Temperature model for 3D ultrasound computer tomography

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Background

- Ultrasound Computer Tomography (USCT) is an emerging method for early breast cancer detection
- A 3D USCT II demonstrator was built at Karlsruhe Institute of Technology (KIT) [1]
- Currently 3D USCT is in a clinical trial at Medical center Mannheim
- 3D USCT II system is built around the idea of an synthetic aperture with many non-focused independently acting transducers grouped as transducer array systems (TAS)
- Millions of pressure over time signals are collected in over minutes of measurement time

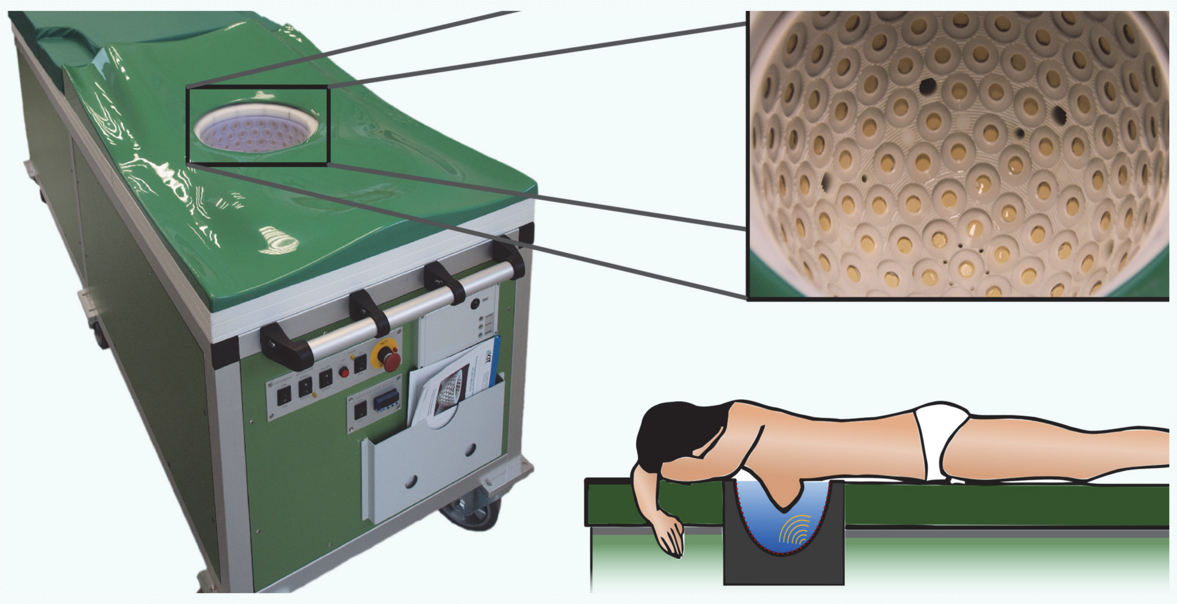


Figure 1: KIT 3D USCT II demonstrator (left), aperture (right top) and schematic use case (right bottom)

Motivation

- Fidelity of the time of arrival information is crucial for the imaging methods applied
- A significant source of errors are variations of the medium speed of sound due to temperature variations.
- Speed of sound of ultrasound waves in water is significantly temperature dependent [3].
- Several factors contribute to a non-static and non-trivial temperature distribution in the 3D-USCT system:
  - USCT used in hospital environments which are not perfectly stable or well defined as laboratories.
  - Pre-heated water at body temperature to minimize transfer losses from water to body.
  - Background temperature is room temperature.
  - USCT system components act as heat sources, e.g. the DAQ electronics with 1 kW.
  - Water evaporation and heat dissipation from the open water surface.
  - The patient itself heats with approx. 100 W, stirs the water and blocks partly the water surface.
- Complicated and uncontrollable temperature behavior.
- Significant spatial and also temporal dependent temperature variations.
- The approach to tackle this problem is to monitor and log the temperature behavior with a suitable temporal as also spatial resolution and apply this information to the measurement data.

