The biomedical photoacoustic radar imager: Principles, signal-to-noise ratio, contrast and resolution

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Presentation Outline

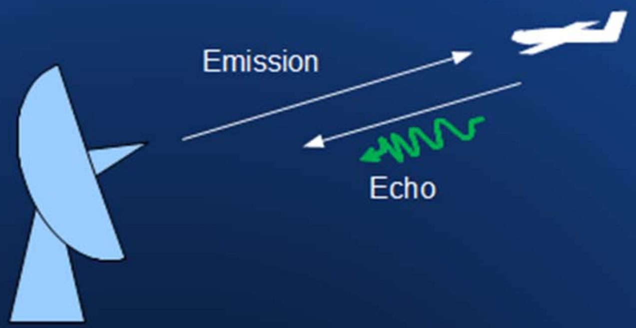
Frequency-swept (chirped) cross-correlation PA methodology: The Photoacoustic Radar (or Sonar). Portability!

- *PA Radar System: A tunable low-pass filter*
- *SNR: Effect of chirp bandwidth tuning*

  Effect of laser power
- *SNR and contrast comparison between pulsed laser PA and PA radar*
- *Lateral Resolution and Contrast Factors*
- *Axial resolution comparison*
- *SNR with non-linear chirp waveforms*
- *PA phase array with chirped signals*
- *Summary and conclusions.*

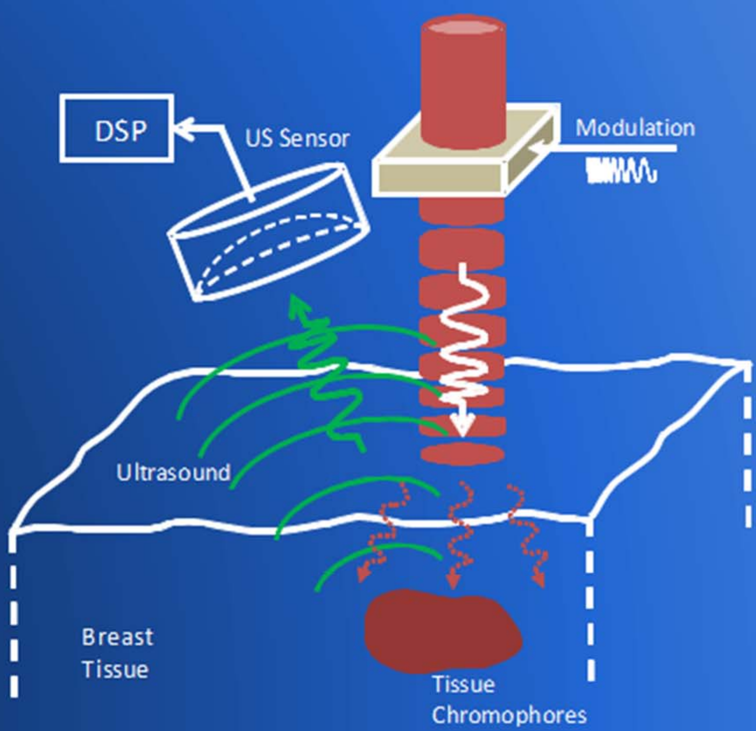
Experimental Implementation of PA Sonar Principle

Radar target detection with chirped waveforms



Matched Filter Signal Compression

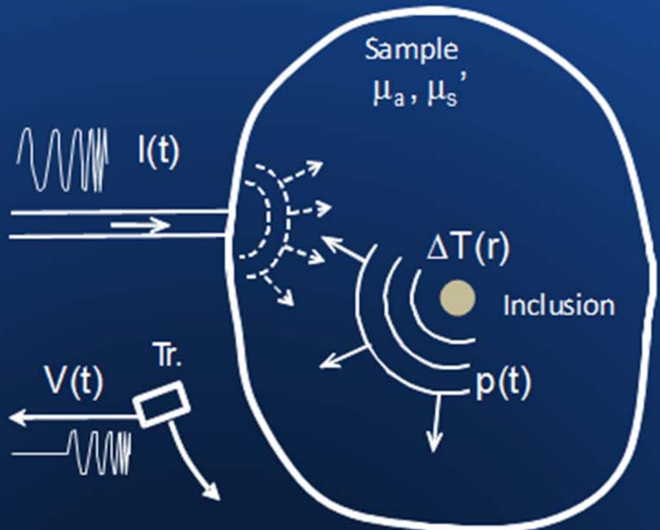
Photoacoustic Imaging with chirped signals



What is the PA Sonar?

- Method of acoustic waves generation by optical radiation with specific modulation pattern
- Takes advantage of coherent detection to increase SNR
- Signal compression is employed to achieve high axial resolution
- Multi-element ultrasound sensor array and beamforming algorithm can be used for *B*-mode imaging

Mathematical Formalism



Frequency-domain equation for acoustic pressure:

$$\nabla^2 \tilde{p}(\vec{r},\omega)+k^2 \tilde{p}(\vec{r},\omega)=\frac{-i\omega\beta}{C_p}\tilde{q}(\vec{r},\omega)$$

Method of transfer functions (V. Gusev & A. Karabutov)

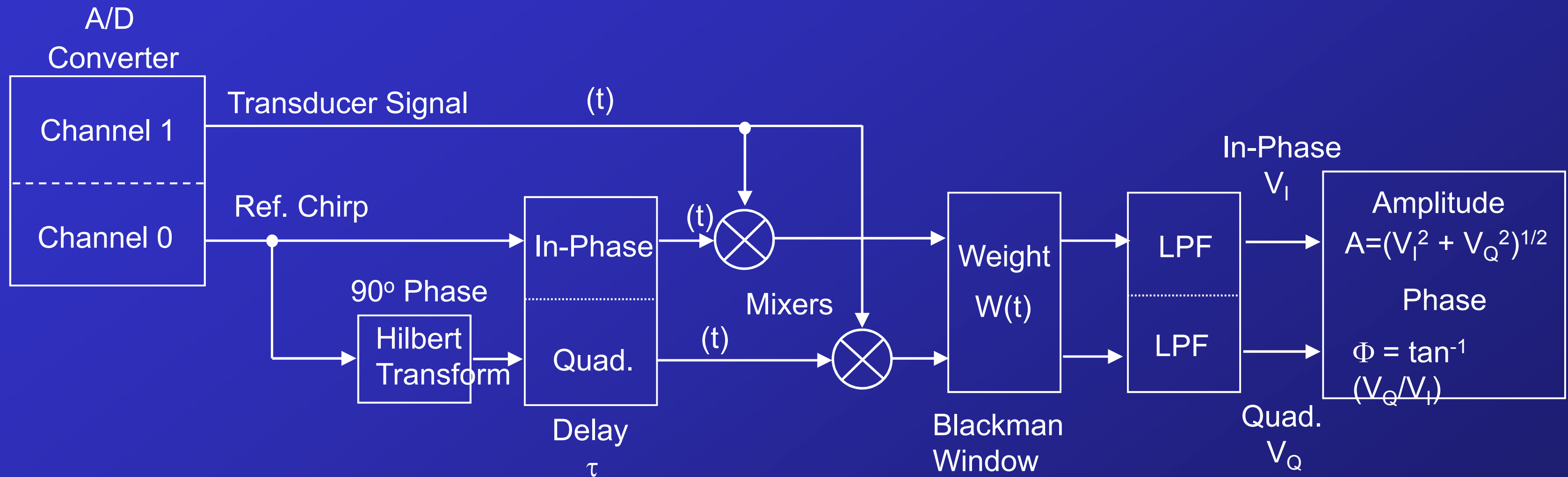
$$\tilde{p}(\vec{r},\omega)=\underbrace{\tilde{H}_{PA}(\omega)}_{\text{PA transfer function}}\cdot\underbrace{\tilde{F}(\omega)}_{\text{Modulation spectrum}}\cdot\underbrace{\Phi(\vec{r})}_{\text{Spatial light distribution}}$$

1-D geometry:

$$\tilde{H}_{PA}(\omega)=\frac{\omega\beta\mu_a}{C_p(\mu_a^2+\omega^2/c_a^2)}$$

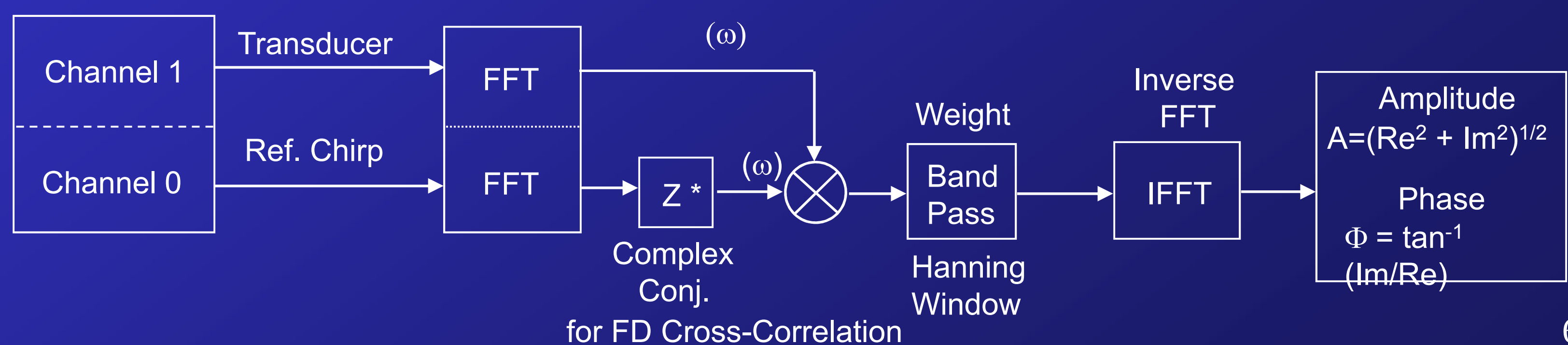
PA Radar: Correlation Processing (Matched filter compression)

1. Digital correlation processor with quadrature demodulation.
(Records multiple chirps, averages and time-shifts post-processing) – SLOW!



