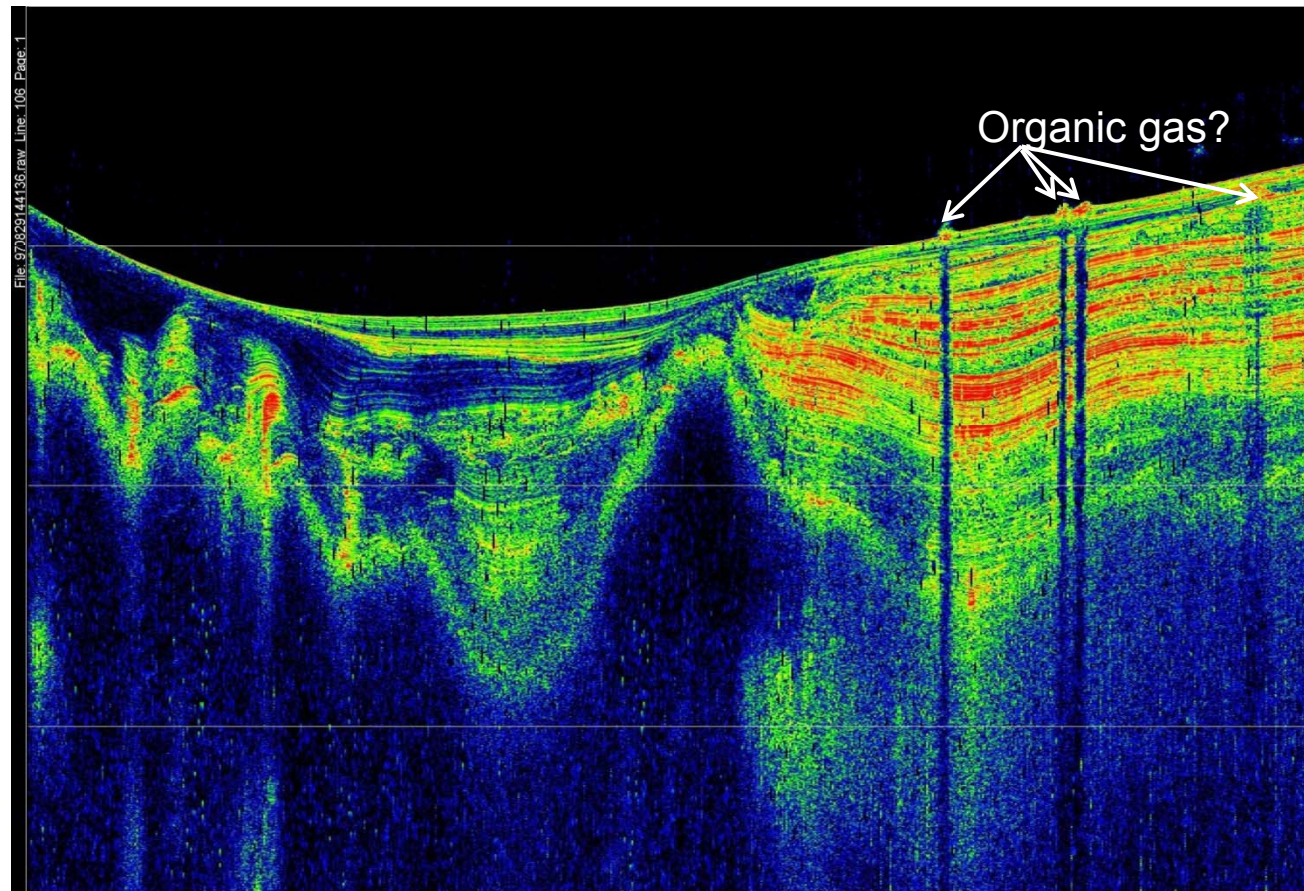1.5 to 5 kHz, 20 ms Chirp signal
Courtesy of CSIC, Spain.
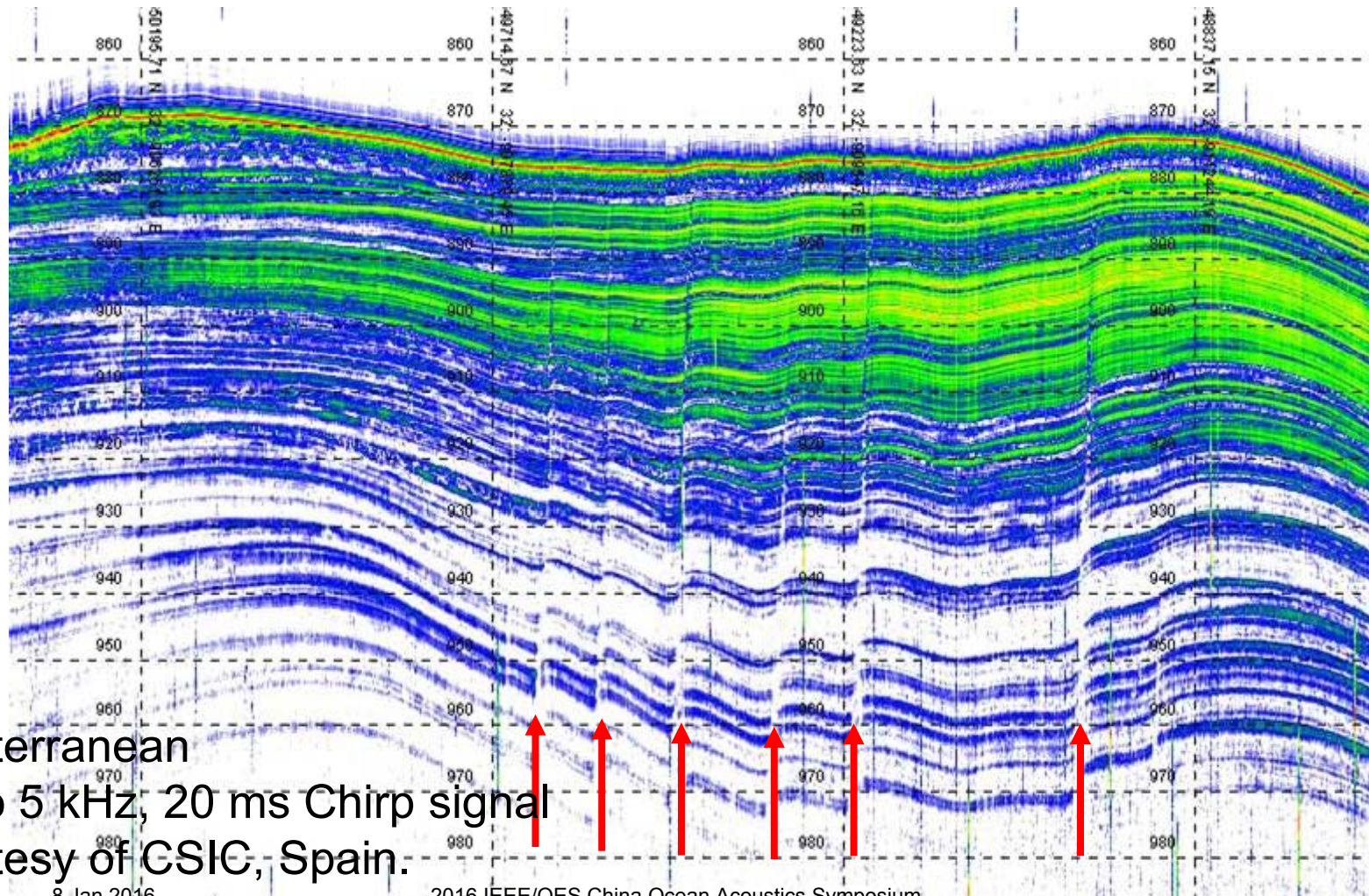
Kongsberg TOPAS PS 18

