37th UIA Symposium, Washington DC

Workshop 2:
Acoustic Output Measurements

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Workshop material

- Background
  - Why measure?
- Measurement techniques
  - Hydrophones
  - Radiation Force balances
- Summary
- Hands-on session

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Background

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Relevance of acoustic output information

- What is it?
  - Numerical data that describes the ultrasonic field generated by a source and transducer combination: provides information on 'how much ultrasound is emitted'
  - Defined broadly in terms of
    - Forces exerted (*pressure*)
    - Energy transfer (*power*)

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What is it used for?

- Safety and performance assessment
- Prototype evaluation
- Routine quality checks
- Acceptance testing
- Patient satisfaction
- Compliance with regulation
- Good manufacturing practice
- Research

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Trends

- Significant advancements in technology
  - Diversity of applications
    - Diagnostic
    - Therapeutic (HIFU)
  - Need for increased imaging quality
  - Ever-increasing complexity of equipment
- Steady increases in acoustic output
  - Greater implications for safety
  - Necessary advancements in standards
    - Application-specific limits
    - On-screen displays
- Increased drive for equipment QA

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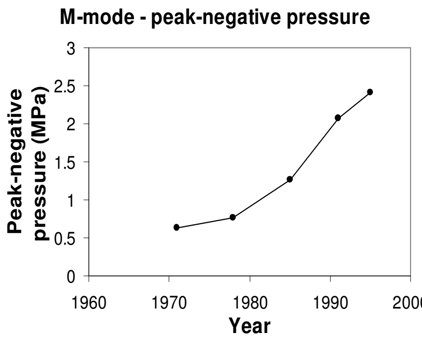
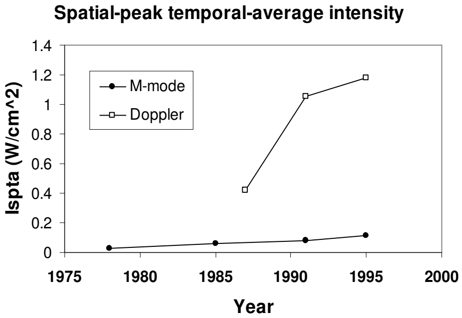
Technology advances





(after Duck and Henderson, Safety of Diagnostic Ultrasound, 1998)

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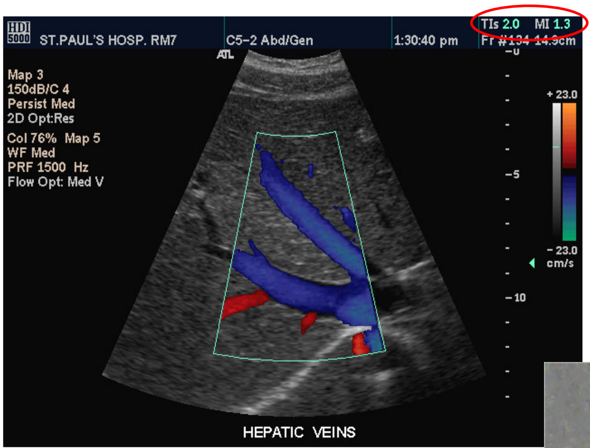
Where do you come across it?



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Who needs to know about it?

- You do
- Your customers do
- Your regulatory authorities do

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Standards and conformance

- National and international requirements exist to evaluate acoustic output
  - US Food & Drug Administration (FDA)
    - Conformance is a legal requirement before goods may be sold in North America and Canada
  - International Electrotechnical Commission
    - Supports the European Medical Devices Directive (CE marking)
- Local company procedures may exist
  - Periodic QA

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What standards are important?

- FDA 510(k)
- IEC 61157
- IEC 61847
- IEC 62359
- IEC 60601-2-37
- IEC 60601-2-5
- AIUM/NEMA UD-3

- AIUM/NEMA UD-2
- IEC 62127-1
- IEC 61161

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Measurement devices and techniques

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Determining key acoustical parameters

- Need capability to make measurements of high spatial and temporal resolution
- Also need to make measurements of bulk parameters
- In general, ultrasonic fields can be described in terms of
  - Acoustic pressures
  - Acoustic intensities
  - Ultrasonic power

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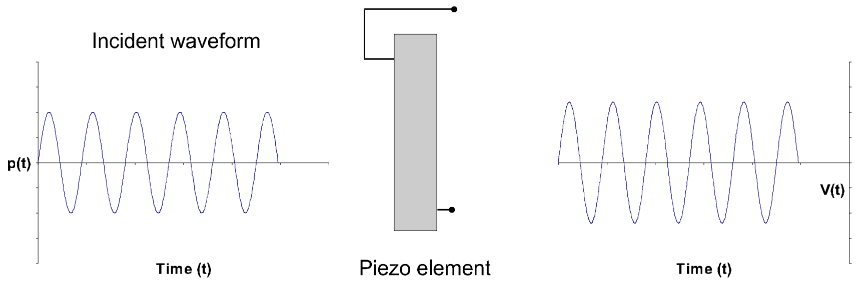
Measurement devices

