POROSITY DETERMINATION IN FIRN ICE CORES USING QUANTITATIVE COMPUTED TOMOGRAPHY METHODS

Markus FIRSCHING, Virginia VOLAND, Susanne BURTZLAFF, Norman UHLMANN
Fraunhofer IIS, Development Center for X-Ray Technology, Dr.-Mack-Str. 81, 90762 Fürth, Germany

1 Introduction

The constitution of polar ice cores, especially inclusions of air, porosity and their distribution are an important field of glaciology. An automated analysis of ice cores from various depths in glaciers allows conclusions about climatic changes during the past millennia. In the context of this work, cores with a length of 1 m and with a diameter of 10 cm of firn ice have to be processed in their full size in order to determine the mean porosity of the ice core. The state of the art method for porosity measurements of ice cores is using a radioactive source with mono-energetic gamma emission lines and calculating the irradiated path length directly from the attenuation. This method depends on the exact knowledge of geometric dimensions of the firn core and is sensitive to changes in them. Broken pieces or cut-outs distort the calculated porosities immensely.

Computed Tomography (CT) is not a quantitative method per se when a polychromatic X-ray spectrum is used, because of effects as for example beam hardening and scattered radiation. Both effects lead to an artefact known as cupping. It describes the effect of the attenuation coefficient being reconstructed too small, resulting in a cup shaped grey value profile in the reconstructed cross-section of an actual homogenous object. Provided these effects are accurately corrected, the mass density ρ of a mono-material can be calculated from the reconstructed CT-value (the attenuation coefficient) by calibration with a known test object of the same material with mass density ρ_0.

2 Methods

2.1 Correction of beam hardening artefacts and scattered radiation

In a two stage approach, both above-mentioned artefacts are corrected leading to a quantitatively accurate CT image. In the first stage, the scattered radiation is dealt with. As the geometry of the object is known, it is feasible to simulate the amount and distribution of scattered radiation with Monte-Carlo-Simulations. Monte-Carlo-Algorithms rely on the repeated computation of random numbers. In this case, billions of single X-ray photons are processed individually, respecting the probabilities of interaction and production of secondary particles of the respective materials in the implemented setup. The utilised simulation tool ROSI [1] is derived from the Monte-Carlo-Simulation packages EGS4 and LSCAT. The simulation provides the amount and intensity of the scattered radiation, allowing the subsequent subtraction of the proportion of scattered radiation from the acquired projection images.

In the second stage, the effect of beam hardening is corrected. This is achieved by using a look-up table (LUT) which maps the grey value of the X-ray detector to an irradiated path length through the material. The LUT is generated using a linearization technique called Iterative Artefact Reduction (IAR) [2].

2.2 Calculation of the porosity

In case of a porous material, the porosity p can be obtained by performing a CT scan with less resolution than the pore size, yielding an averaged value for the attenuation coefficient μ. For one type of material, be it an element or compound, the mass attenuation coefficient μ/ρ is constant for a given X-ray spectrum. In this case the porosity can be calculated by $p = 1 - \mu/\mu_0$, where μ_0 is the reference attenuation coefficient of this material at a given density and X-ray spectrum. Since the production of ice with zero porosity as a reference object requires considerable effort, water was used instead. It is chemically identical, but has a different density, which must be considered. Equation (1) shows the complete formula:

$$p = 1 - \frac{\mu_{meas}}{\mu_0 \cdot \frac{\rho_{ice}}{\rho_{water}}} \quad (1)$$

where μ_{meas} is the measured attenuation coefficient, i.e. the absolute CT number, of the porous ice, μ_0 is the attenuation coefficient of water, obtained by a calibration measurement with the same imaging parameters and ρ_{ice}/ρ_{water} is the density ratio between pure ice and water.

2.3 Facility and equipment

Actual computed tomography measurements were taken with a standard CT system for NDT. The main components are an Yxlon FXE 225.45 (directional) as an X-ray source and a PerkinElmer XRD 0820 AN15 detector.

3 Results

3.1 Reduction of artefacts

Fig. 1 shows a CT image of a PMMA (also known as Perspex or Plexiglas) tube filled with water without applying the above mentioned corrections. Clearly visible is the cupping artefact, i.e. the reconstructed CT value is too small in the centre region and appears darker. This images can not provide quantitative information as the grey value of the same homogenous material (liquid water) depends on the position in the image. Hence, it is necessary to correct these artefacts. In the final analysis, the ice cores will be contained in PMMA tubes, thus it is appropriate to do the calibration with an PMMA tube as well.