Deep water (~3,750

meters), high

penetration

(> 200 meters)

South Georgia
1.5 to 5 kHz, 20 ms
Chirp signal.
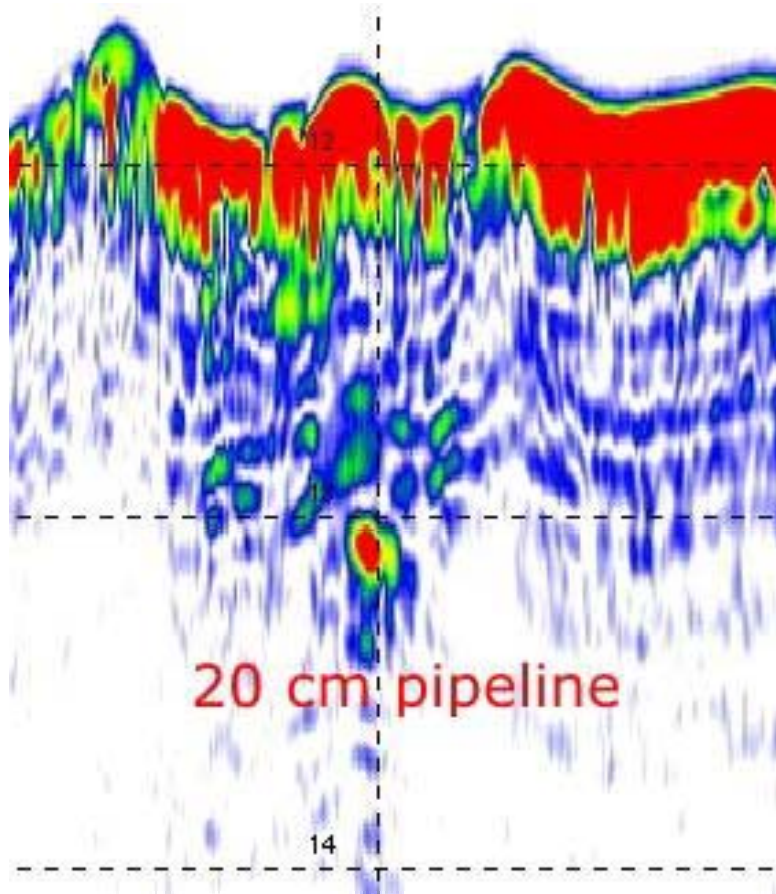Courtesy of CSIC,
Spain