- Acoustic pressure determined in ultrasound fields using calibrated hydrophones
- Operate via direct piezoelectric effect



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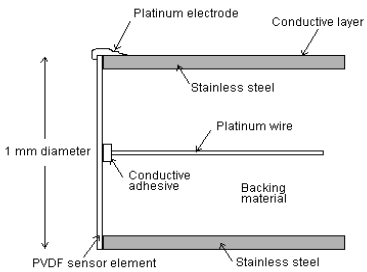
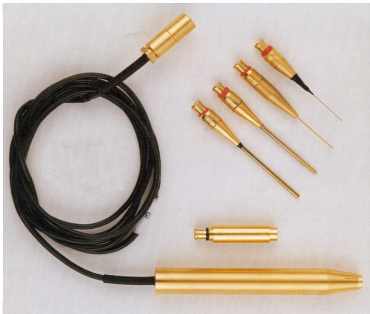
Hydrophone construction

– Needle-type
  • Small hollow tube, with active element at tip; connections made via casing and inside





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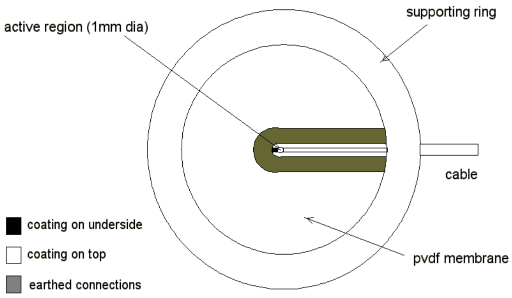
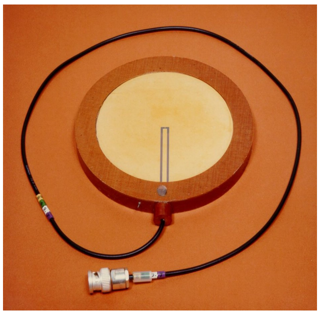
Hydrophone construction

– Membrane-type
  • Plastic ring, over which is stretched polymer film: "spot-poled" in centre to form active element





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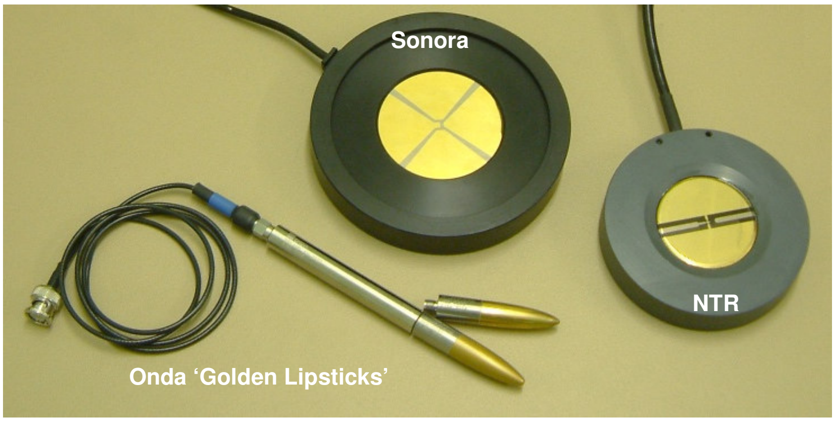
Commercially available devices



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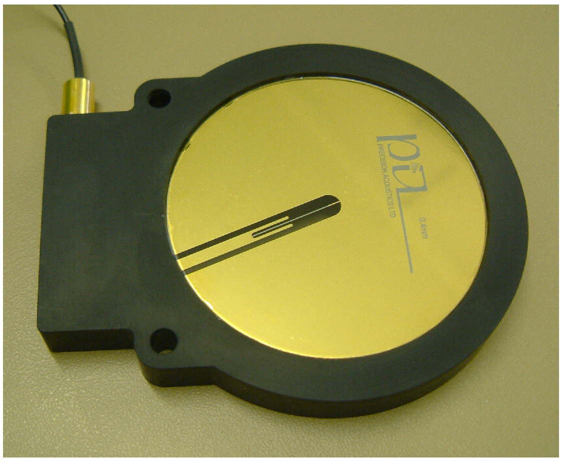
Precision Acoustics, UK