(I)

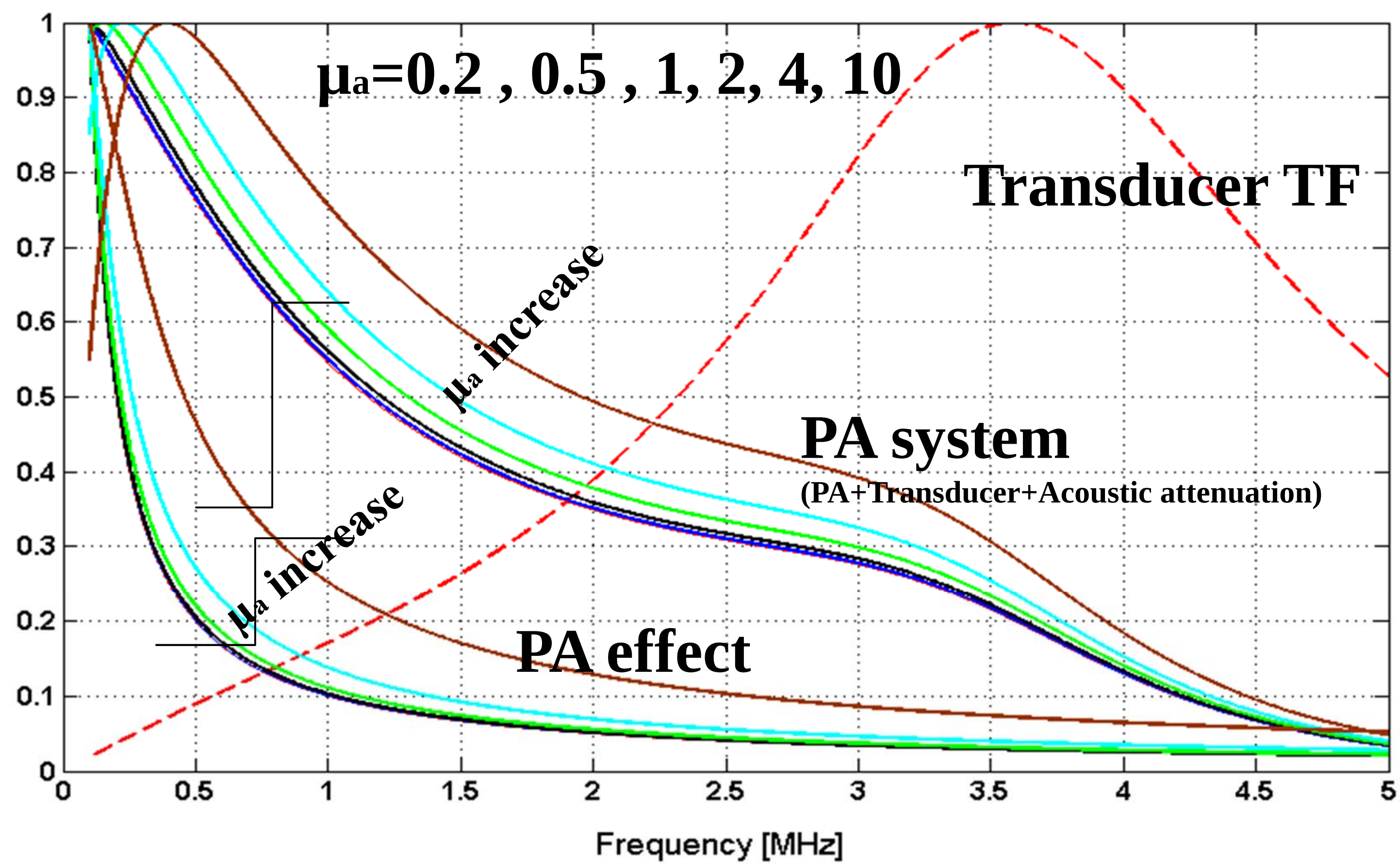
2. Fourier-domain cross-correlation signal processing (FD mixing) – FAST!



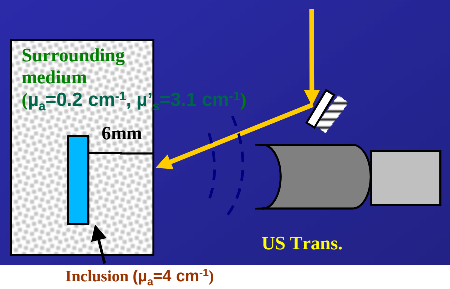
(II)

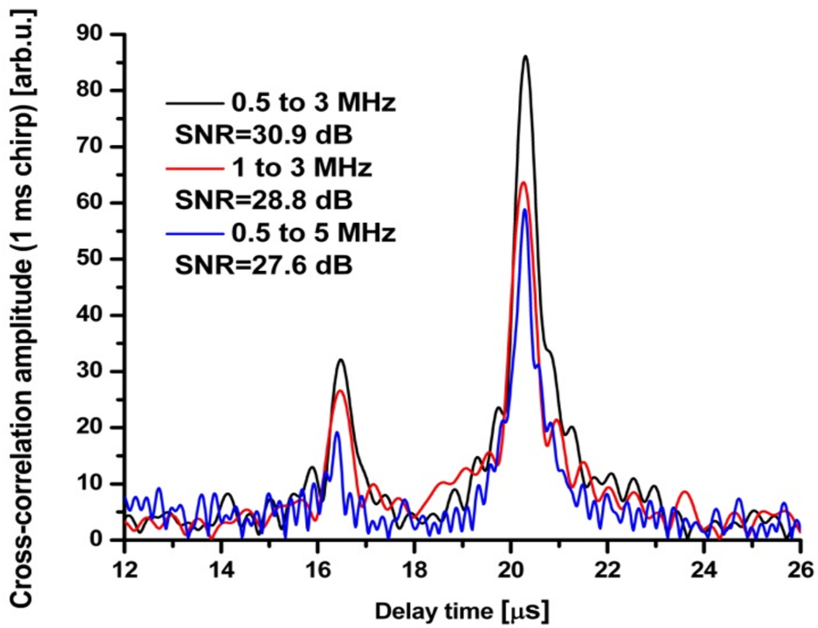
S. Telenkov and A. Mandelis, JBO **11**, 044006 (2006)

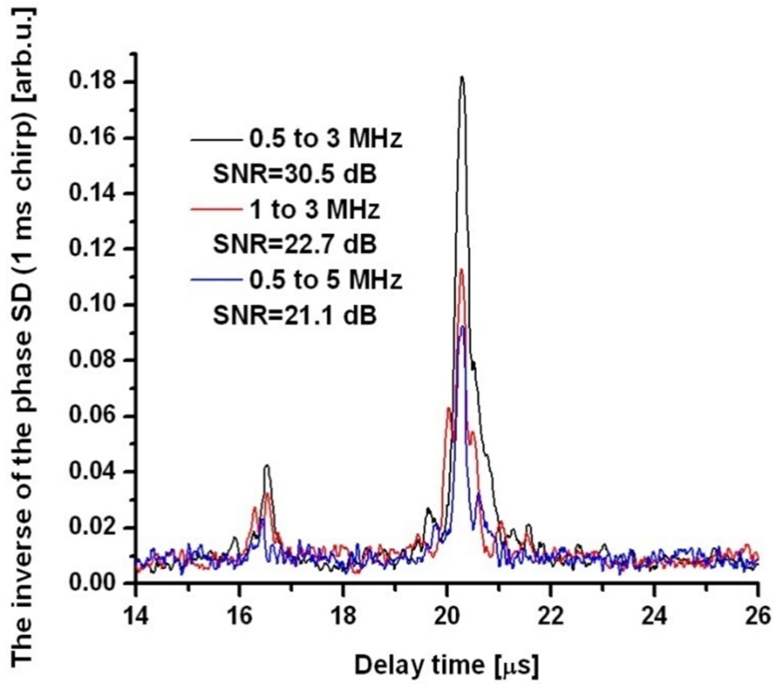
Absorption coefficient (μ_a) and frequency response effects in PA system: a low-pass filter



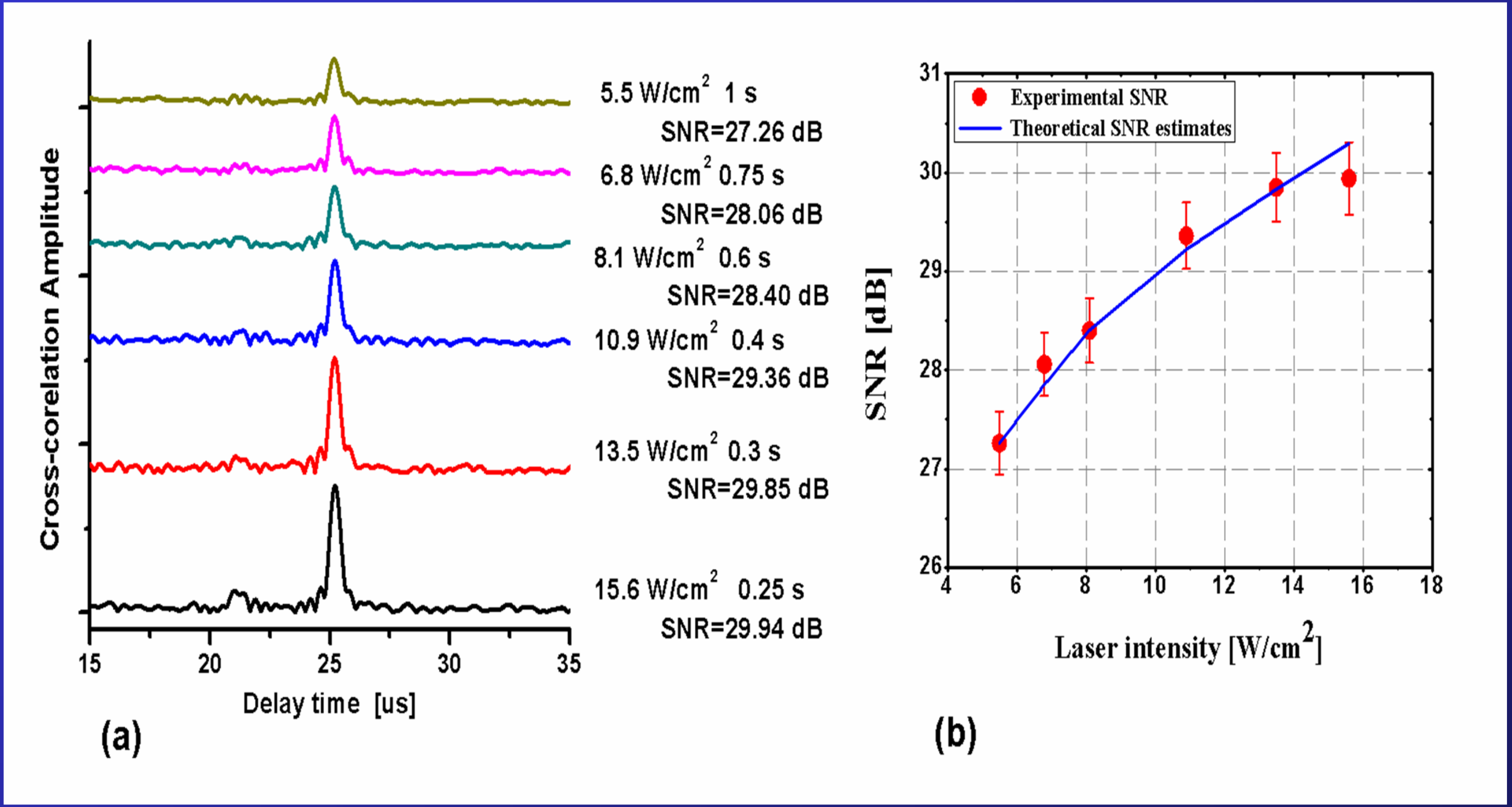
Effect of Chirp Bandwidth tuning (BW) on SNR (High-f transducer)