200 m
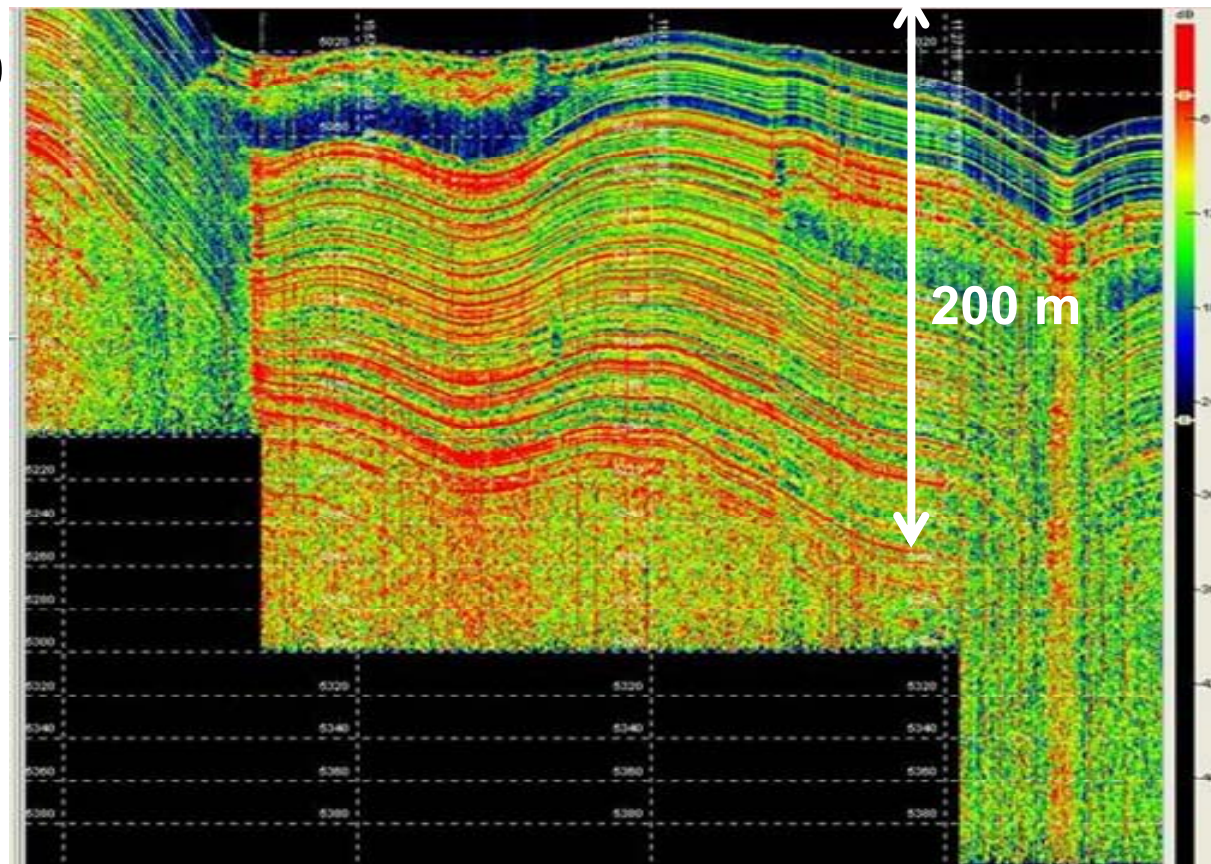
Kongsberg TOPAS PS 40

5 kHz Ricker pulse, from the Stockholm Archipelago, Sweden

TOPAS PS 40 – buried pipeline

20 cm pipeline

Sheng Li area, China.
(No heave compensation used)
Courtesy of SOA, China.

Harmonic imaging in sonar

1. Success in medical imaging

2. Observation of target strength estimates in fishery research that fall with sonar power

3. Frequency response for target characterization

4. Wideband transducers are now feasible

UiO : Department of Informatics
University of Oslo

Feasibility of Second Harmonic Imaging in Active Sonar: Measurements and Simulations

Fabrice Prieur, Sven Peter Näsholm, *Member, IEEE*, Andreas Austeng, *Member, IEEE*, Frank Tichy, and Sverre Holm, *Senior Member, IEEE*

Abstract—Nonlinear acoustics allows for applications like tissue harmonic imaging in medicine and parametric arrays in underwater acoustics. Mainstream sonars transmit and receive signals at the same frequency and up to now energy transferred to higher harmonic frequencies has been mainly seen as a disturbance for target strength estimation, e.g., in fishery research. This paper investigates the feasibility of utilizing the part of the signal generated around the second harmonic frequency band by nonlinear propagation of sound in water. It presents the potential enhancements the second harmonic signal may provide for target imaging as well as multifrequency target recognition. It compares measurements of the pressure field radiated by commercial transducers in water at 121 and 200 kHz up to a range of 12 m with numerical simulations. The detected levels of higher harmonic signals agree with simulations of nonlinear wave propagation. This verifies the implementation of the simulator and allows a comparison of the beam characteristics at longer ranges when filtered around the fundamental or second harmonic frequencies. An example of pulse-echo imaging with spherical targets is also shown using signals at the fundamental and second harmonic frequencies where the second harmonic signal can detect one of the targets that the fundamental signal cannot. Using the active sonar equation to estimate the maximum range, simulations based on a simple model including ambient noise and volume reverberation confirm that with a source level of 228 dB and a detection threshold of 12 dB the fundamental signal at 200 kHz can detect a fish of target strength −36 dB to approximately 343 m while the detection range of the second harmonic signal is approximately 243 m. The combined use of the signal components in the second harmonic and fundamental frequency bands provides a high-resolution image at short range and a long-range imaging capability at a lower resolution as well as a multifrequency characterization of targets.