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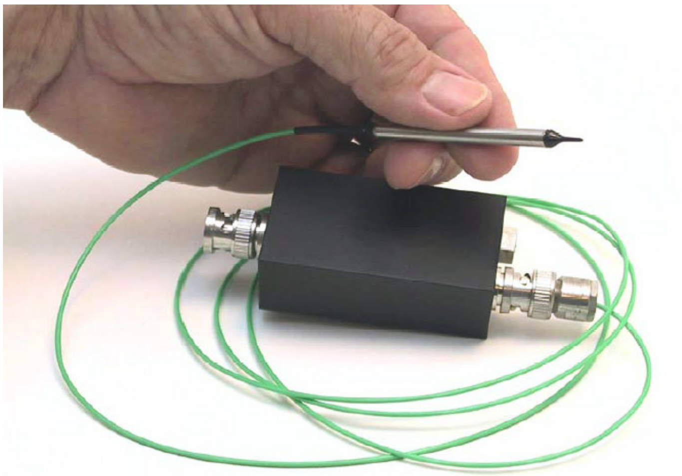
Force Institute, Denmark



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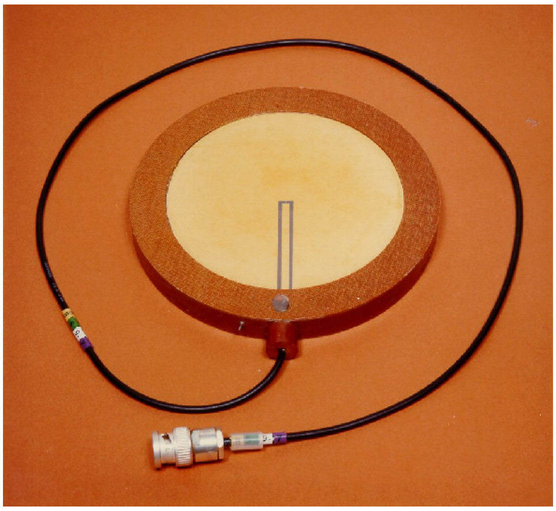
GEC-Marconi, UK



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Multi-element hydrophone

- Nonlinear element spacing
- Smaller elements at centre
- Complex shielding mask

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Operational differences

PVDF needle hydrophones

- Active element diameters as small as 40 µm: film thicknesses of 9 µm
- Less stable
- Complex frequency response below ~7 MHz
- Minimally-perturbing construction
- Fairly robust (tip excepted)
- Susceptible to electrical noise
- Less expensive

Membrane hydrophones

- Active element diameters as small as 200 µm: film thicknesses of 9 µm
- Very stable – established track record means that they are "gold standards"
- Flat frequency response
- Mechanical access can be limited
- More delicate
- More expensive

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Measuring acoustic fields

- Hydrophones often used with associated amplifier
- Waveform-processing oscilloscope required to evaluate parameters
- Motion control required to derive spatial variation of acoustic field
- Hydrophone and system under test immersed in water tank

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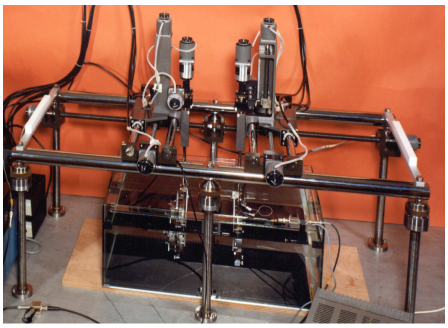
NPL Beam Plotting Facility



Sonora AMS

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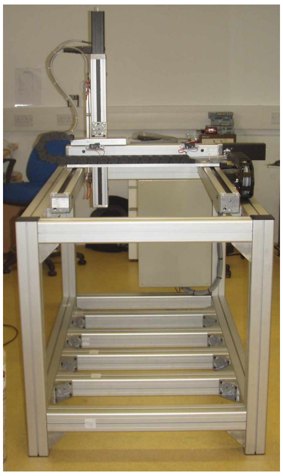
NTR Systems AIMS

Precision Acoustics UMS2



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Ultrasound field propagation

- Wave motion is predominantly longitudinal (compressional and rarefactional)
- Speed of sound, frequency, wavelength
- Pulsed excitation; repetition rate, duration
- Attenuation
- Nonlinear propagation

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Ultrasound field propagation

- Velocity of sound, c depends on density, r and elastic modulus, k of medium

$$c = \sqrt{\frac{\kappa}{\rho}}$$

- Velocity of sound, *c* related to frequency, *f* and wavelength, λ

$$c = f \times \lambda$$

- The product of the velocity of sound, *c* and the density, ρ, is the acoustic impedance, *Z*

$$Z = \rho \times c$$

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Ultrasound field propagation