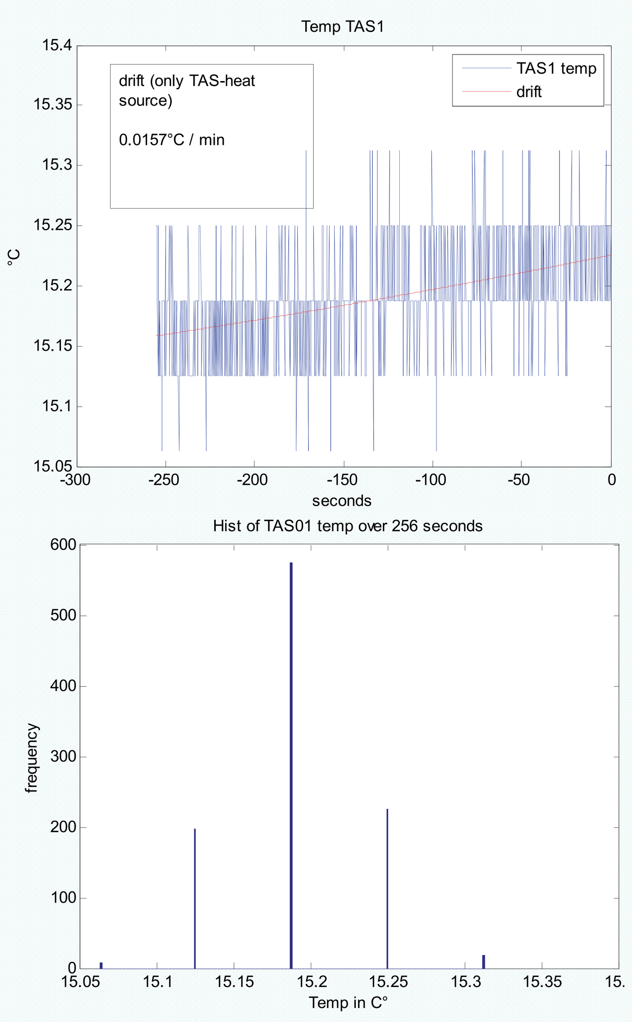
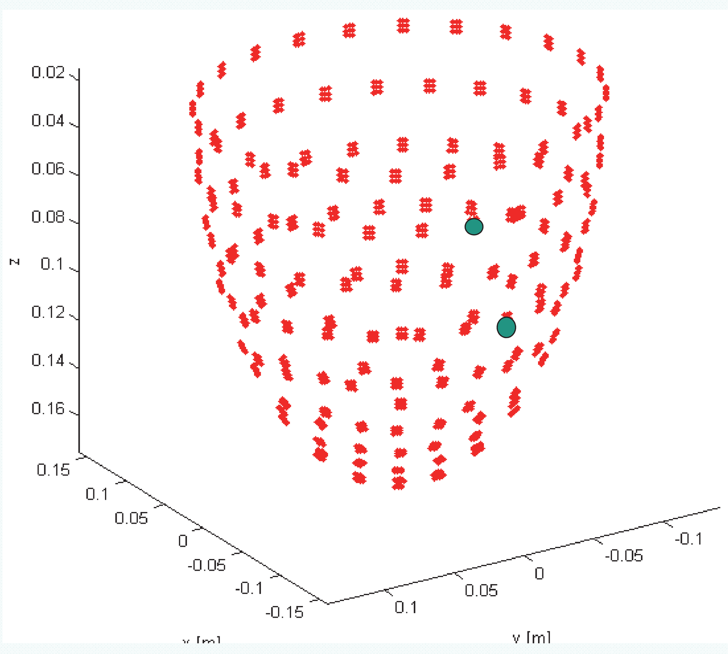


Figure 2: Top: temperature measurement over four minutes (blue curve). Visible noise and temperature drift Red curves is the low order polynomial fit. Bottom: histogram of the measurement

Hardware and Setup

- USCT system has two kinds of on the aperture surface distributed temperature measurement devices
- **157x MAX6627 temperature sensors,** accuracy of ±1°C, digital 12bit (0.0625°C per bit), measurement speed is 320ms [5].
- **2x JUMO dTRANS T03 B Typ 707031,** high precision temperature sensors, Pt100 based, calibrated (DIN EN 60751) accuracy of 0.08°C, digital 12bit (0.0625°C per bit), measurement speed is <100ms [4].



Requirements and constraints

- Required accuracy for USCT imaging assumed as <1 m/s which translated to 0.1°C
- Measurement time for patients in the order of several minutes.

Figure 3: USCT II aperture, the red dots indicate the receiver positions per TAS, the middle positions are the MAX6627 temperature sensor , the blue dots are the JUMO dTRANS T03 B temperature sensors

[1] J. Ferlay et al.. (2012 v1.0), Cancer incidence and mortality worldwide: IARC cancerbase no. 11, Lyon, France: International Agency for Research on Cancer 2013, Available: http://www.globocan.iarc.fr

[2] H. Gemmeke and N. V. Ruiter, 3D Ultrasound Computer Tomography for Medical Imaging, Nucl. Instr. Meth., in press, 2007.