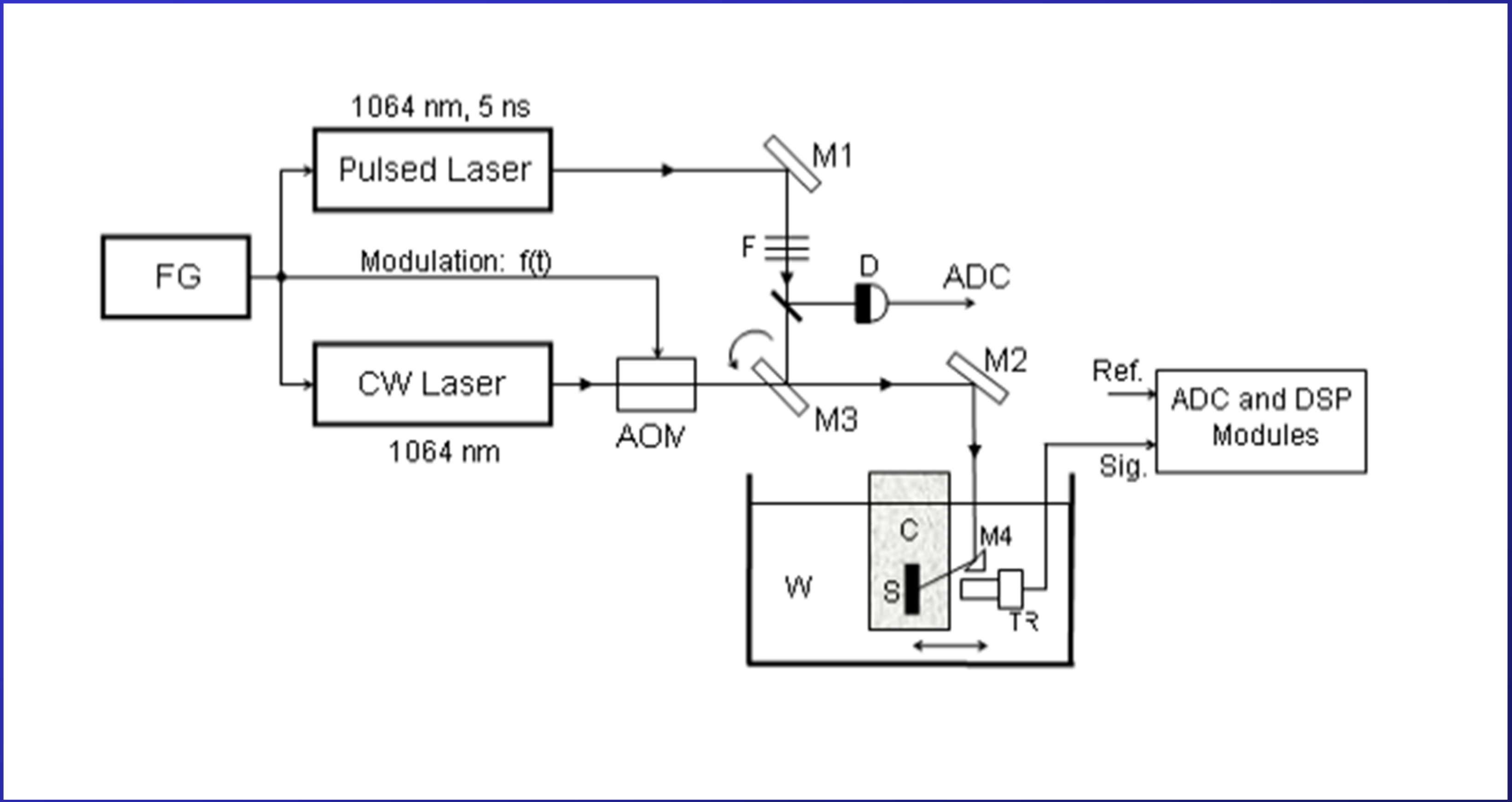




Effect of laser power on SNR
(High-f transducer)

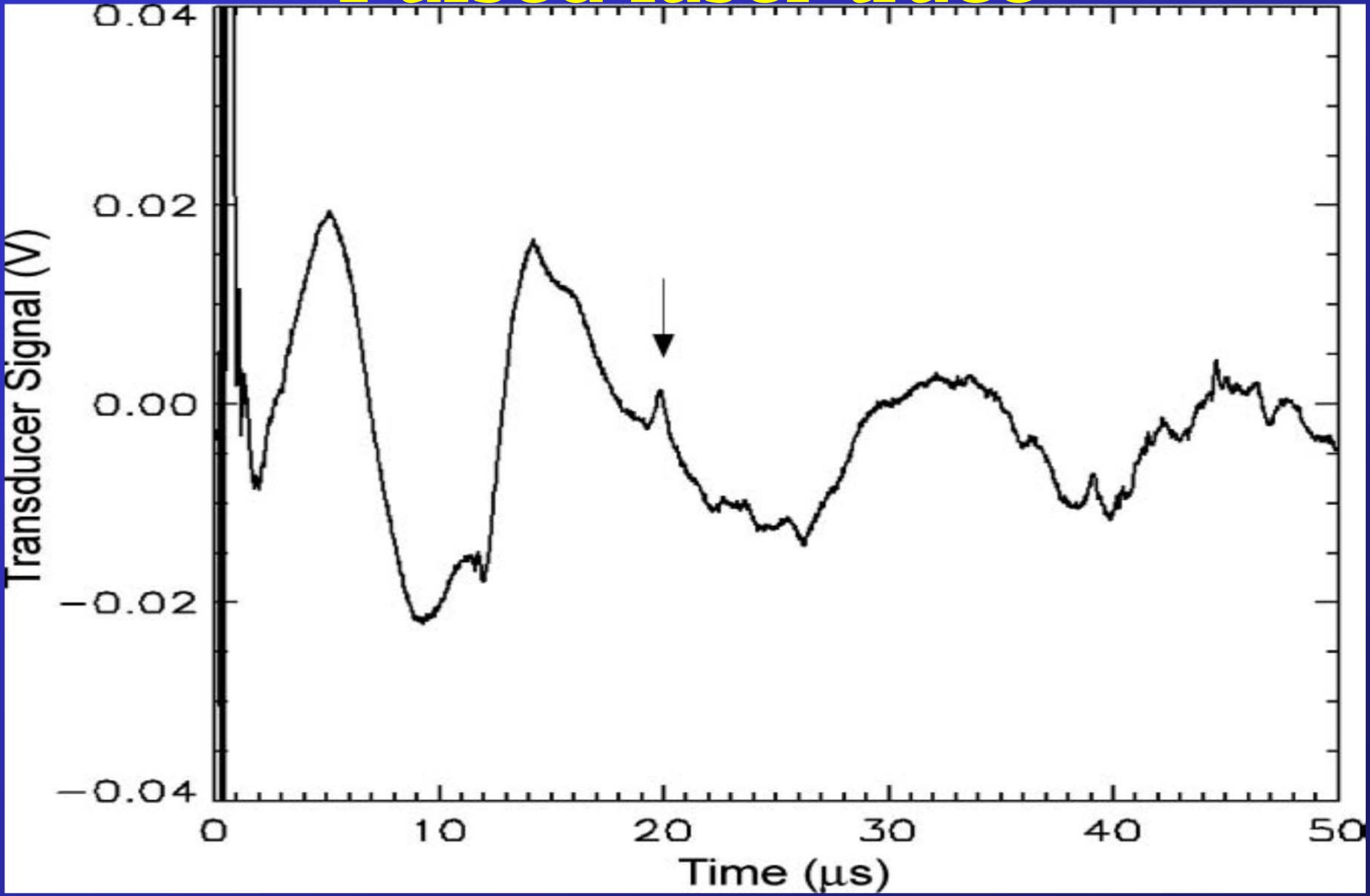


SNR and contrast comparisons between pulsed laser and PA radar



Dual-mode PA experimental set-up for time- and frequency-domain measurements.

Pulsed laser trace



Voltage signal recorded with a wideband focusing ultrasonic transducer (3.5 MHz) in response to pulsed optical irradiation of a light-scattering phantom. Photoacoustic response of a subsurface chromophore with μ_a = 2 cm^{-1} is indicated with the arrow.

Theoretical SNR estimates: TD vs FD PA

$$\frac{\mathbf{SNR_{TD}}}{\mathbf{SNR_{FD}}} \propto \frac{\mathbf{E_o^2 B_{ch}}}{\mathbf{A_I^2 T_{ch}}} \qquad \frac{SNR_{out}}{SNR_{in}} = T_{ch}\Delta f \equiv m$$

where $\mathbf{E_o}$ *: pulsed laser energy,* $\mathbf{A_I}$ *: CW laser intensity,*

$\mathbf{B_{ch}}$ *and* $\mathbf{T_{ch}}$ *: chirp bandwidth and duration, respectively; m: time-bandwidth product ~* 2×10^6

The r.h.s. ratio estimates ~ 10 dB higher SNR for pulsed PA. However experimental results show much smaller SNR difference due to:

1- In the FD modality we can tune the laser irradiation energy frequency spectrum within the transducer optimal bandwidth

2- The pulsed PA baseline largely compromises the estimated SNR even after high-pass filtering.

Safety Limits and Frequency-Domain Photoacoustic Sonar Imaging

Laser power and duration must be consistent with the safety limit

SNR of ideal matched filter:

$$SNR = \frac{2E_s}{N_0} = \frac{A_s^2 T_{ch}}{N_0}$$

N_0 — noise spectral density

Power of a CW source is limited

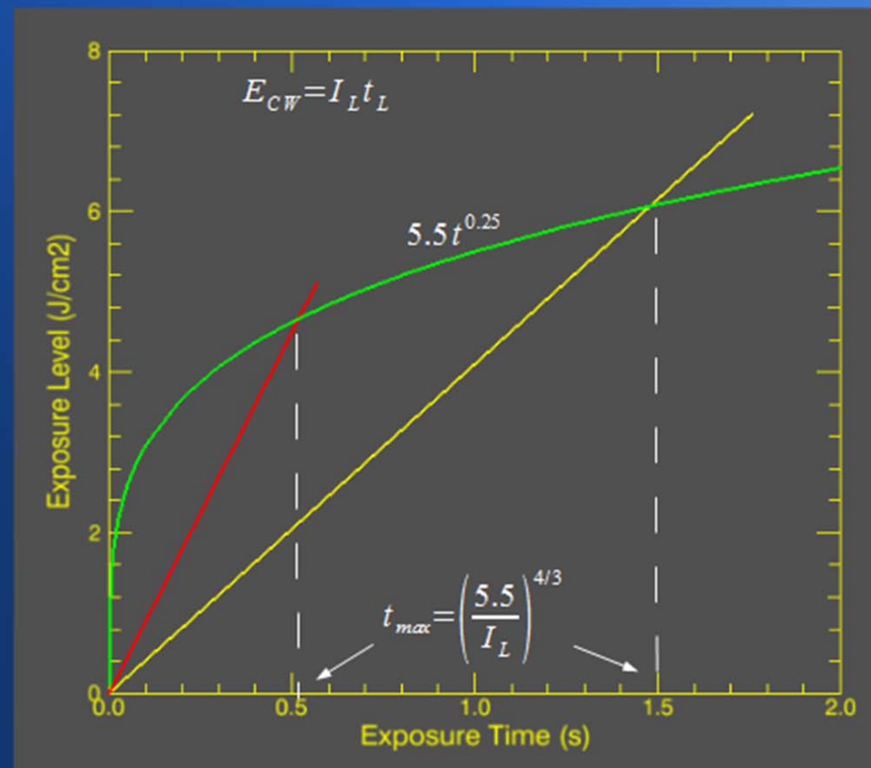
$$\left.\begin{array}{r} P = 1.76\,W \\ a = 0.5\,cm \\ \Delta f = 4\,MHz \end{array}\right\} \Rightarrow t_{max} = 500\,ms \Rightarrow m = 2\times10^6$$

