# COMPUTED TOMOGRAPHY (CT) SYSTEM FOR AUTOMATIC ANALYSIS OF ICE CORES

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**Abstract**

An automated analysis of ice cores from various depths in Antarctic glaciers allows conclusions about climatic changes during the past millennia. According to the respecting depth from which the ice core had been obtained, varying porosities of the ice are to be expected. A computed tomography (CT) system enables us to analyse ice cores, to determine the porosity of the ice and to correlate those results to the climate of the respective range of time. The ice cores to be scanned have a length of 1 m and a diameter of 10 cm. Since high image quality is required to get precise results, a vast amount of measurement data will arise. Geometric challenges raise the requirements on X-Ray components and furthermore measurements will be made in an environment of -15 °C.

The setup of the CT-system, the implemented methods for data acquisition and analysis and results will be presented.

## 1. Introduction

Cylindrical ice cores with a diameter of 10 cm and 1 m in length have to be scanned and reconstructed in their full size in order to analyse their mean porosity and porosity distribution. The porosity allows direct conclusions about the amount of $CO_2$ contained in the air in certain time periods. In this context one has to distinguish between analyses of firn ice, which occurs in depths down to 100 meters, and of porous ice, which is obtained from depths down to 3000 meters. Furthermore inclusions of dust or volcanic ashes occur in different amounts and in various depths.

The complete cores of **firn ice** are measured by means of a Helical-CT with a low spatial resolution of a minimum of 100 µm voxel size. Using a quantitative calibration measurement of a phantom without any porosity, the mean density and hence the mean porosity of the firn core can be measured. In this context, a low spatial resolution is required which leads to comparably short measurement and reconstruction times, a lower amount of data due to detector binning and finally a faster analysis of the reconstructed volume.

For an analysis of the **porous ice** in an adequate precision, a reconstruction of the complete volume in a high spatial resolution (12.5 µm voxel size) is essential. Because of the huge object size and the stringent requirements on spatial resolution, an immense amount of data arises during the measurement and the reconstruction. Novel procedures are able to merge data such that magnification can be increased into ranges where the projection of the object exceeds the width of the detector. Information about background intensity can't be read out of the detector image directly and still artefact reduced measurements can be made. In this context, challenges regarding the CT setup and the automatic image analysis arise.

Since for the analysis of inclusions pure qualitative measurement methods easily reach their limits, additional quantitative physical information as density $\rho$ or atomic number $Z$

will be used in a **dual-energy** measurement procedure (2X-CT), in order to allow the detailed analysis of sedimentations of dust or volcanic ashes. For the realization of this method, two CT data sets of the objects are necessary; one acquired with an X-Ray spectrum of lower energy and one acquired with an X-Ray spectrum of higher energy and/or more pre-filtering.

Therefore at first the CT **setup** will be presented, where our choice of the X-Ray components will be explained. After that we will go into detail about the **measurement** and **analysis methods.** Finally the extreme conditions of the measurements are highlighted, results will be presented and an outlook will be given.

## 2. Setup

For a laboratory system using cone beam geometry, the X-Ray components are the limiting factor for achieving a specified spatial resolution. In X-Ray imaging the magnification is defined by

$$M = \frac{FDD}{FOD}, \qquad (1)$$

where FDD denotes the focus-detector-distance and FOD denotes the focus-object-distance. Hence, with an increasing FDD, also the geometric unsharpness increases as it is defined by

$$U_F = (M-1) * D_F = \left(\frac{FDD}{FOD} - 1\right) * D_F, \qquad (2)$$

with focal spot size $D_F$. As illustrated in Figure 1, in high-magnification applications the size of the focal spot is essential in order to obtain images with an extremely low geometric unsharpness.