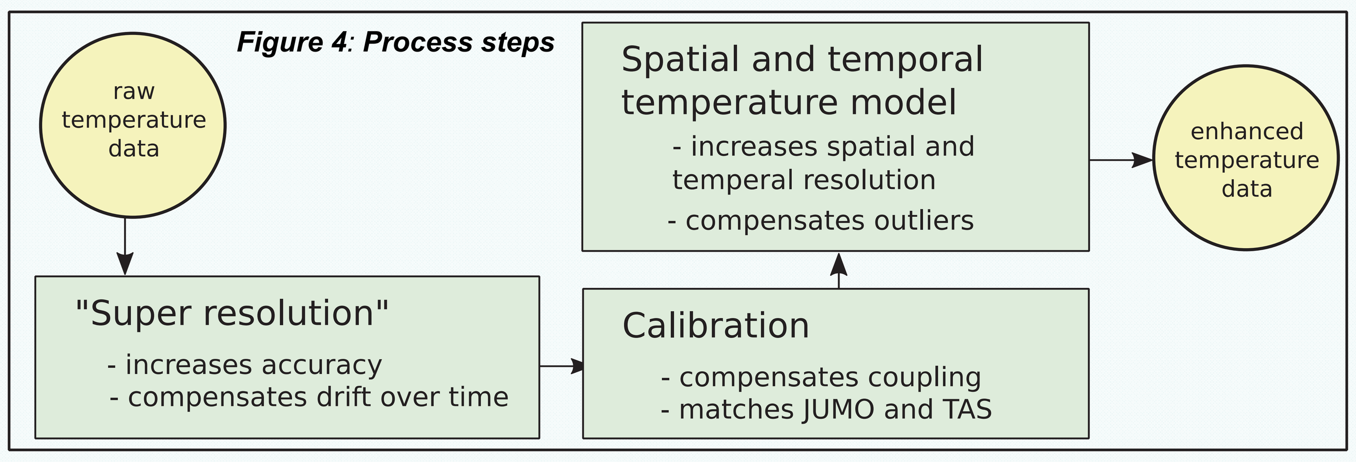
[3] S. J. Norton and M. Linzer, "Ultrasonic reflectivity imaging in three dimensions: Reconstruction with spherical transducer arrays," in Ultrasonic Imaging, 1979.

[4] http://www.jumo.de/attachments/JUMO/attachmentdownload?id=4486&filename=b70.7030.0de-en.pdf.

[5] https://datasheets.maximintegrated.com/en/ds/MAX6627-MAX6628.pdf

Approach

Figure 4: Process steps



Super sampling

- Digitization noise and temperature drift . The analog to digital converter (ADC) used to digitize the temperature was characterized to have a standard deviation of 0.0405°C. This correlates for a standard-error derived confidence interval and reliability of 68% to 0.081°C (1.29bit) and for a reliability of 95.5% of 0.162°C (2.59bit).
- Signal processing and sampling theory suggests that oversampling by plainly averaging over time could be used to achieve higher reliability and accuracy, for typical gauss-noise data with a ratio of the square-root of the number of utilized data points.
- But due to limited measurement read-out speed and expected significant dynamic over time of the temperature the drift needs to be taken into account, and direct averaging cannot be applied, see Figure 6 top. The synchronous "on demand" TAS measurement pattern was changed to an autonomous measurement. orchestrated by the TAS embedded TI430 microcontroller. A µC internal RAM buffer is filled every 0.3s and readout later in block.
- Drift modelling was achieved by a polynomial fit of the first order over the measurement time, which substituted also averaging for resolution gain. This results in increased accuracy and resolution below 1 bit ("super resolution").

Calibration of the TAS temperature measurement

- After the individual TAS position measurements are reliable and sufficiently digitized, the data needs to be calibrated. The TAS temperature data suffers from a significant offset, partly due to bad coupling to the water medium (additionally insolated by a 0.5mm ceramic plate) of the TAS temperature sensors. In comparison to the good coupled JUMO sensor, which sensor tip is almost directly in the water with a stain-less steel tip.
- The calibration was done utilizing the raw data of several months consisting of approx. 1300 individual measurements, spanning a range of 19 to 37°C.
- The fit of the TAS temperature to the calibration data from approx. 1300 measurements resulted in a slope compensation of 1.49% and a shift of -2.34°C over the temperature range. The deviation of individual TAS could be mostly eliminated and missing data for faulty TAS could be extrapolated.