$$For\ z = 3\,cm; \quad \mu_{eff} = 1.5\,cm^{-1}$$

$$SNR_{OUT} = m\cdot SNR_{IN} \approx 16\,dB$$

- Detection of tissue chromophore as deep as 3 cm is feasible

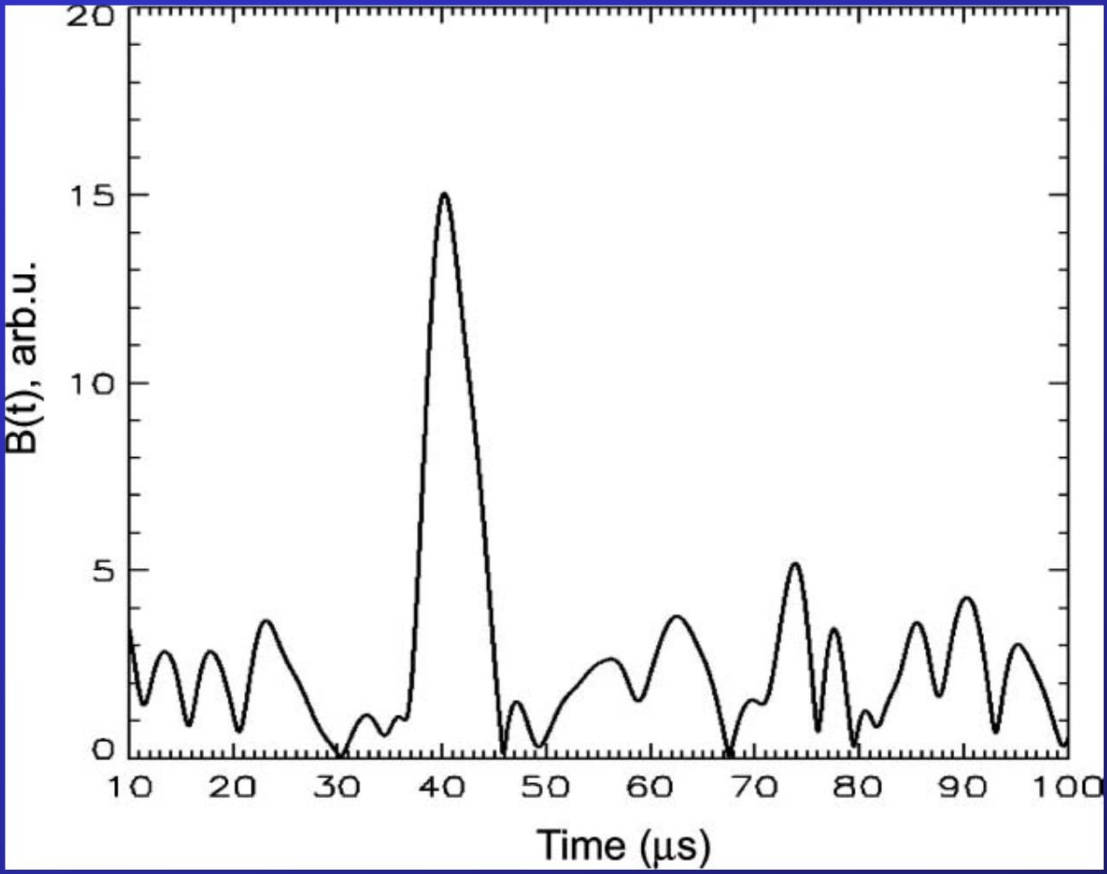
Laser Safety Limits for λ = 1064 nm and t = 10^{-7} – 10 s



P = 1.76 W; P = 0.8 W (a = 5 mm)

Laser safety curve

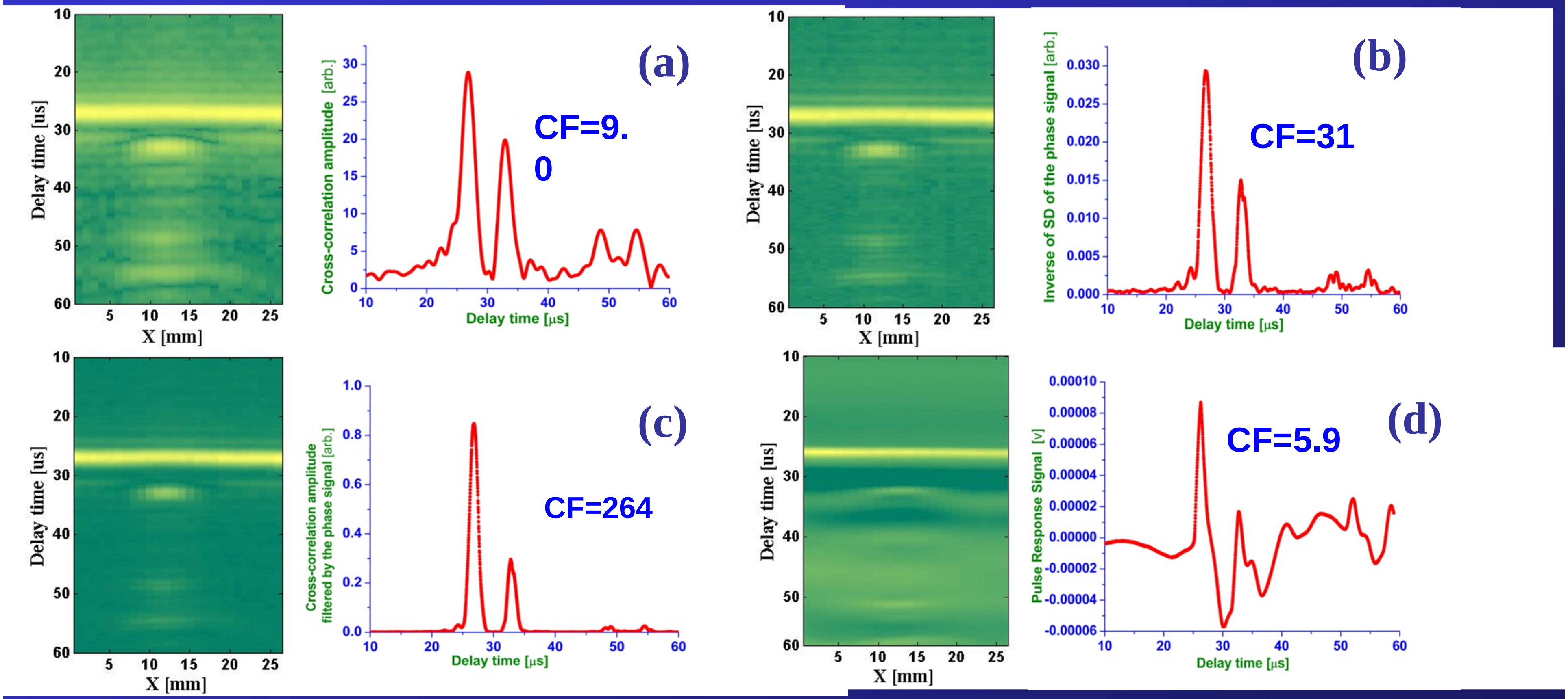
PA trace with CW laser after matched filter correlation processing



Experimental correlation function of a chirped photoacoustic response received from a planar chromophore with μ_a = 2 cm^{-1} immersed in tissuelike Intralipid solution 2 cm deep. Focusing transducer: 0.5 MHz and focus: 5.08 cm; chirp parameters: f = 0.2–0.8 MHz, T_{ch} = 1 ms.

Telenkov and Mandelis, Rev. Sci. Instrum. 81, 124901 (2010)

Resolution and Contrast Factors (CF)



CF = (Signal mean in the lesion – Signal mean in the background) / Signal mean in the background

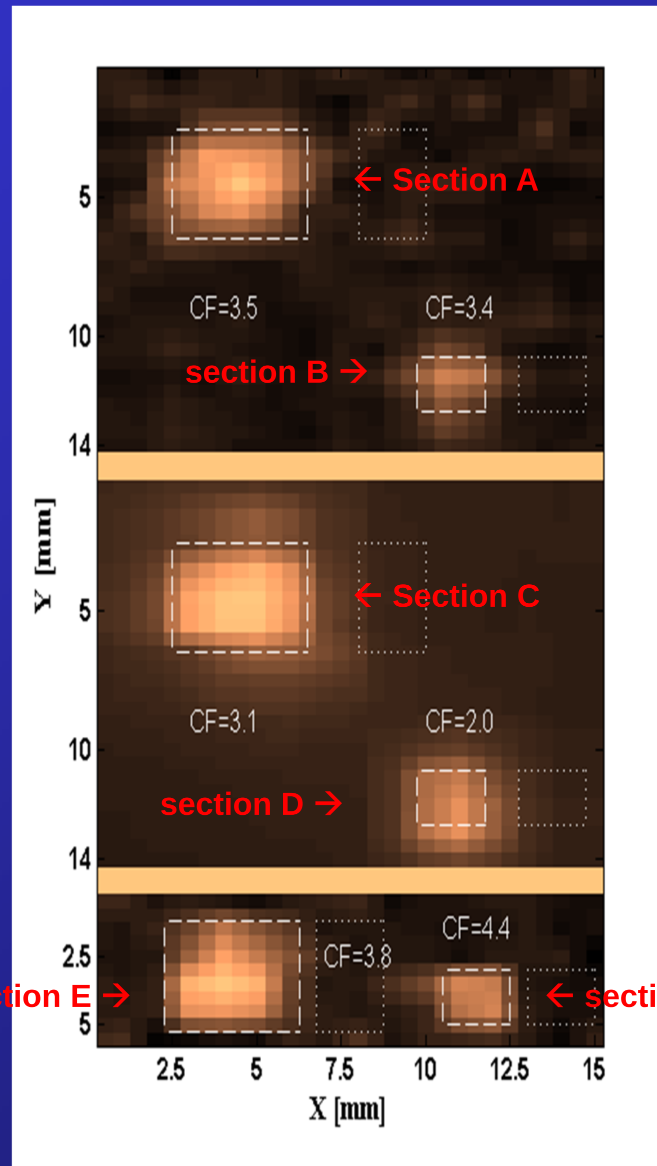
Comparing Pulsed and PA Radar Lateral Resolution and Contrast

The phantom is two black rubber squares 4x4 mm and 2x2 mm at the depth of 16 mm intralipid solution (0.47 %).

The images demonstrate the section at the position of squares in the Interalipid solution.

The dashed squares show the position of the squares. The dotted lines depict the area outside the chromophore where the contrast factors (CF) are compared.

CF affects lateral resolution



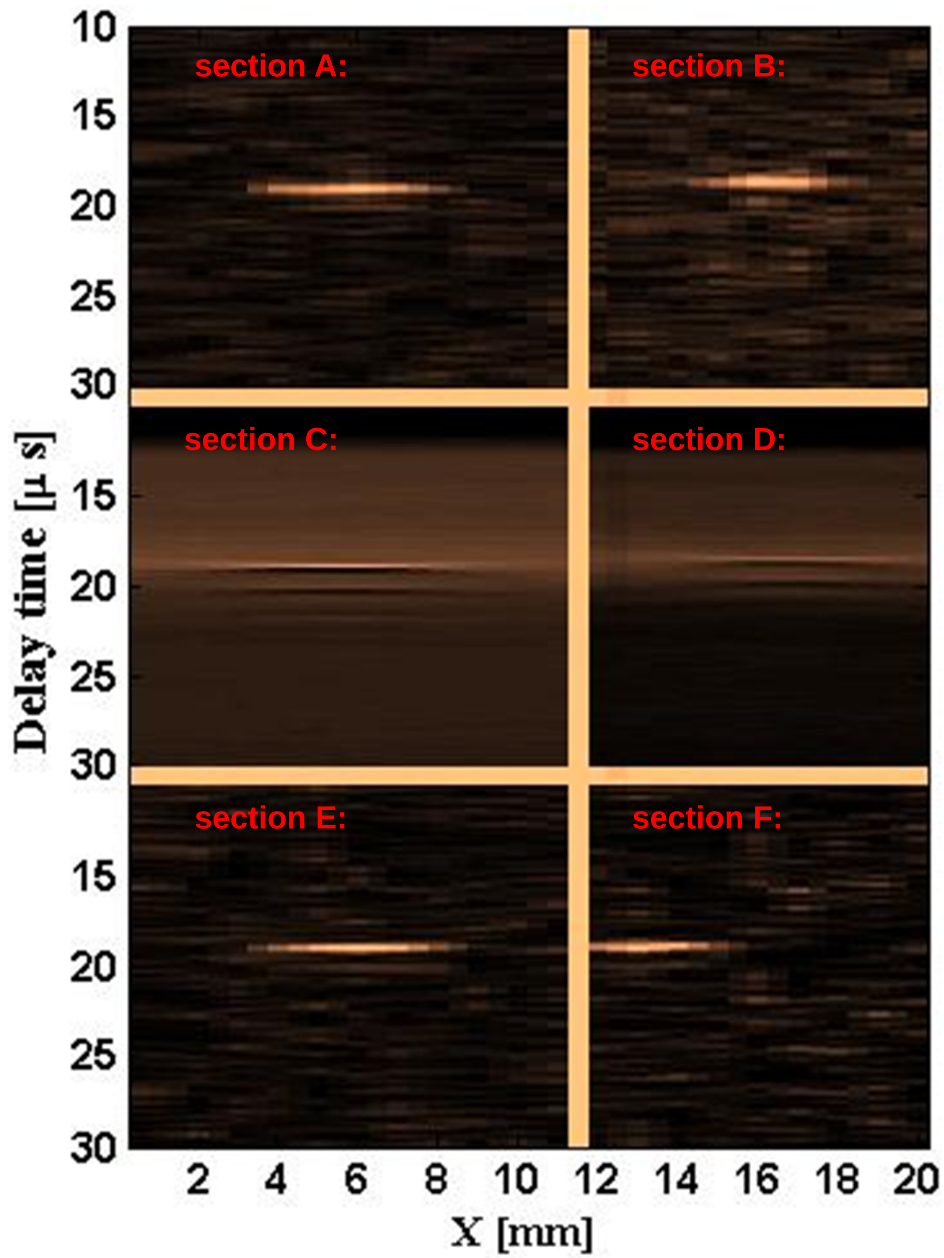
FD amplitude section image
(power 6.5 W/cm^2 , Laser exposure at each point 800 ms)