Index Terms—Harmonic analysis, nonlinear acoustics, sonar applications.

that can potentially improve target imaging. An application that found a use for nonlinear propagation is the parametric sonar. In 1963, Westervelt [1] predicted that when transmitting two high-frequency beams at slightly offset frequencies the beams would interact due to nonlinear effects and the wave generated from this interaction would propagate at the sum and difference of the transmitted frequencies, the signal at the difference frequency being the more applicable. Berktay [2] further developed this theory and evaluated several possible applications of nonlinearity in underwater transmitting applications. As an implementation of this, the parametric sonar is a technology that exploits nonlinear propagation in underwater acoustics. It is an industrial product that helps sub-bottom characterization [3] and buried object detection [4] thanks to the directional low-frequency beam, its long range, and bottom penetration capability. In his review, Bjørnø [5] describes the characteristics and the performance of the parametric sonar.

About 15 years ago, use of nonlinear propagation of sound also reached the field of medical ultrasound with the development of tissue harmonic imaging (THI). In THI, the image reconstruction is made from receiving signals in the second harmonic frequency band. In many clinical applications, THI results in enhanced image quality compared to reconstructing the image from echoes in the transmitted frequency band. Duck [6] presents a comprehensive review explaining why THI allows for better image quality. It is due to, among others, a narrower main lobe, a better main-lobe-to-sidelobe ratio, and limited reverberation for the second harmonic signal compared to the fundamental signal. THI is implemented in most commercial scan-
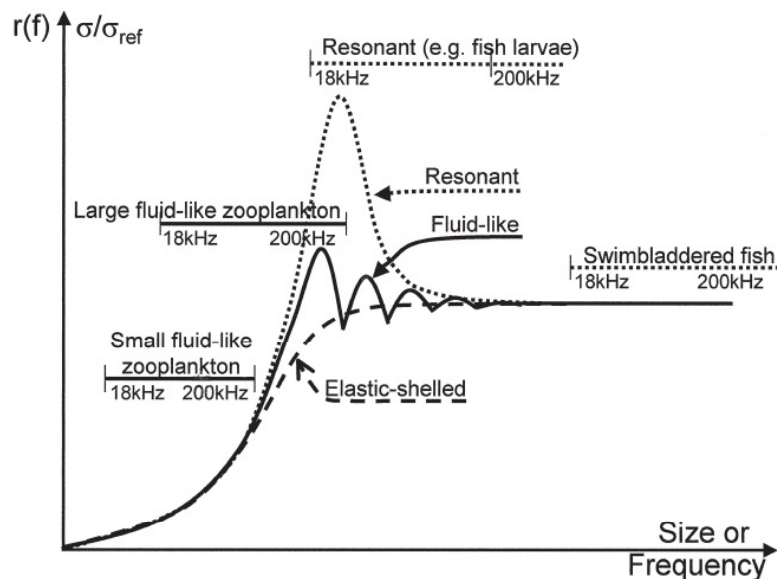
Observed underestimation of target strength (TS) in fishery research

TS falls with power due to nonlinear conversion
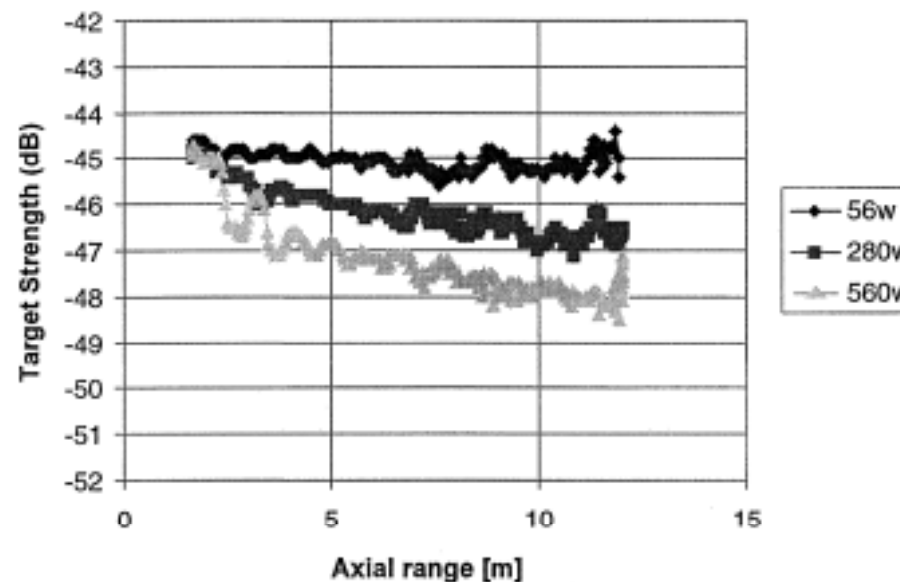
- Tichy, Solli, Klaveness. "Non-linear effects in a 200-kHz sound beam and the consequences for target-strength measurement." *ICES J. Marine Science,* 2003
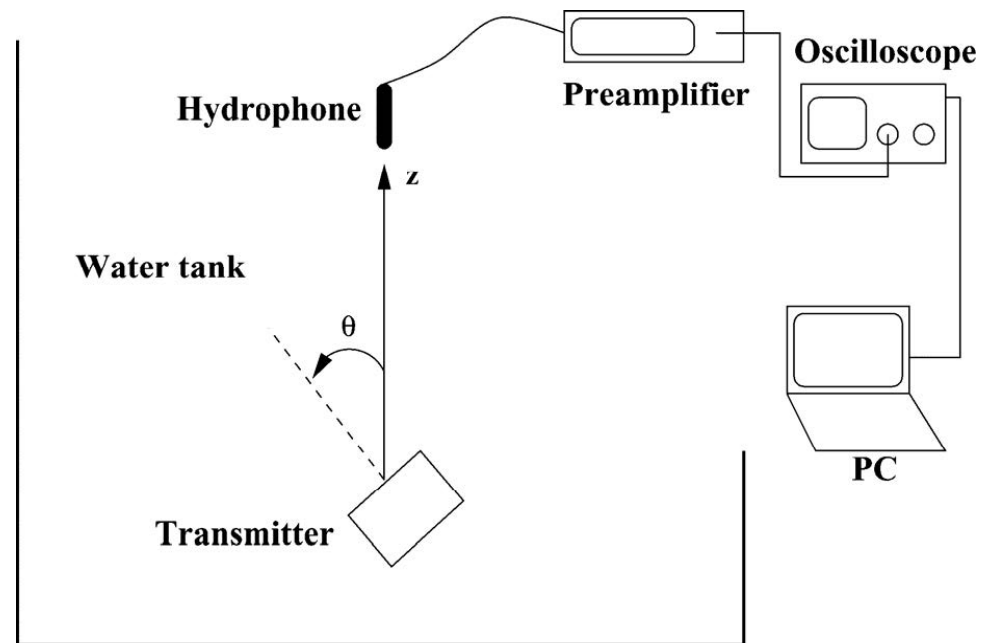
TS estimation at different frequencies is useful to aid in target classification