Spatial and temporal temperature modelling

- The spatial locality information was utilized to minimize the production variations among the individual TAS temperature sensors.
- For this the spatial distance among them calculated the impact on the nearby neighbors weighted by the distance to their neighbors' median value. TAS measurements which value deviated more than 10 times the standard deviation of the 10 next neighbors were considered faulty and removed.
- After this sanitizing step, a second order polynomial fit over the spatial measurement domain was applied, using the assumption that temperature variation happens only slowly.

Results

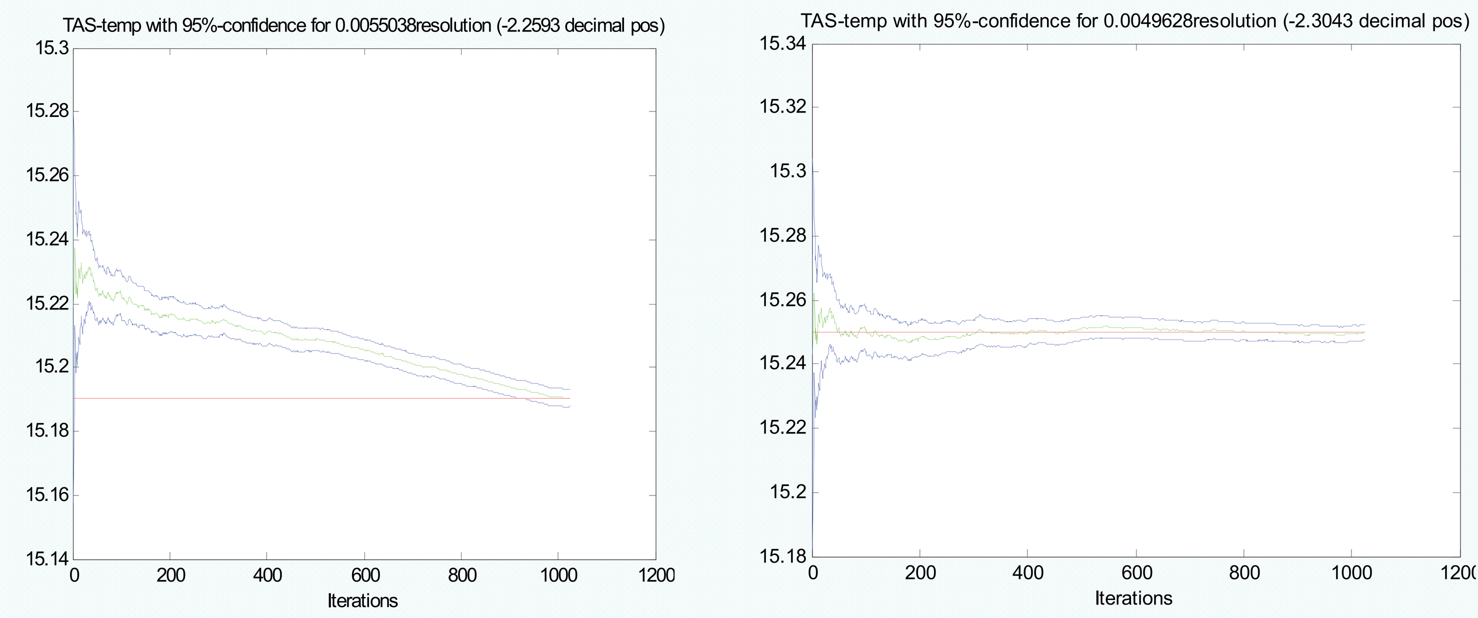


Figure 4: Blue lines 95% confidence interval, green line actual temperature measurement value, red line final end result. Top: Temperature measurement .without drift compensation, red line leaves the confidence interval. Bottom: with drift compensation, the red line is always inside the confidence interval.

