A High-Resolution Ultrasonic Thermometer for Measuring Absorbed Dose in Water Calorimeters

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Motivation

• The Domen design -- two thermistor probes inside a sealed glass vessel mounted within a large water phantom
  – nonwater materials complicates conduction and, in some cases, convection effects
  – few other temperature sensing techniques apart from thermistors can provide the $\mu$K sensitivity needed for the dose measurement.
  – ultrasonic technique: noninvasive, high-resolution temperature sensing
Experimental Setup

- $^{60}\text{Co}$
- Ultrasound transducer
- Frequency Counter
- Lock-in amplifier
- PPLL
- Wheatstone Bridge
- Shutter

Components:
- Insulation
- Thermistor
- Water
- 10 cm
Testing with Co-60 source
(alpha-prototype)

Small water tank with attached ultrasonic transducer

Alpha-prototype test cell under the Co-60 source at NIST
## Operational parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$ Ultrasound detection frequency</td>
<td>$5 \times 10^6$</td>
<td>Hz</td>
</tr>
<tr>
<td>$T_0$ Ultrasound period</td>
<td>0.2</td>
<td>$\mu$s</td>
</tr>
<tr>
<td>L Nominal length of ultrasound path</td>
<td>30</td>
<td>cm</td>
</tr>
<tr>
<td>$\Delta t$ Time delay for a round trip in the water tank</td>
<td>0.4</td>
<td>ms</td>
</tr>
<tr>
<td>Reference pulse rate</td>
<td>6000</td>
<td>Hz</td>
</tr>
<tr>
<td>Reference pulse width (number of cycles at $T_0$ period)</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Number of “sample and hold” cycles</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
Radiation heating results

Water temperature history in the tank before, after, and during thirty 120s exposure cycles to the Co-60 radiation.

Larger scale view of a short segment of the same plot demonstrating high resolution at the $\mu$K level.
Absorbed dose estimation

- Analyze periodic heating data in Fourier domain. Filter out thermal noise and convection.
- Derive dose from the energy of the main harmonics. Correct for the beam profile.

**Preliminary results:**
- 30 x 120s Co-60 exposures, 50% duty cycle
- Dose rate derived from acoustic data: 1.8 Gy/min
- Estimated nominal dose rate: 1.65 Gy/min

**Sources of error:**
- Non-standard water tank size
- Inadequate calibration of the alpha prototype at test time.
Beta prototype implementation

**Hardware:**
- New large 1ft³ water tank to meet calorimetry standards
- More convenient foam enclosure
- Improved analog PPLL module

**Software:**
- New user interface
- Built-in acoustic calibration procedure
- Intuitive operation
Calibration and noise issues

- $\Delta f$, deviation from $f_0$, linearly proportional to $\Delta v$
- $v = v_0 + a(T-T_0) + b(T-T_0)^2$
- $\Delta T = \alpha(f,T)\Delta f$
- $\alpha$ -- experimentally calibrated $\sim 95.5$ mK/Hz
  - $f_0 = 5$ MHz at 20 °C
  - $v = 1482$ m/s
- $f$ can be resolved to 0.01 Hz or better, $\Delta T \sim \mu$K.
- A root-mean-square (RMS) noise of 3.2 $\mu$K
  - 30x30x30 cm$^3$ water tank
  - averaging over 400 s
  - sampling rate of 4 per second
Temperature sensitivity test

- 1ft³ thermally insulated water tank
- Thermal equilibrium (heating/cooling) rate is ~4 (μK/s)
- Temperature measured every 4s over 400 s period.
- Noise estimate from the linear fit: $\Delta T_{\text{RMS}}=3.2$ (μK)
Compared to thermistor

- 10 kΩ thermistors (size usually less than 1 mm) in a Wheatstone bridge with a lock-in detection scheme
  - RMS noise in the output voltage of 50 nV (3 μK)
- ultrasound technique comparable to the thermistor technique in resolution in temperature.
Convection Issues

Convection:
- Overlaps with the periodic heating data.
- Exhibits nonlinear behavior. Hard to isolate from the signal.
- Depends on the tank geometry and beam profile.

![Temperature history graph]

- Single 240s radiation exposure
- Convective oscillations
Observed convection in the large water phantom by ultrasound temperature measurements. The shutter opens for 60 s, the temperature rises initially, then enters into oscillations after the shutter closes.
Convection and periodic data collection

Suggested resolutions:

- Use shorter exposure periods to stay away from the convective resonance.
- Create convection barriers in the water tank.
- Use non-convective phantom medium with acceptable ultrasonic properties.
Measured dose rate using ultrasound as a function of radiation shutter period. The estimated nominal dose rate of 4.5 mGy/s is plotted for comparison.
Simultaneous measurements using ultrasound and thermistor in the phantom

Graph showing temperature changes over time with dashed line for sound and solid line for thermistor.
Shutter 180 s on/off
360 s period
$f_0 = 1/360s = 0.002778$ Hz

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**Temperature change (mK)**

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**FFT amplitude**

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$f_0 = 1/360s = 0.002778$ Hz

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**Temperature change (mK)**

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**FFT amplitude**
observed signs of convection at 240 s

- ○ - thermistor at 10 cm
- □ - ultrasound at 10 cm

Measured dose rate (Gy/s)

Shutter opening time (s)
thermistor open
ultrasound
33 mm cell
45 mm cell
240 s
Beam cross-section imaging

Circular ultrasonic array:

- No moving parts
- Fast signal acquisition
- Generate thermal beam profile in seconds
- Speed up clinical calibration
- Refine absorbed dose measurement

Imaging prototype components:

1) Water tank
2) Radiation beam
3) Circular ultrasonic array
Cylindrical water tank in the foam insulation jacket with the cover off.

Split foam jacket

14”-diameter, 128-element submersible ultrasonic array

Alpha-prototype components
Temperature profile reconstructions in water tank from fan beam tomographic acoustic experiment with 64 projections, 45 rays per projection. (a) The radiation source (heat lamp) off; (b) Radiation source on for 30s. Area dimensions: 300 pixels = 230 (mm); Relative height of the temperature dome is ~0.008 (K)
2D representation of the data shows reconstruction of water temperature profile in cylindrical tank after 30s heating with incandescent light mounted over the center. The red area in the center outlines the hottest (within 0.003K) spot in the tank.
Linear temperature profiles in the water tank retrieved from the 2D tomographic reconstructions of the same area prior to heating (black curve) and after 30s exposure to incandescent light (red curve). The peripheral features beyond +/- 80mm from the center are reconstruction artifacts. The circular area of 60mm radius is an artifact-free zone that can be used for quantitative measurements in sub-mK temperature range with the highest spatial resolution.
Summary

• Ultrasound thermometer test in radiation, noise level 3.2 μK, comparable to thermistor
• Advantage: non-invasive, no non-water material, self-heating negligible
• Disadvantage: (?) temperature averaged over the entire beam path, convection distortion
• Simultaneous measurements using thermistor and ultrasound track each other and both observe the similar distortions due to conduction and convection.
• Data acquisition improvements: digital pulsed phase-locked loop better locked to the phase without adjusting the reference frequency
• Circular array of ultrasound transducers used to create tomography of temperature profile in water at 5 mm spatial resolution and sub-mK temperature resolution.