- Fish or zooplankton
  - Varies with size
  - Presence of swimbladder
- Other: Bathymetry, buried object detection, gas seep detection

R. J. Korneliussen and E. Ona ICES J. Mar. Sci., 2003

Measurements in 6 x 15 x 6 m tank

- Fig. 1 Setup for measurements of pressure fields in water tank. The hydrophone is positioned along the z-axis and θ is the angle between the transducer's main propagation direction and the z-axis.

Simulation, distilled water

Parameter	Value
Frequency (f)	121 kHz / 200 kHz
Source radius (R)	57.5 mm / 35 mm
Water density (ρ)	998 kg$\cdot$m^{-3}
Sound speed (c)	1479 m$\cdot$s^{-1}
Nonlinearity coefficient (β)	3.5
Attenuation coefficient (α_0)	0.025 Np$\cdot$m$^{-1}\cdot$MHz^{-2}
	$\Rightarrow$ 3.0 dB$\cdot$km^{-1} at 121 kHz
	$\Rightarrow$ 8.4 dB$\cdot$km^{-1} at 200 kHz
Number of harmonics (M)	50
Step size (Δz)	1 mm

Measured spectra @ 3 m, 121 kHz

2.: harm -12, -19 dB
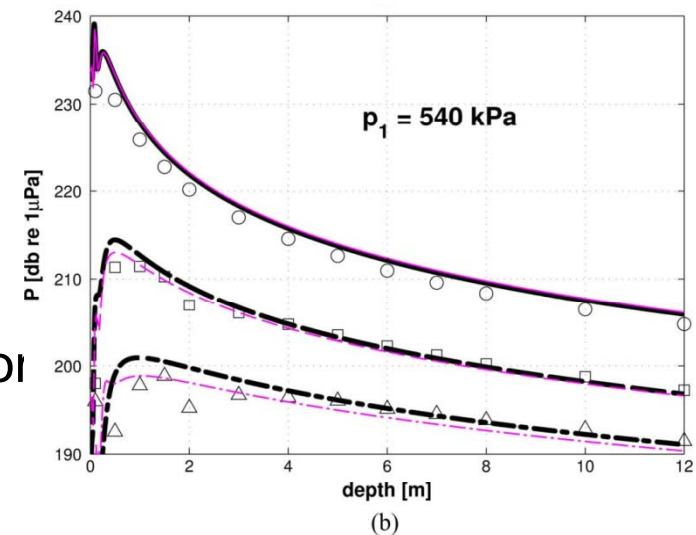

3. harm: -25, -42 dB
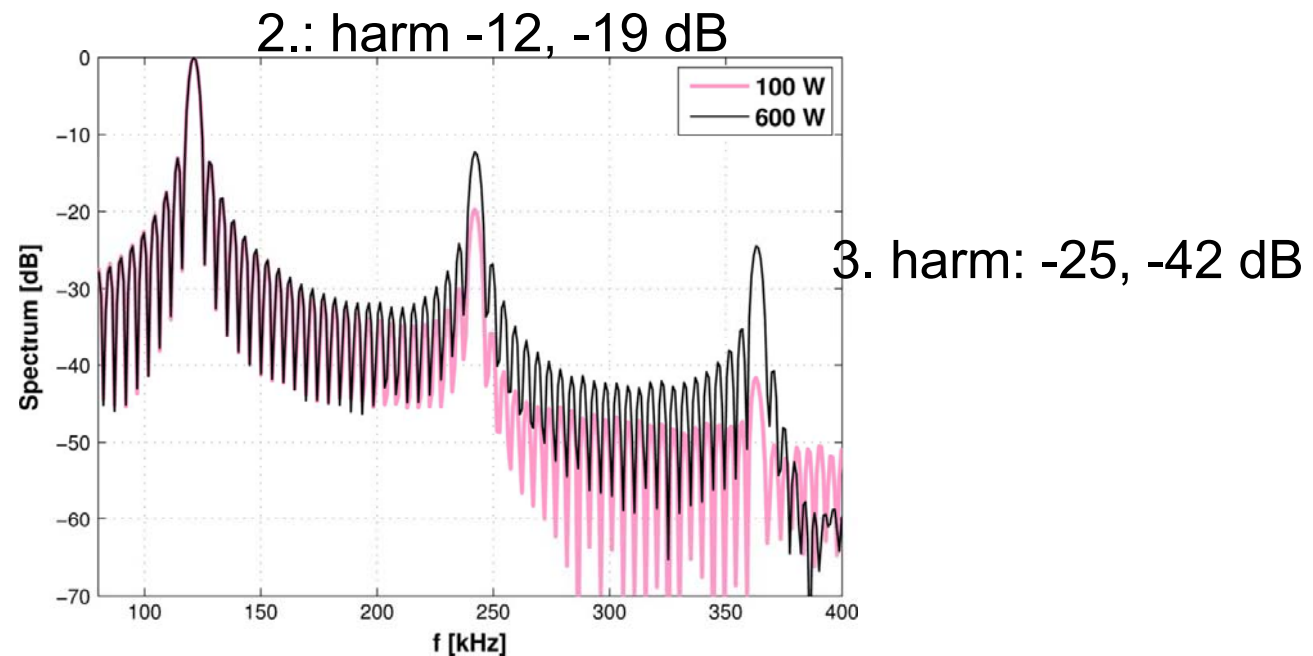
100-W (thick line) and 600-W (thin line) input electrical power.

Axial response: Simulation vs measurement, 121 kHz
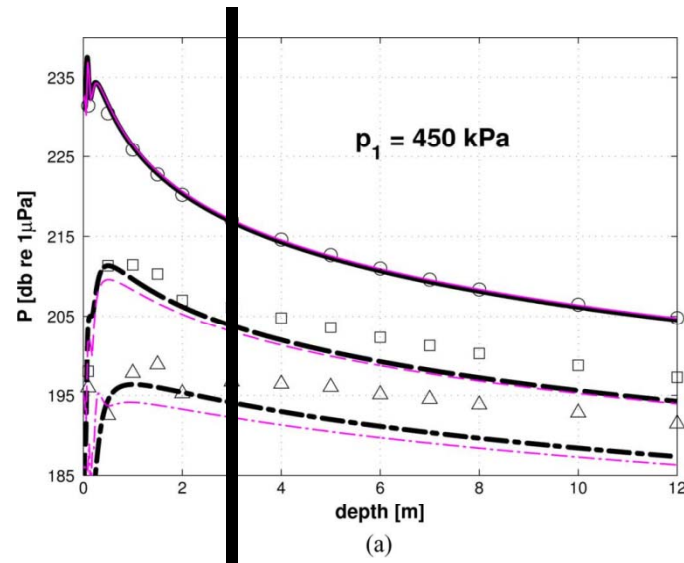
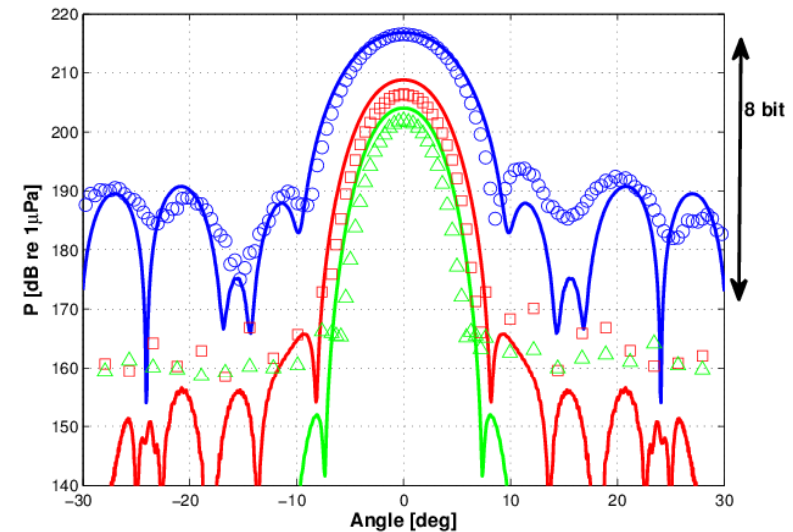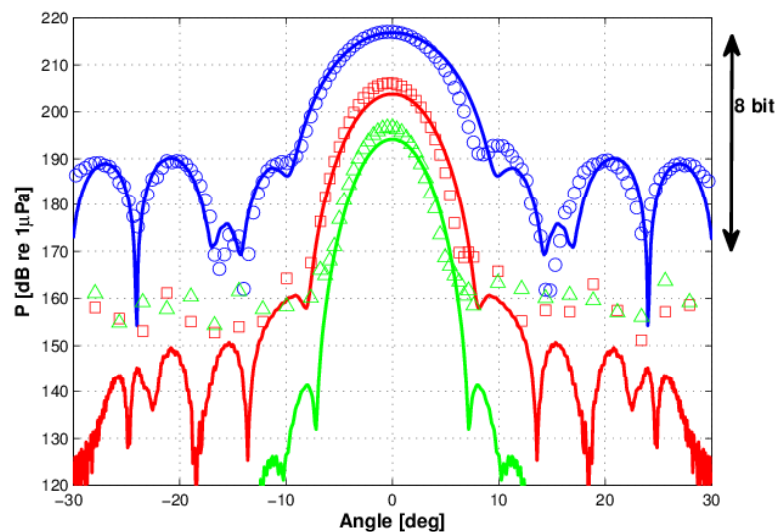