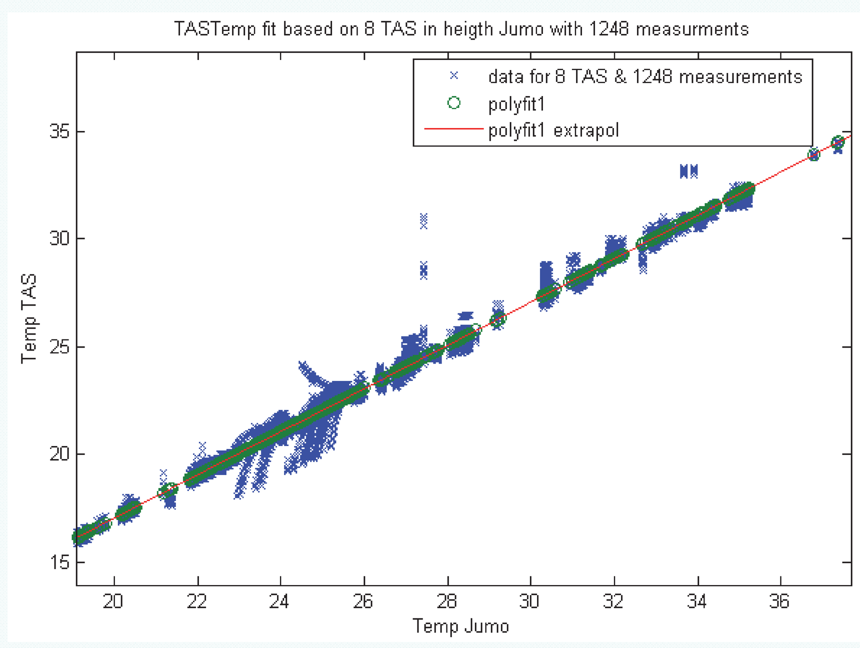


Figure 5: Calibration fit of the many low resolution TAS devices against the accurate JUMO data

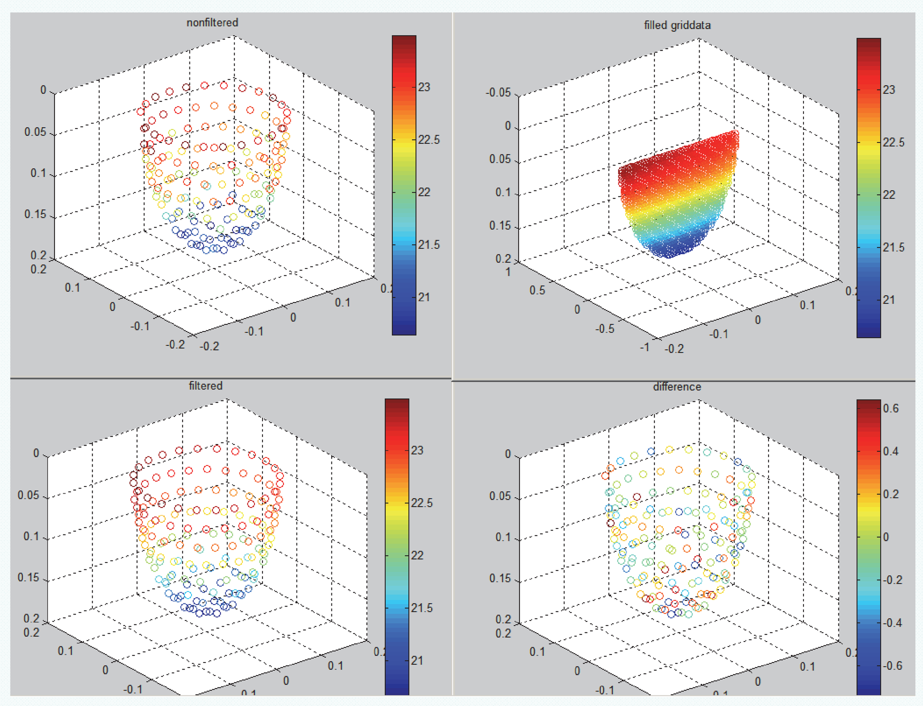


Figure 6: Top-left: TAS raw data, bottom left fitted TAS data, top-right: modelled data for a dense slice (extrapolation), bottom-right: temperature difference

Discussion and Contribution

- The accuracy and precision of the TAS temperature was increased by more than one order of magnitude, 36.3 times and 12.6 times ("super resolution"), accuracy of 0.00496°C was achieved with a 95% confidence interval (originally ±1°C).
- Outliers and faulty temperature data is automatically substituted by robust model interpolated data.
- No time overhead was added to the USCT measurement process.
- New insights about the USCT hardware system and several significant sources of temperature errors. E.g. significant water temperature layering approx. 1°C and significant front to back temperature gradient originating in the DAQ electronics 1-2°C (minimized to 0.1-0.2°C by constructive insulation).

Outlook and future steps

- Further refinements of the calibration process including "run time" of the USCT device and air temperature.
- The temperature models offered new degrees of freedom promise improvements and new possibilities for image reconstruction.