Pulsed section image
(pulse energy 100 mJ/cm^2)

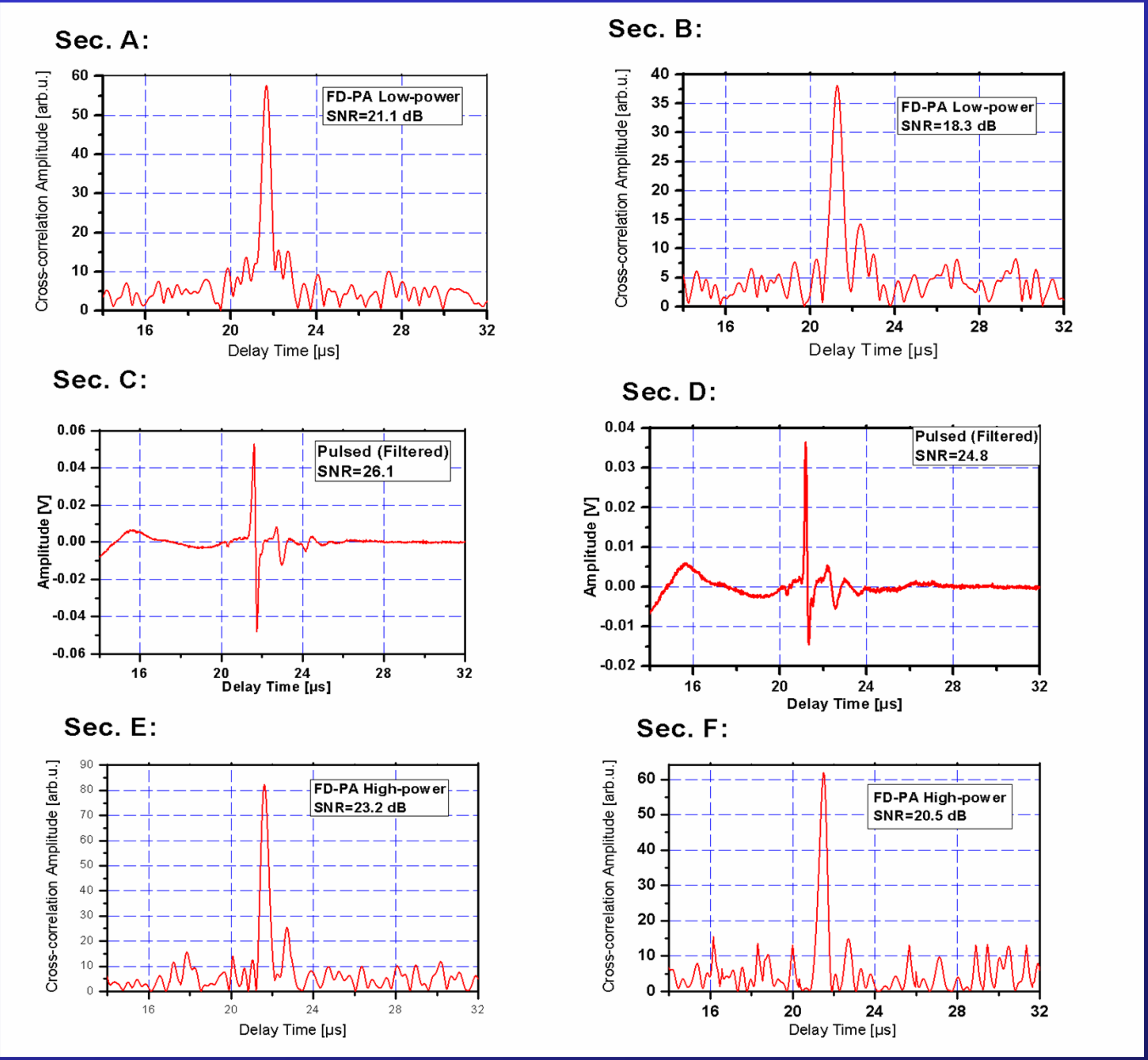
FD amplitude section image
(power 15.6 W/cm^2 , Laser exposure at each point 250 ms)

CF = (Signal mean in the lesion – Signal mean in the background) / Signal mean in the background

Comparing the contrast of pulsed and FD-PA in vertical section images:



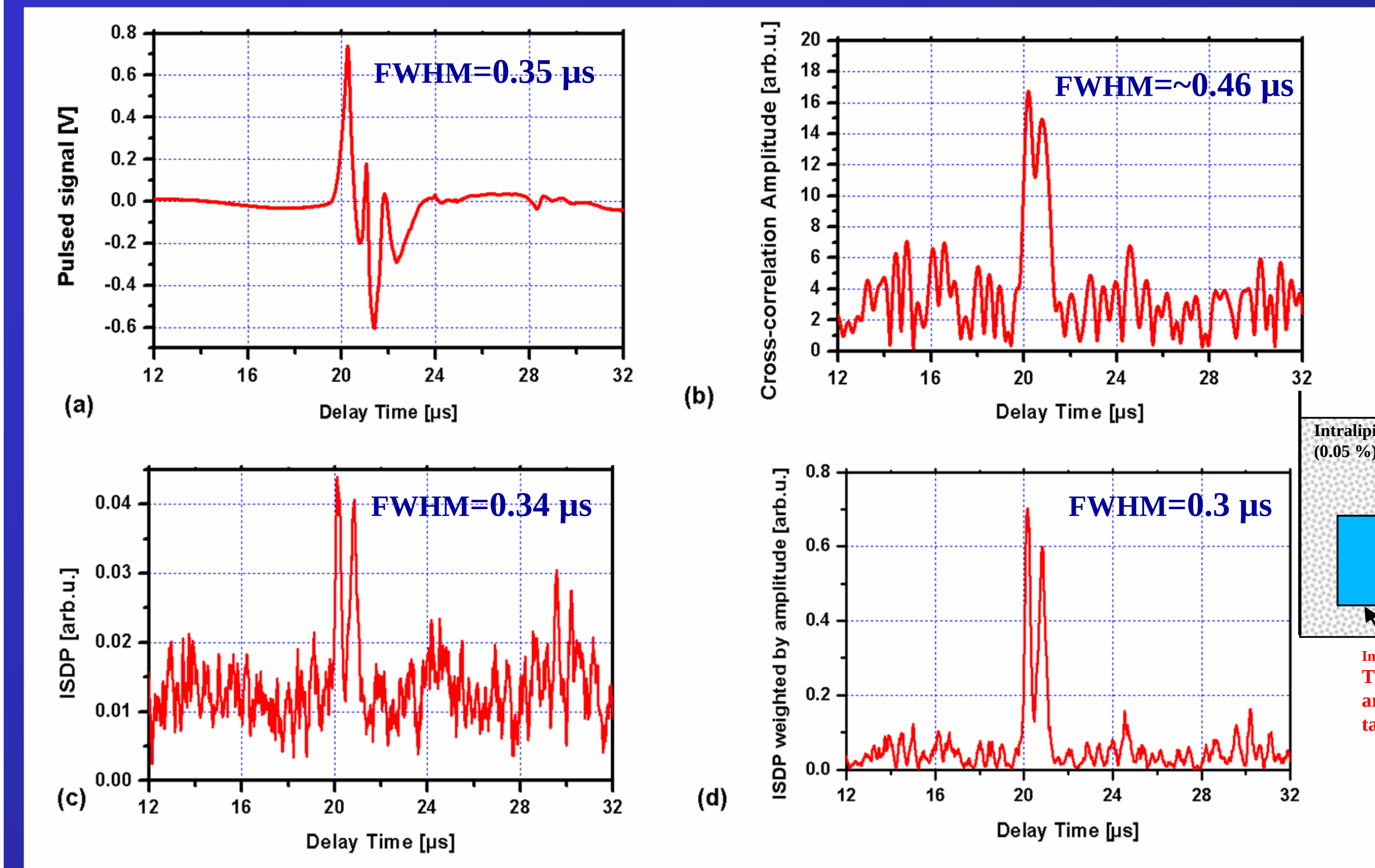
SNR Comparison between pulsed PA and PA radar with a high-frequency transducer

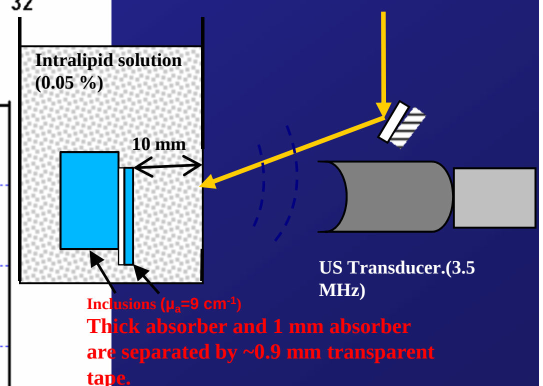


Axial Resolution comparison:

The sample is a 1 mm layer of plastisol (μ_a=9 cm^{-1}) separated from a thick plastisol chunk with a transparent layer of tape (~0.9 mm).

The absorbers are located in 1 cm of Intralipid solution.