- Instantaneous acoustic intensity *I(t)* is related to instantaneous pressure *p(t)* and particle velocity *v(t)* by

$$I(t) = p(t)\,v(t)$$

- In a plane propagating wave, the pressure and particle velocity are related by

$$v(t) = \frac{p(t)}{\rho c}$$

- Thus, acoustic pressure, *p(t)*, is related to instantaneous acoustic intensity, *I(t)*, by

$$I(t) = \frac{p^2(t)}{\rho c}$$

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Describing ultrasound exposure

- 4 main parameters of interest:
  - Peak-negative acoustic pressure (p-, p_r) ➔ *MI*
  - Spatial-peak-pulse-average intensity (I_{sppa})
  - Spatial-peak-temporal-average intensity (I_{spta}) ➔ *TI*
  - Acoustic power output (W)
- Other parameters also needed
  - Acoustic working frequency (f_{awf})
  - Beam widths
  - Pulse duration
- Attenuation in real tissue accounted for
  - Derating of 0.3 dB/cm/MHz

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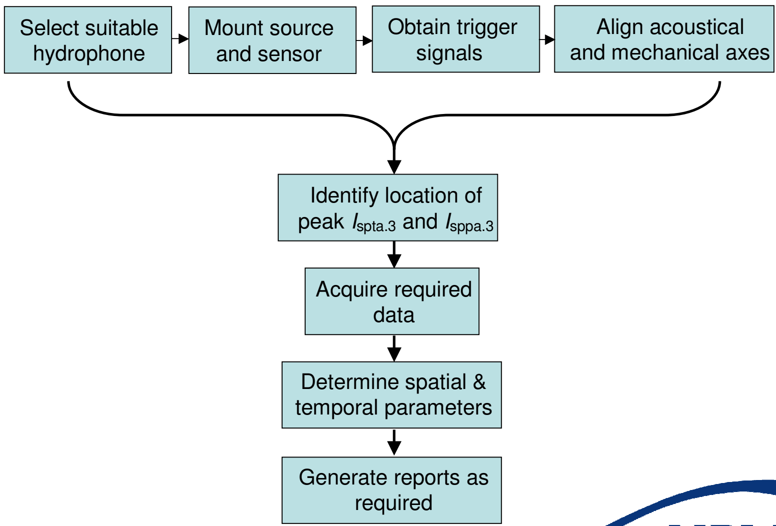
Measurement roadmap



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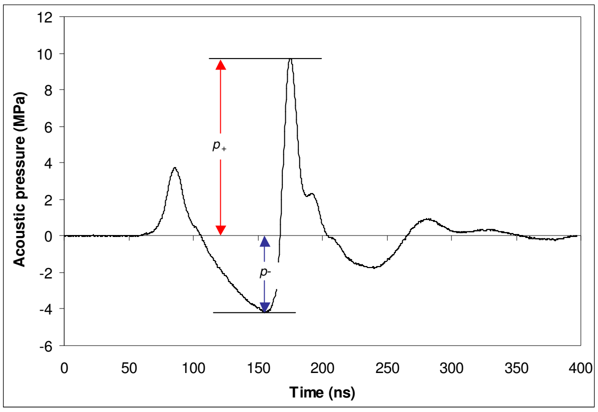
Acoustic pressure



- Acoustic waveform measured at focus of typical diagnostic scanner
- Short pulse duration
- Significant asymmetry
- *c.f.* atmospheric pressure of 100 kPa
- Important parameter is MI = $p_r/(freq)^{0.5}$

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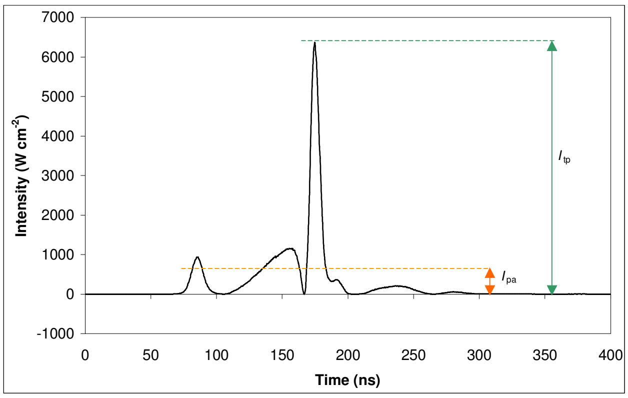
Intensity



- Derived from acoustic pressure waveform
- Several different parameters defined: is space and time-dependent
  - I_{sptp}
  - I_{sppa}