- ASA simulator
-.- KZKTexas

1. harmonic matches measurement;   2, 3. harmonics match measurement

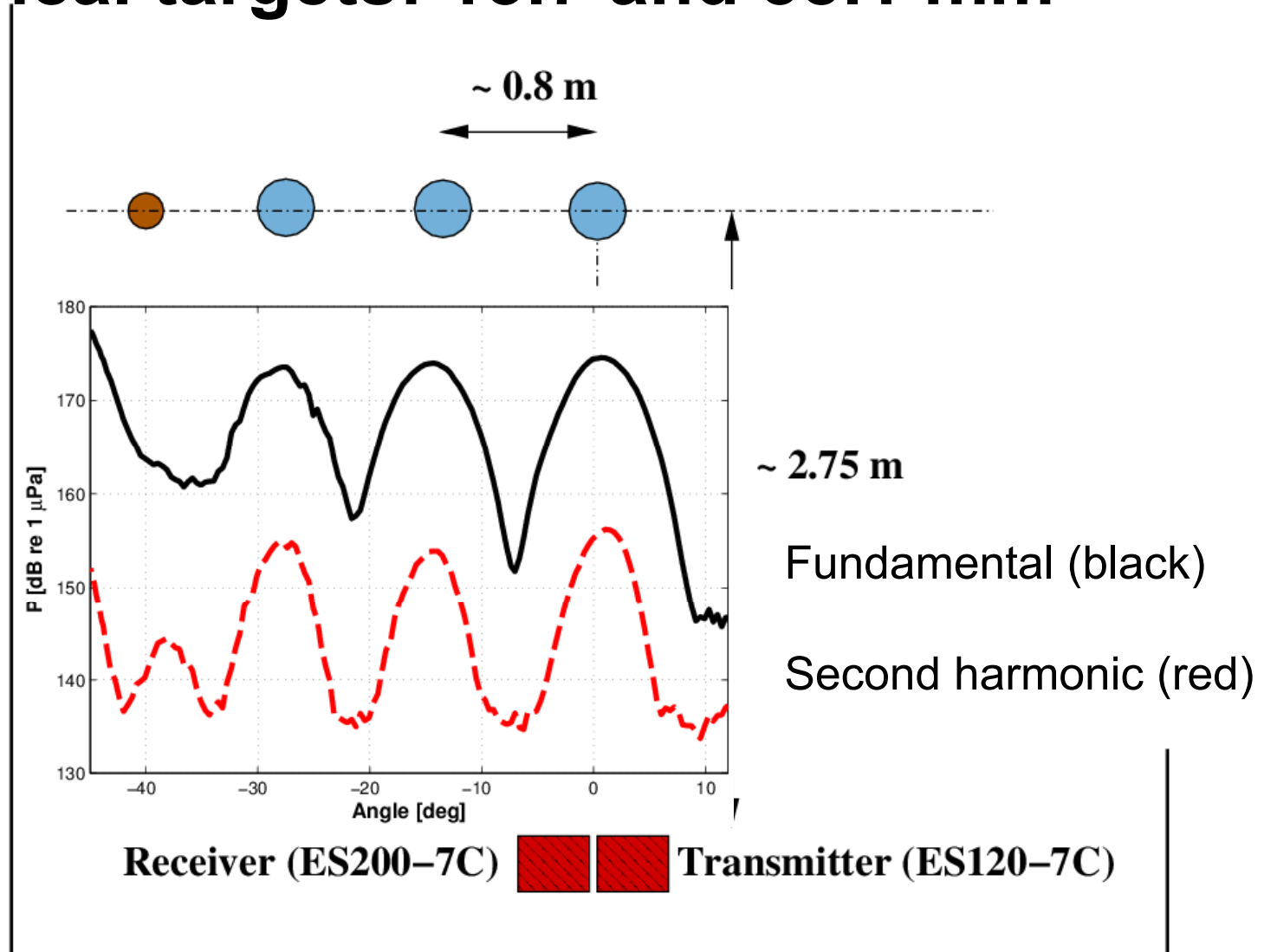ES120-7C transducer—input electrical power level: 600 W.

Radial profile: Narrower main lobe and lower sidelobes, 121 and 200 kHz

1. sidelobe: -29, -41 dB

Radial profiles, 3 m, ES120-7C (left) and ES200-7C (right).
Input pwr = 600W (450 kPa, 800 kPa). Markers = measurements,
lines = ASA sim. Deviation < 4dB (left) and 9db (right).