Axial resolution comparison, Images:

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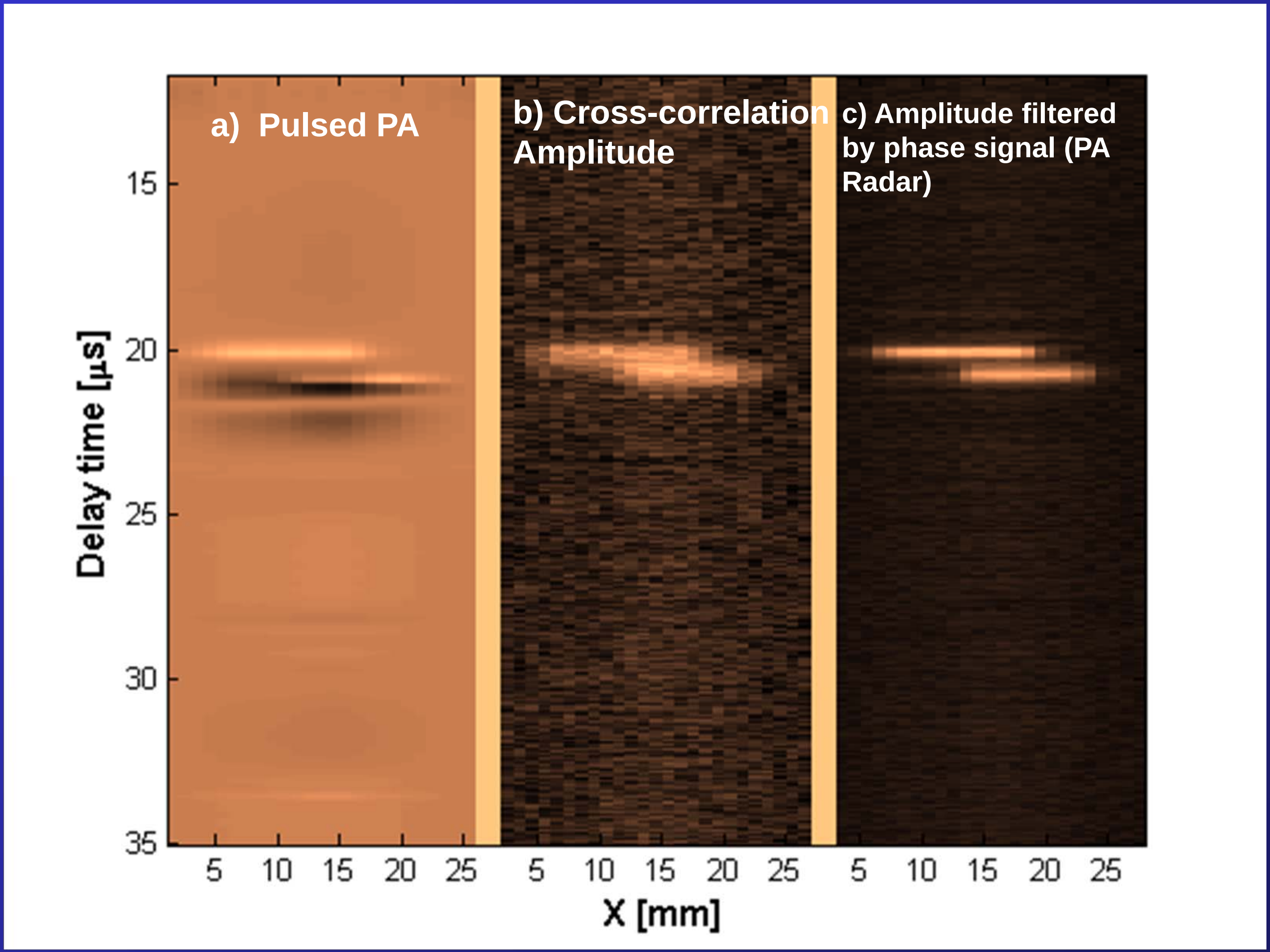
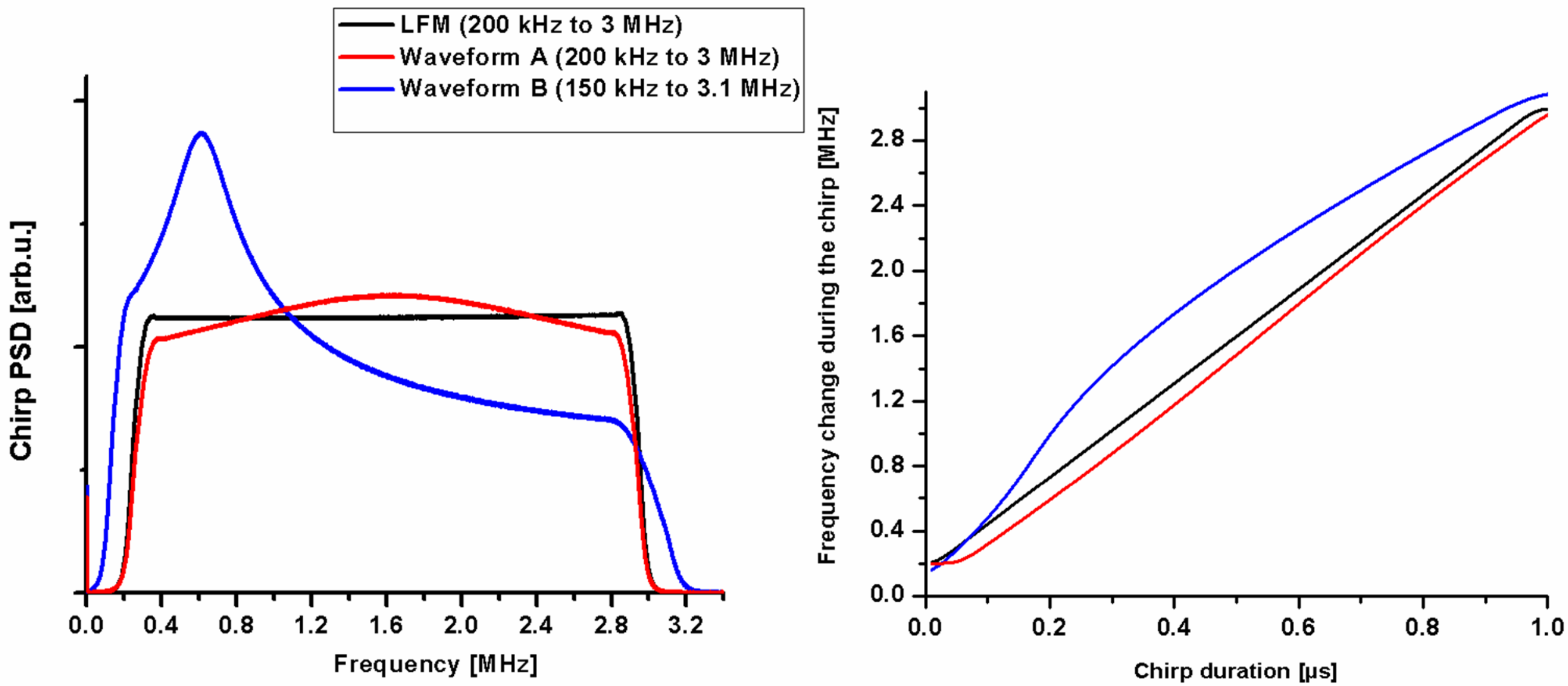
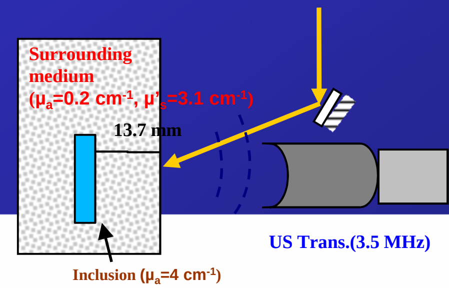
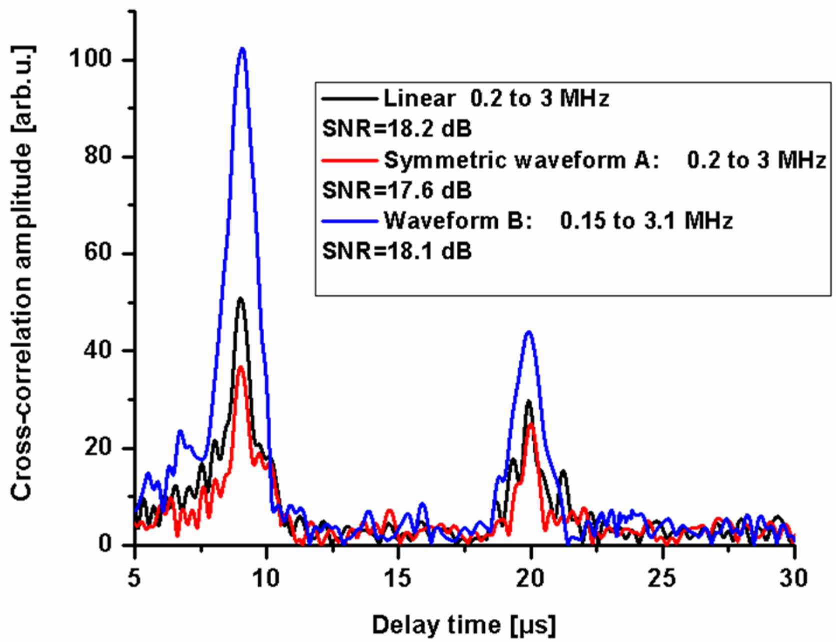