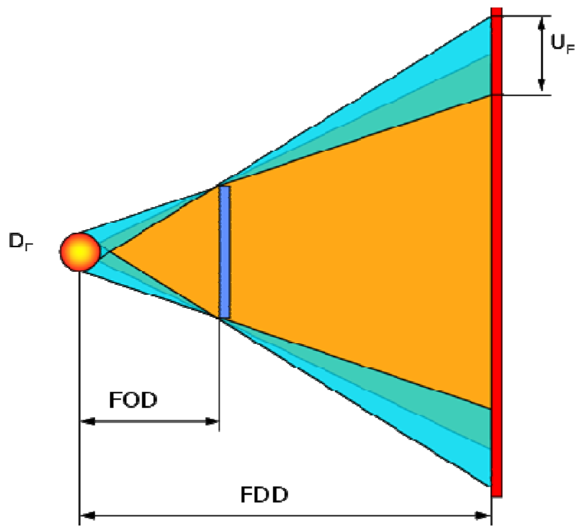


**Figure 1: The geometric unsharpness increases with both, increasing focal spot size and increasing magnification. This particularly influences the quality of high resolution measurements.**

At the same time a minimal focus-detector-distance (FDD) is preferable in order to enlarge the solid angle covered by the detector as it enhances the used X-Ray flux. Hence, an X-Ray detector with a small effective pixel size is needed to obtain high spatial resolution with the limited magnification available. Additionally the detector has to be radiation hard because doses will be high due to the long measurement times.

For this setup we use a Feinfocus 225 kV microfocus X-Ray tube with an exchangeable transmission and reflection tube head. Focal spot sizes are specified as 5 µm with reflection target and 1 µm with transmission target. The transmission target on the one hand allows less power to be applied than the reflection target. On the other hand the distance between the focal spot and the tube's exit window is significantly smaller; therefore the transmission tube head allows realizing a higher magnification. If necessary, aluminium- and copper-pre-filters of various thicknesses are used.

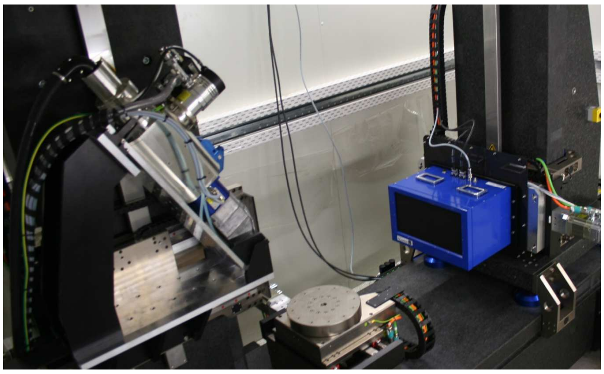

**Figure 2: Overview of the CT setup. The X-Ray tube and X-Ray imaging detector are placed on high-precision manipulation axes, which allow an adequate alignment of the CT-system.**

The radiation imaging detector we use is the detector Fraunhofer IIS XEye with 8000 x 4000 pixels and 50 µm effective pixel size. Due to the large active area (400 mm x 200 mm) in low magnification no horizontal displacement is necessary to cover the ice core in its full diameter. The detector's image lag is extremely small (< 0.1%) and an external trigger mode is available. Both circumstances cause a noticeable reduction of scan time. Additionally an accurate manipulation system with a vertical wobble of only 0.8 µm on 1 m traverse path allows a high-precision alignment of the system.

## 3. Measurement Methods

In order to cover the object in its full length, the core will be inspected with a **Helical-CT**. In contrast to conventional computed tomography, the Helical-CT uses a vertical feed of the object axis with a simultaneous rotation. Thereby, Feldkamp artefacts that are caused by transversal penetration of the object near the outer borders of the X-Ray cone beam are reduced. The focal spot and the vertical center row of the X-Ray detector span the central plane of the CT system. Only those parts of the object that are penetrated by the X-Ray beam parallel to the central plane can be reconstructed without Feldkamp-artefacts. Since standard 3D-CT systems work with cone beam geometry, this part only consists of the intersection of the object with the central plane itself. A vertical feed of the object with a simultaneous rotation ensures artefact reduced information about more than only one slice of the object. Depending on the mechanical limits of the used manipulator, objects of arbitrary height can be scanned. In this case the vertical feed is used to measure the ice core over its full length.