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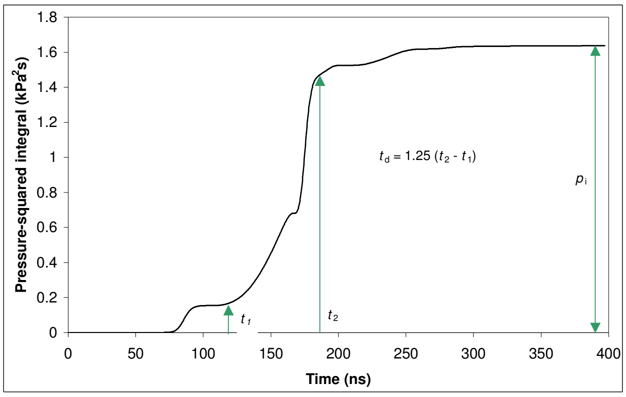
Pulse-pressure-squared integral



- Derived from acoustic pressure waveform, by summation
- Used to define pulse duration, t_d

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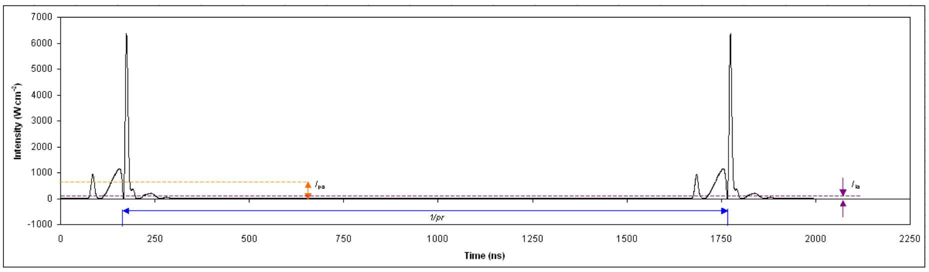
Time-averaged intensity



- Derived from the time average of the instantaneous intensity in the pulse, taken over an integral number of acoustic repetition periods
- Assumes all pulses are identical
  - Pulse duration *PD (from time integral)*
  - $I_{spta} = I_{sppa} \times PD \times prr$

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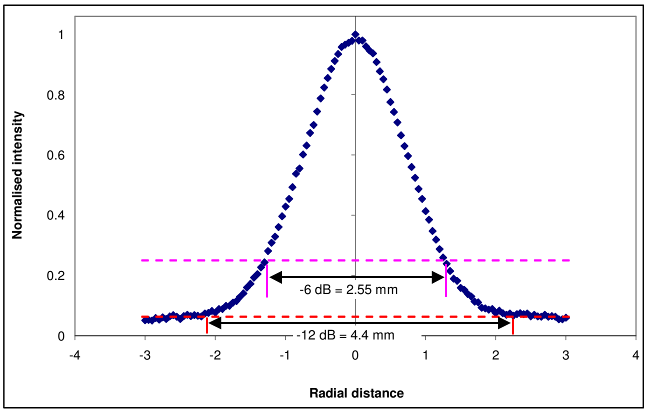
Beam dimensions



- Can be determined at –6 dB or –12 dB level depending on standard requirement and field location

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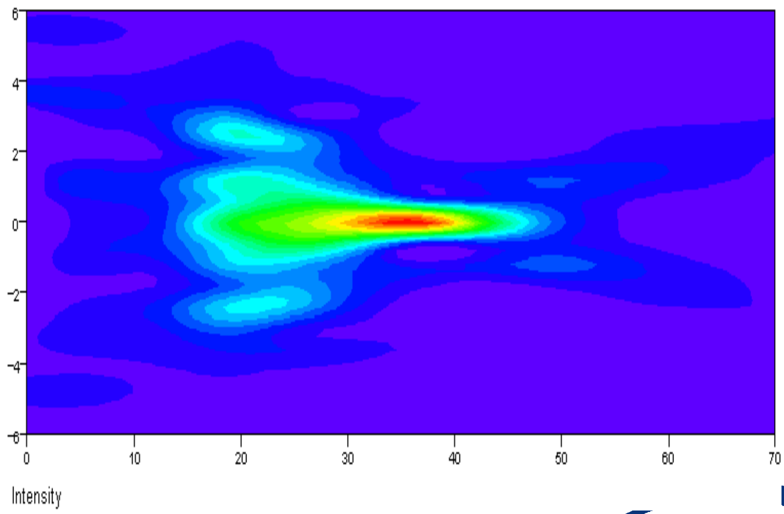
Example of intensity profile



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Measuring diagnostic fields

- Most commercial scanners have a large number of output settings
  - Focal zones (single and multiple)
  - Single and combination scanning modes
- Settings which produce maximum ‘acoustic output’ must be found
  - This can take a long time!
  - May require *a priori* knowledge of system