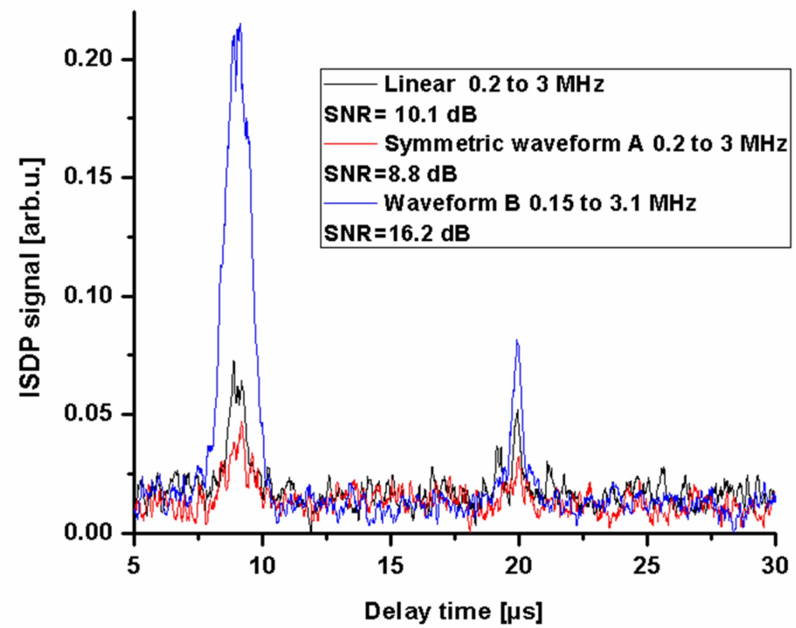
Experiments with nonlinear waveforms



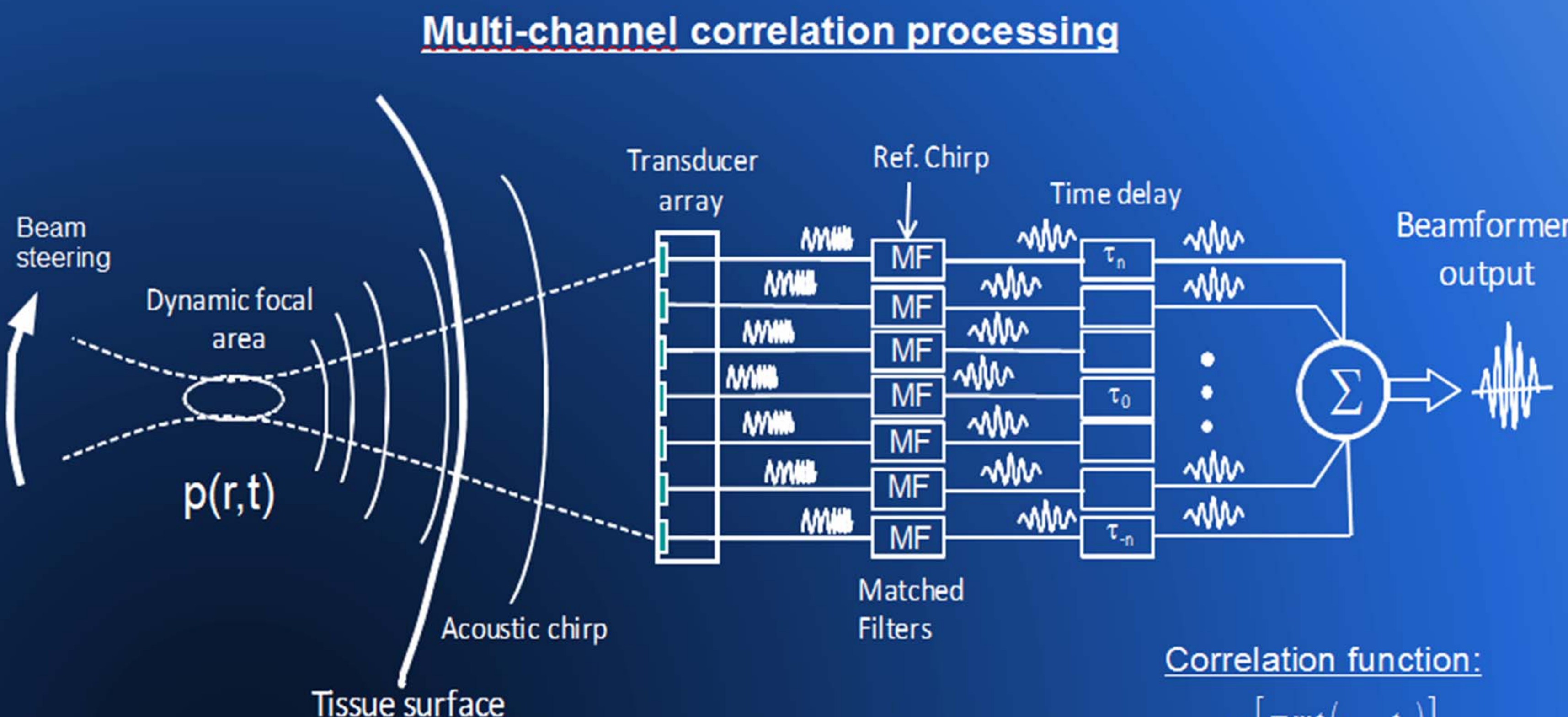
Comparison of SNR’s







Phased Array Imaging with Chirped Signals



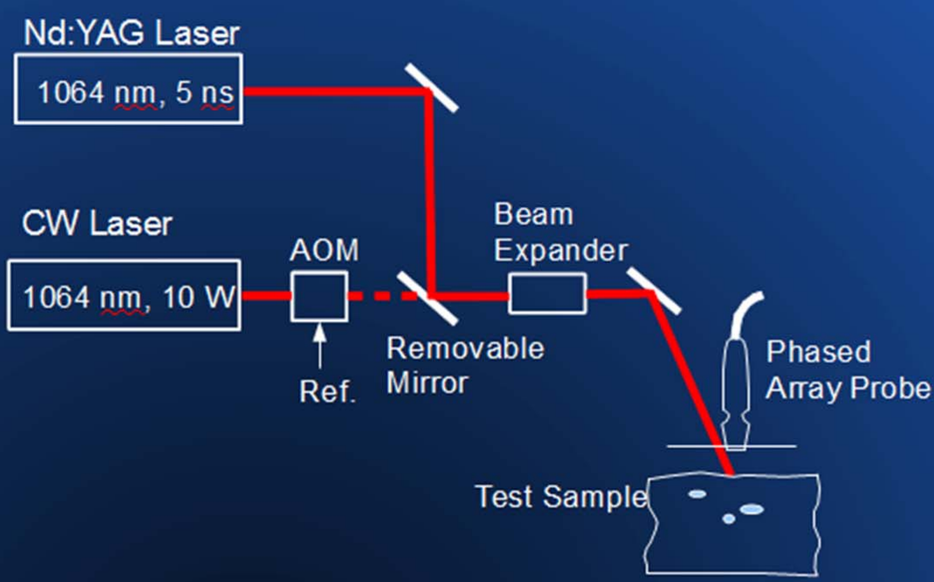
Correlation function:

$$B(t)=\frac{A_s^2 T_{ch}}{2}\cdot\frac{\sin\left[\frac{\pi m t}{T_{ch}}\left(1-\frac{t}{T_{ch}}\right)\right]}{\frac{\pi m t}{T_{ch}}}\cos(\omega_0 t)$$

- Dynamic beam focusing and steering is achieved by controlled delay times

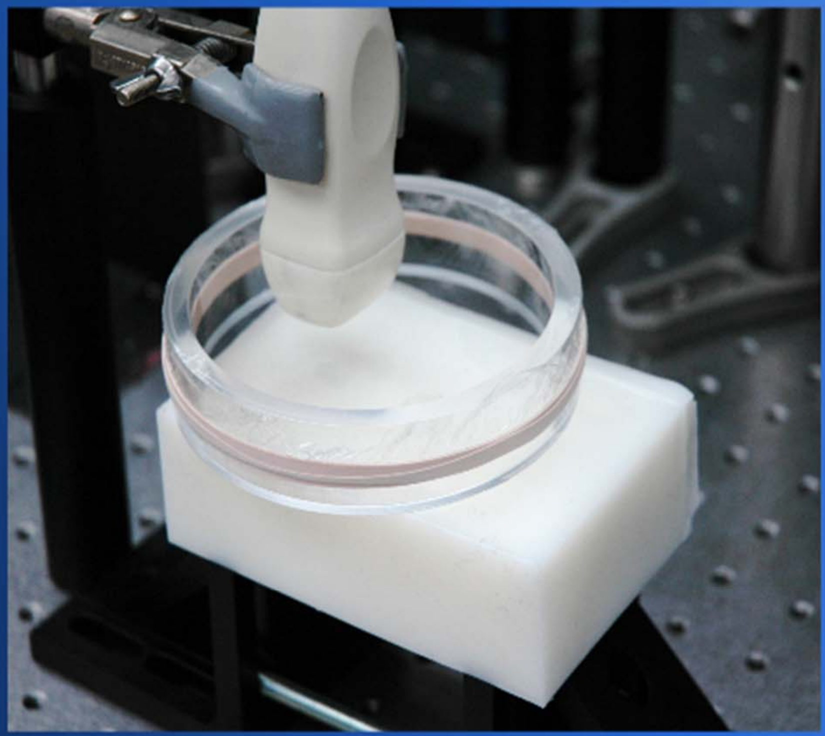
Dual-mode Photoacoustic Imaging System

Optical Setup



Test samples can be exposed to pulsed or intensity modulated beam for dual-mode PA imaging

64-element phased array probe

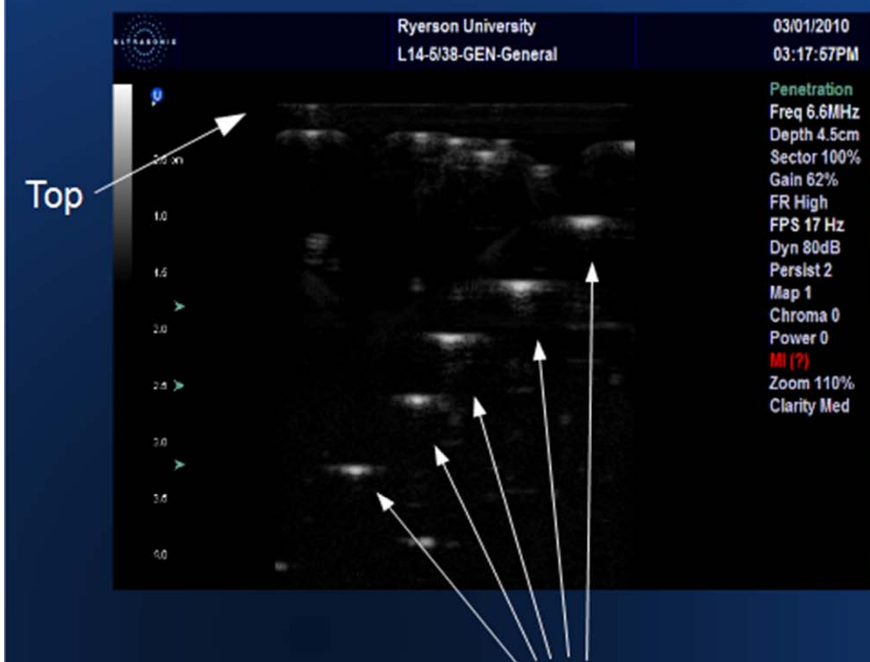


- **Conventional ultrasound instrumentation can be upgraded with PA imaging capability**

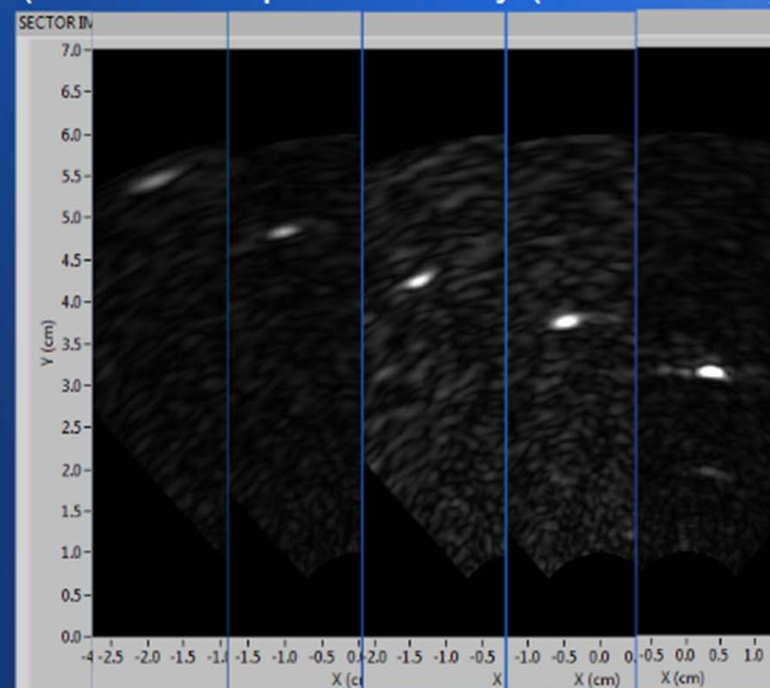
Ultrasonic and PA Imaging of Test Phantoms

Clear gel-like phantom with 5 threads (Ø 0.5 mm) positioned at different depths

Conventional ultrasound image

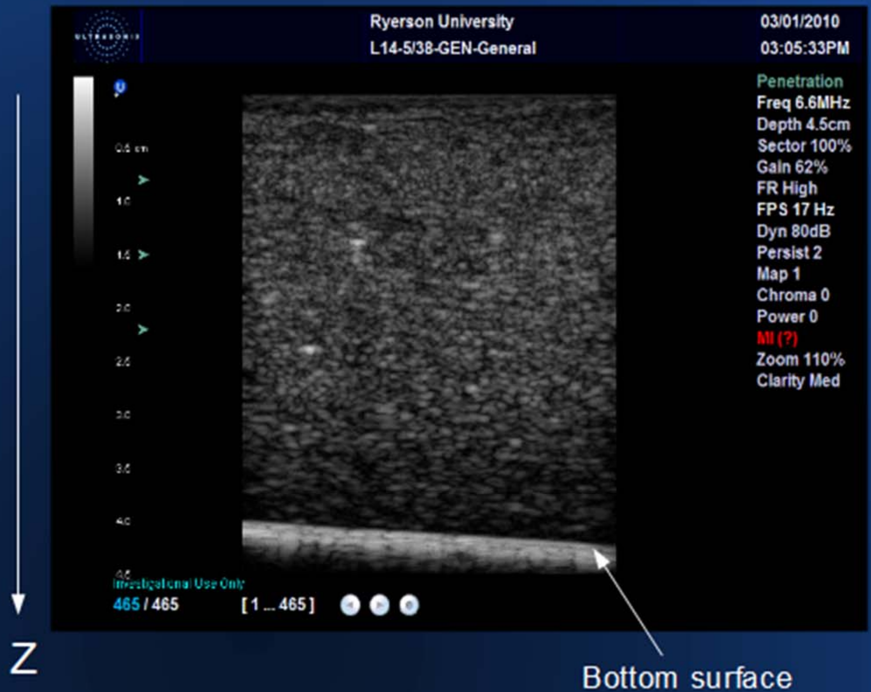


PA correlation image
(64-element phased array (f = 3.5 MHz)