Spherical targets: 13.7 and 38.1 mm

~ 0.8 m

~ 2.75 m

Fundamental (black)

Second harmonic (red)

Receiver (ES200–7C)   Transmitter (ES120–7C)

Range estimation: Parameters in active sonar equation

| Parameter	Value
Input pressure (p_1)	800 kPa
Fish size (L)	30 cm
Salinity	34 ppt
pH	7.7
Depth	100 m
Temperature	5°C
Volume scattering strength (S_v)	−85 dB
Pulse duration (τ)	1 ms
Detection probability (P_d)	95%
False alarm probability (P_f)	0.01%

Sonar equation: Fundamental, 200 kHz Reverberation-limited
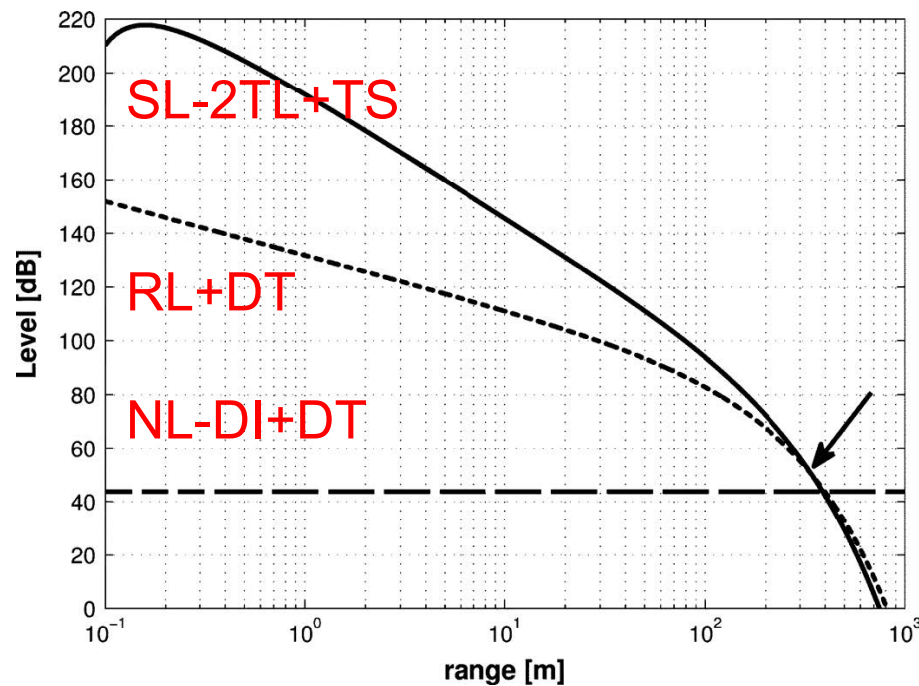
Reverb-limited: 343 m

Sonar equation: 2. harmonic, 400 kHz Noise-limited

SL-2TL+TS

RL+DT

NL-DI+DT
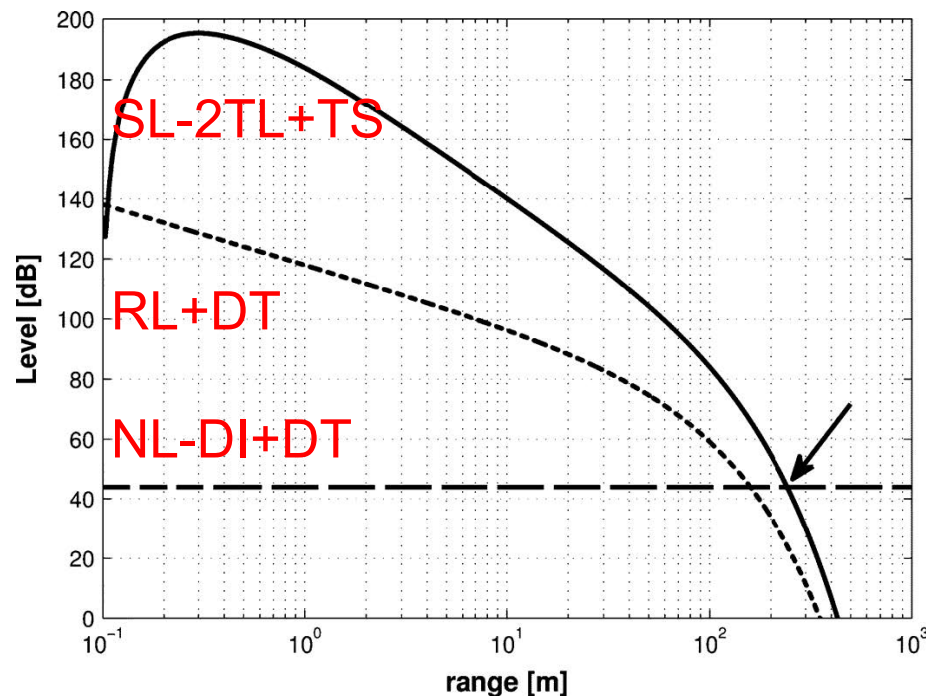
Noise-limited: 243 m
Reverb-limited: 660 m

Counterintuitive: In a reverb-limited scenario, range would be ~2x fundamental's range

Conclusion: Second harmonic imaging in active sonar

- Will obtain useful range even at 2. harmonic

- Wideband transducers are now feasible

- Comparison to wideband sonar which transmits at fundamental then at 2. harmonic:

  - Much better sidelobe suppression than if one had transmitted at 2x frequency

  - Twice the update rate

- Improved image resolution

- Better target characterization