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Actual measurement considerations

- Bandwidth
- Sampling rate
- Signal-to-noise
- Spatial-averaging and directionality
- Triggering
- Uncertainties

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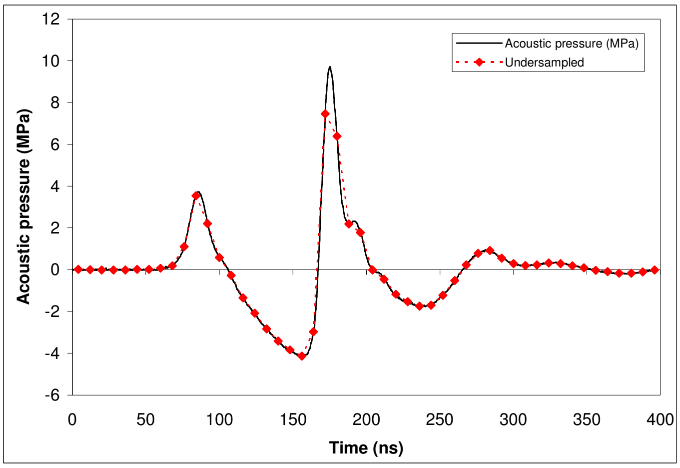
Sampling rate



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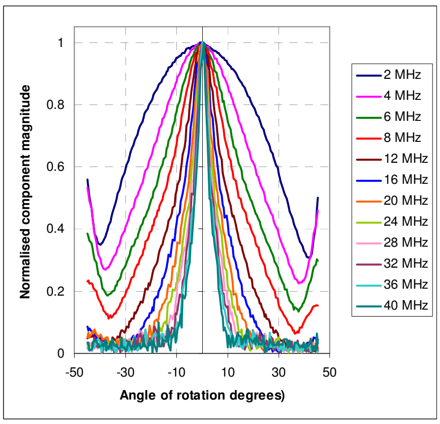
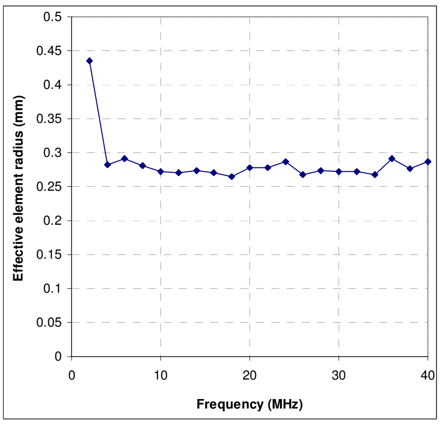
Spatial-averaging and directionality





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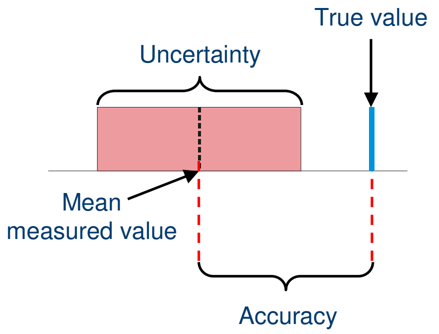
Uncertainties



Uncertainty budget:

Hydrophone calibration	16%
Oscilloscope	4%
Temperature	2%
Standing waves	15%
Noise	5%
Position	2%
Spatial averaging	4%
Repeatability	6%
Combined	**31%**

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Power measurement

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Determination of power

- Acoustic power can be measured in two main ways:
  - Planar scanning using hydrophones
    - Performed close to output face of scanner head
    - Intensity integrated over beam area
  - Radiation force methods
- Often useful to perform both, to obtain independent check of results

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Radiation force - principles

- Travelling acoustic wave has associated momentum
  - Net transfer of energy from transducer into medium
- A target placed in the path of the beam experiences a "radiation force", which is proportional to the power contained in the beam
  - Requires target large enough to intercept whole beam
- Methodology and principles described in IEC61161

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Radiation force balances

- Reflecting target balance
  - Incident energy reflected away to container edges
    - Flat plane target
    - Conical target
  - Requires acoustic absorber around edges of vessel to prevent multiple reflections
  - Needs ‘ideal’ reflecting target interface (air-water)

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Radiation force balances

- Absorbing target balances
  - Incident energy absorbed by target
    - High quality material required
      - Totally absorbing
      - Totally non-reflecting
    - Energy deposition can cause target heating
      - Temporal drifts in balance response
      - Convection currents can be important
  - Less sensitive to alignment