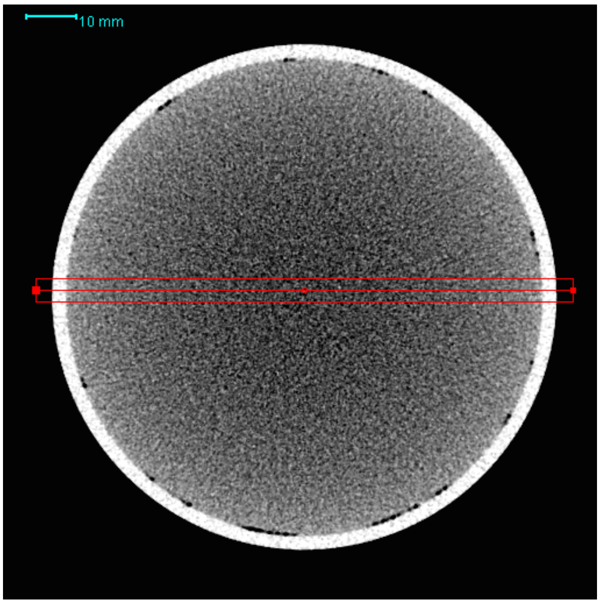

Fig 1: CT reconstruction image of the tube filled with water without corrections. The cupping artefact is visible

At first, the scattered radiation needs to be subtracted. As the shape and material of the object is known, the proportion of scattered radiation can be simulated. Fig. 2 shows the simulated projection of a PMMA tube filled with water. PMMA is used as it has similar X-ray attenuation as water or ice. The dark regions on the top and bottom result from source side collimation of the X-ray beam, to keep scattered radiation as low as possible from the beginning.

Fig. 3 shows the scattered radiation from this setup. Provided that the setup of the real measurement is equivalent to the simulated one, the signal produced by the simulation of the scattered radiation can now be subtracted from the measured projection images. After the scattered radiation is subtracted, the linearization is applied in the second step to reduce beam hardening artefacts.

The resulting projection images are used for a standard CT reconstruction resulting in 3D-CT data sets with no visible remaining artefacts. These data sets now contain quantitative information about the object, i.e. the porosity distribution can be calculated from them according to equation (1).

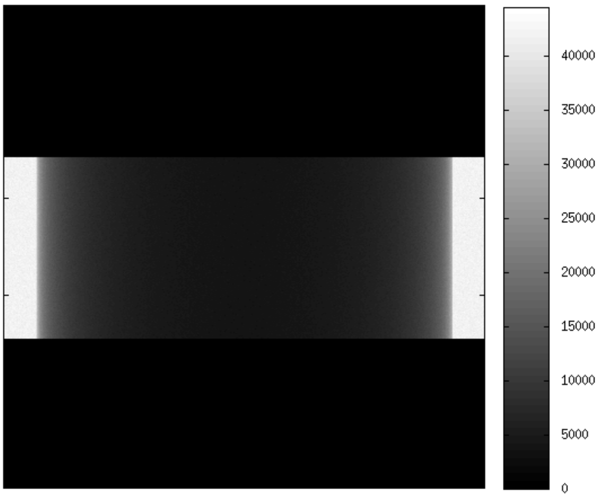

Fig 2: Simulated projection image of the phantom setup

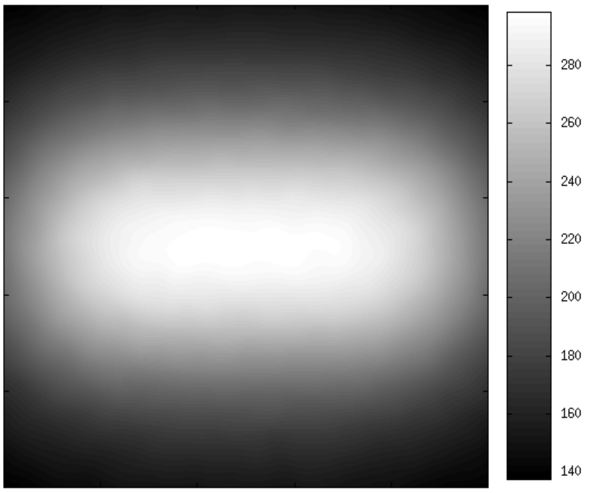

Fig 3: Proportion of scattered radiation (from Simulation)