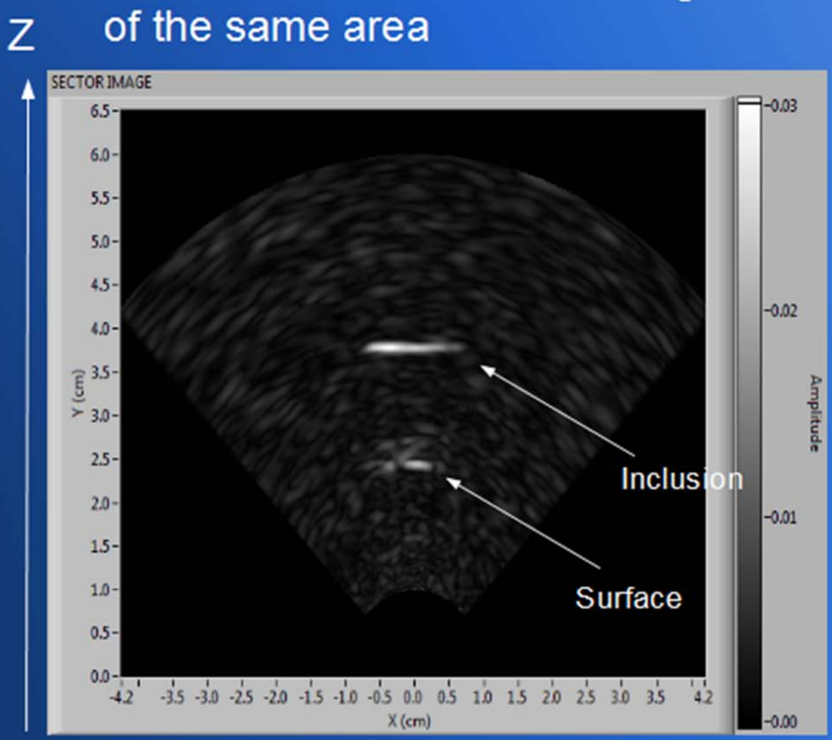


A. Comparison of PA Sonar and Conventional Ultrasound Imaging

Linear array ultrasonic scan above the rectangular inclusion , $\mu_a = 2\ cm^{-1}$



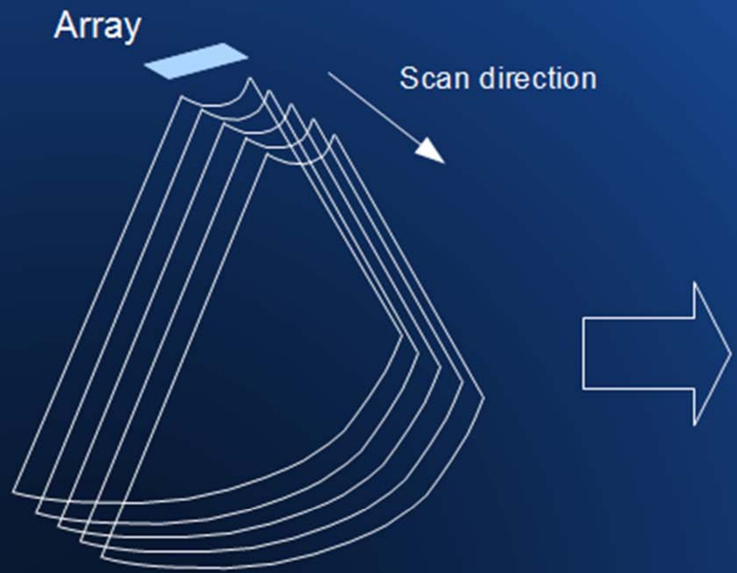
Photoacoustic correlation image of the same area



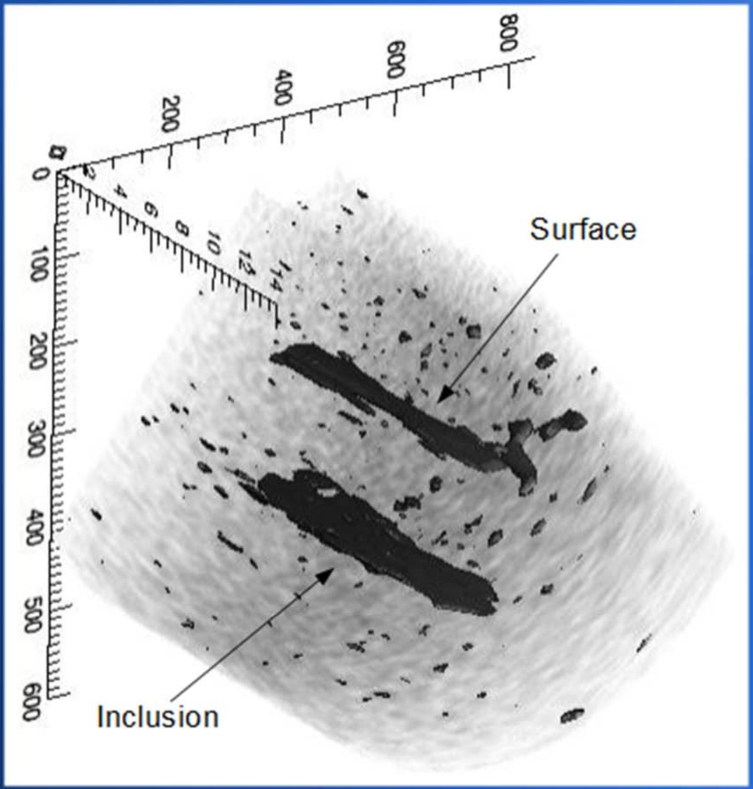
P = 1.1 W, Laser spot ≈ 3 mm

3D PA Imaging with Phased Array

Stack of 2D slice images

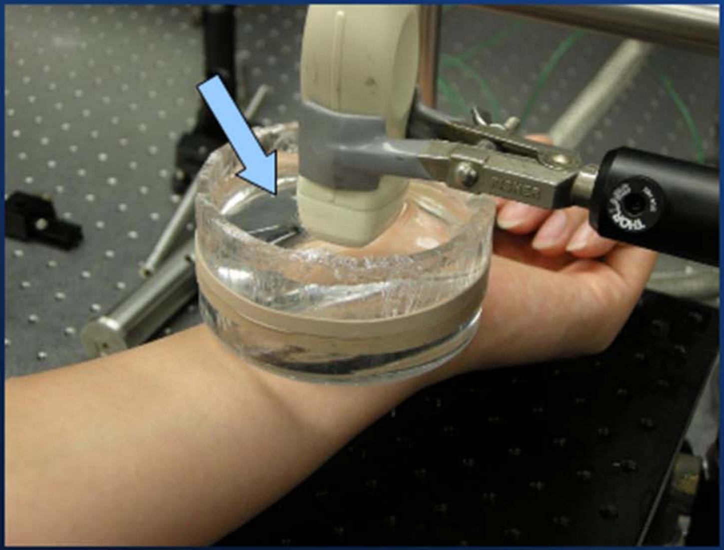


3D reconstruction and isosurface



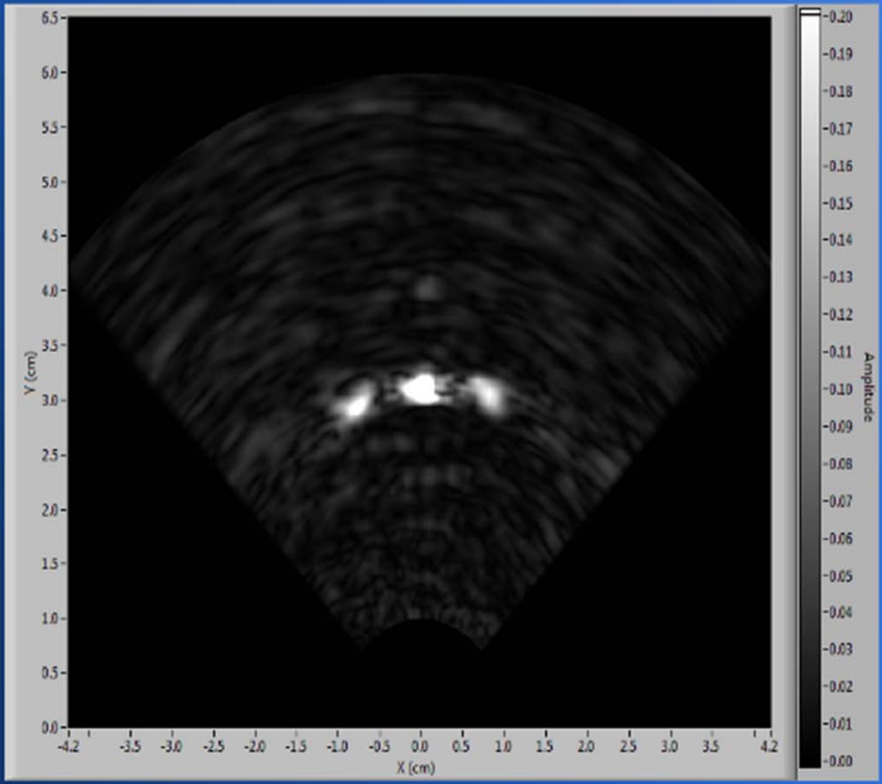
Phased Array Imaging in-vivo

Imaging wrist blood vessels. Position of a volunteer arm and phased array.



Arrow indicates laser beam direction.

Near-surface blood vessels of wrist



Cross-correlation sector image of discrete blood vessels

Conclusions

1) Frequency-domain photoacoustic detection with linear and non-linear frequency-sweep laser source modulation and coherent detection (PA Radar or Sonar) was demonstrated.

2) Time-bandwidth product increases SNR to within ~ 10 dB of pulsed PA. In practice the PA radar SNR can be higher than pulsed PA through chirp frequency bandwidth tuning and cross-correlation baseline interference elimination (even after high-pass filtering).

3) Combined amplitude and phase PA Radar exhibits superior contrast factors than pulsed laser PA.

4) PA radar can exhibit similar or improved lateral spatial resolution over pulsed PA

5) Combined amplitude and phase PA Radar exhibits equal to, or greater than, axial resolution than pulsed laser PA.

6) Judiciously designed non-linear chirp waveforms can further improve SNR at some loss of lateral spatial resolution (phase SNR: ~ 60%).

7) A PA Radar imaging phase array with chirped signals has been constructed and tested with phantoms and human arteries.

8) Potential for building <u>portable & economical</u> PA instrumentation using current-modulated semiconductor laser diodes and fiber optics.

Acknowledgments

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Thank you for your attention!