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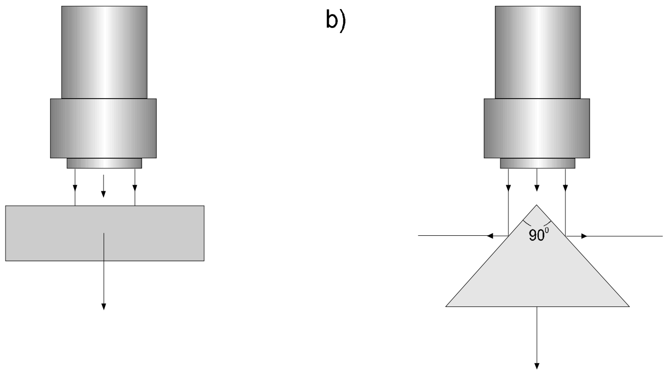
Radiation force balances

a) b)



$P = c \, . \, F$

$P = c \, . \, F \, / \, (2 \, . \cos^2 \Theta)$

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Radiation force balance targets

- Absorbing target
  - NPL Absorber
    - 30 dB cm^{-1} MHz^{-1} transmission loss
    - 40 dB echo-reduction
  - Polycarbonate-backed
- Reflecting target
  - Electroformed nickel cone, 80 mm diameter, 250 μm thickness
  - Air backed

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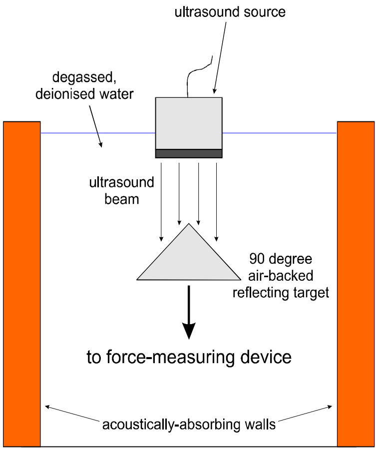
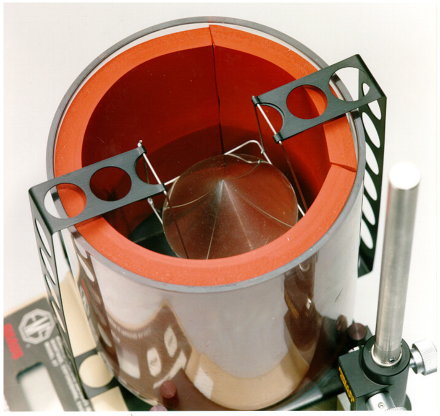
Radiation force balances





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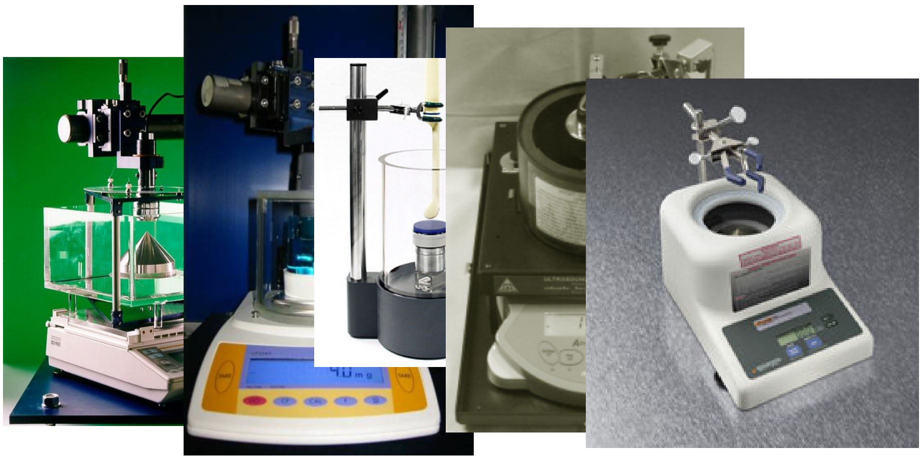
Radiation force balances



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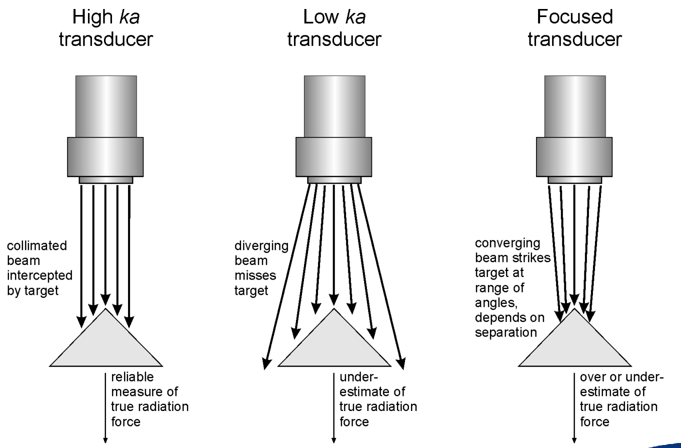
Radiation force measurements