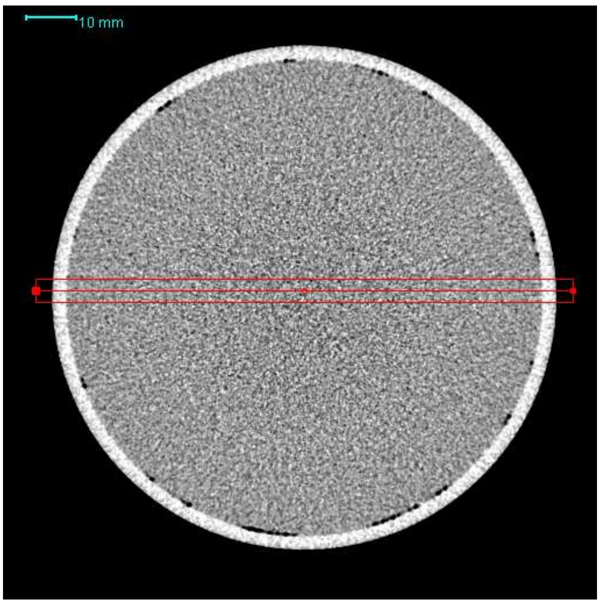

Fig 4: CT reconstruction image of the tube filled with water with corrections applied. The artefacts seen Fig. 1 have vanished.

In fig. 4, the subtraction of scattering and the linearization were applied and the cupping disappears. The black dots on the inner surface of the PMMA tube are air bubbles.

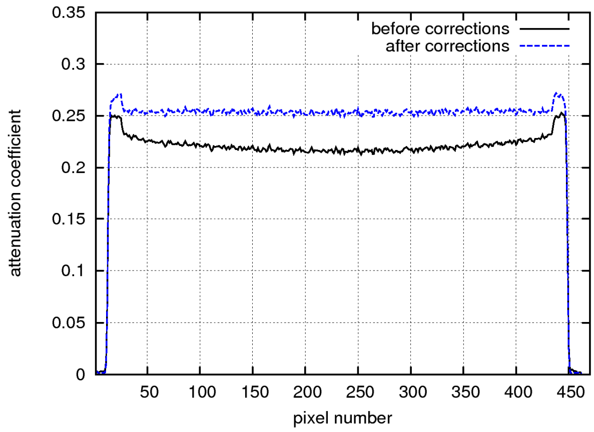

Fig 5: Line scans of Fig. 1 and Fig. 4. After the corrections, the cupping has vanisched completely

After the application of the correction methods, the grey value (i.e. the attenuation coefficient) of the inner region containing only water is constant throughout the object. Fig 5 shows the line scan of through Fig 1 and Fig 4, which are marked with the red line in these figures.

3.2 Application of the method

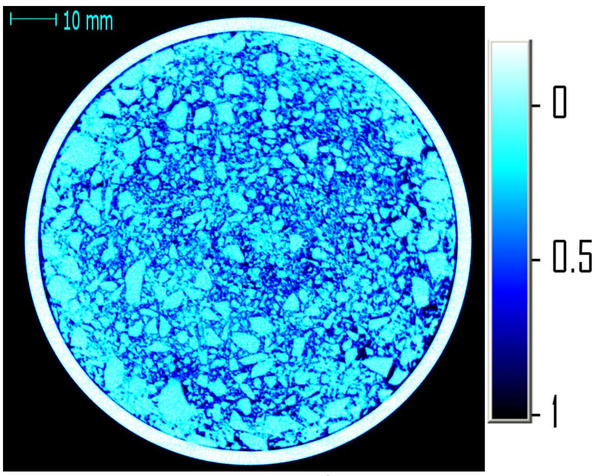

Fig 6: Porosity image of shredded ice. Cyan (turquoise) colours represent small porosity, deeper blue colours higher porosity.

As an example used during the development of this method, we show a measurement of shredded ice, because measurement data of real firn ice cores were not yet available. The shredded ice was pressed into a PMMA tube with a diameter of 10 cm.

3.3 Automated analysis

For large numbers of cores to be analysed, it is not practical to manually analyse the data and an automated analysis is advantageous. For an automated analysis, the PMMA tube, visible as a bright ring in the images, must be removed from the data set.
The average porosity can now be calculated in the segmented region for every layer of the 3D data set.

4 Conclusion

A method for porosity determination of ice cores using a quantitative CT has been presented. The applied correction methods result in data sets with high linearity and allow the calculation of the porosity distribution throughout the complete ice core.

References

[1] J. Giersch, J. Durst; “Monte Carlo simulations in X-ray imaging”, Nuclear Instruments and Methods in Physics Research Section A, Volume 591, Issue 1, 11 June 2008, Pages 300-305

[2] US patent 6975697, S. Kasperl, U. Hassler, I. Bauscher, S. Schroepfer, „Apparatus and method for establishing a correction characteristic curve for a reduction of artefacts in tomography“, filing date 06/04/2005