- Beam geometry impacts on accuracy



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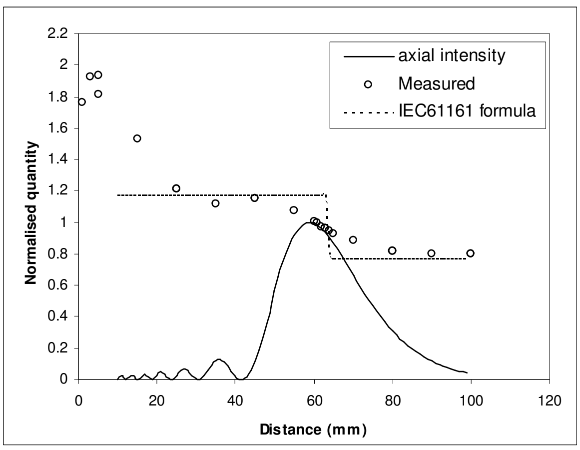
Radiation force measurements

Radiation force measured with a conical reflecting target as a function of distance in a focused ultrasound field (F-number = 1.5)



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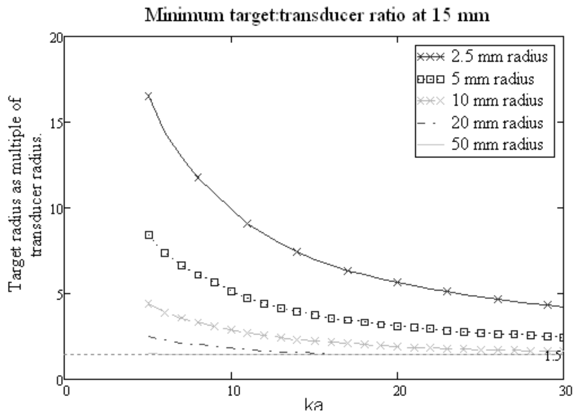
Radiation force measurements

- Target size and transducer-target separation important



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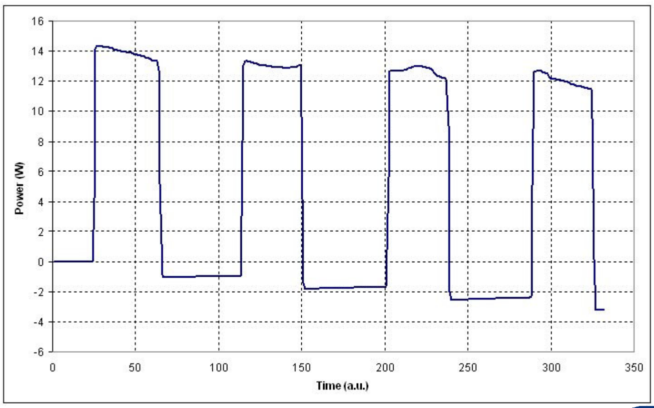
Radiation force measurements

- Target heating can occur – limit ON-times



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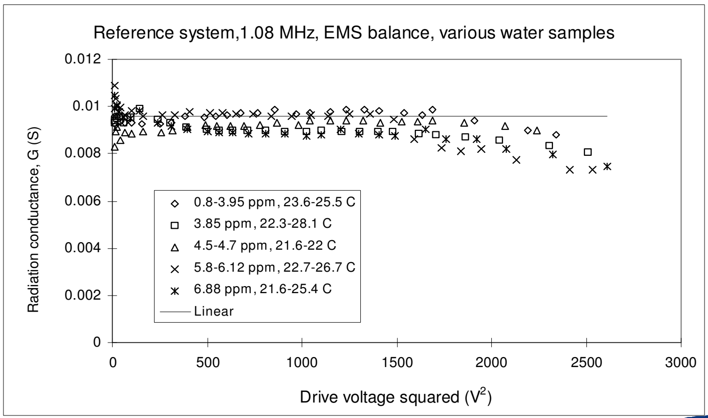
Radiation force measurements

- Cavitation occurs – water quality is important



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Main points to take away

- Measurement of acoustic output is important
  - Safety and efficacy assessments
  - Compliance with regulation
  - Prototype evaluation
- Good quality data can be obtained using a variety of measurement devices
  - Hydrophone-based systems
  - Radiation force balances

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Hands-on session

- Sonora AMS Hydrophone test tank and acquisition system **(Jim Gessert)**
- Precision Acoustics radiation force balance and checksource **(Mark Hodnett)**

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