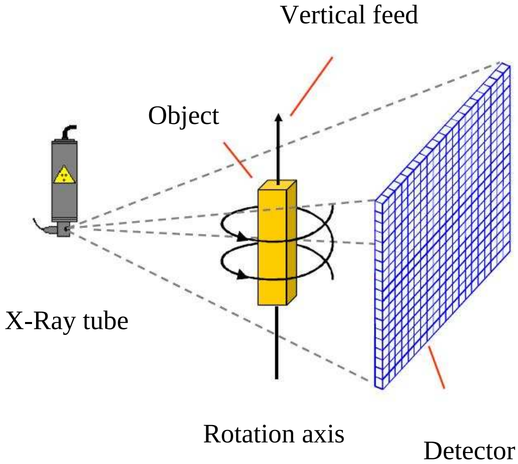


**Figure 3: Principle of Helical-CT**

For a precise determination of the pores' volume distribution high spatial resolution and therefore high magnification is needed. In spite of the large active area of the X-ray detector used in this setup, at the maximum magnification the core cannot be displayed in its full width anymore. Only the inner part of the ice core can be displayed on the detector in full resolution (3.5 µm). However, information about the unattenuated X-Ray intensity is needed for an artefact reduced measurement. A **multiscan** procedure takes images of the object in various magnifications and reconstructs the inner part of the ice core with a high spatial resolution. Between every single measurement, magnification is reduced by a factor of 2, until the object can be displayed in its full width on the detector. The whole diameter of the object can only be displayed with a low spatial resolution and is used additional information for the back projection algorithm to reduce artefacts.

Two options for the high resolution reconstruction **multiscan procedure** or **MRA-ROI-CT** can be chosen. In comparison to a conventional CT scan, the amount of projection data is enhanced by a factor n, where n is the number of measurements used for this procedure.

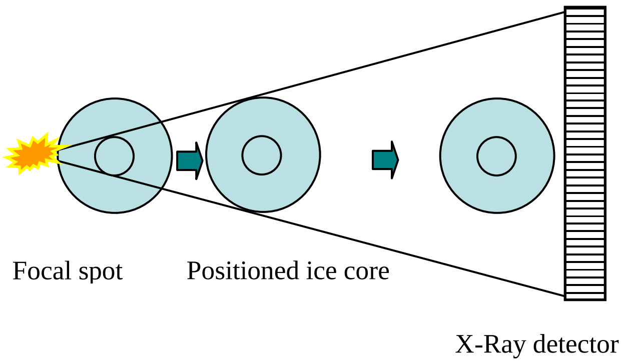


**Figure 4: Schematic view from top on the multiple scans of the multiscan procedure or MRA-ROI-CT. Magnification is reduced by factor 2 until the object can be displayed in its full diameter plus some background intensity.**

As an alternative, in a single scan high resolution procedure missing data are resumed by preliminary assumptions about the object's geometry. As we know that the object has an approximately cylindrical shape, **truncated object data** can be continued by means of fit functions. The amount of projection data is enhanced by a factor of 3 in comparison to a conventional CT scan and this procedure leads to a reconstruction afflicted with artefacts. Finally there is the option of a reconstruction by a gradient method (**lambda reconstruction**), which exclusively reconstructs the bounding surfaces between air and ice. For this procedure the amount of projection data does not increase, but nevertheless information about the primary intensity $I_0$ is necessary to perform the gradient reconstruction. This information must be provided by an external device calibrated on the detector's behaviour. In order to solve this problem, we decided to use an in-house development of an **$I_0$-Monitor**. The primary intensity is determined by a single-pixel detector positioned in the X-Ray beam but outside the field of view of the detector. A reduction of the image size is therefore not necessary. The intensity values of the photodiode-based device have to be matched to the behaviour of the respective detector. Therefore preceding calibration measurements are necessary in order to create useful additional information for the CT measurement.

With these methods, the inner 28 mm of the object can be reconstructed in a sufficient precision.

Especially in medical CT applications the **dual-energy** approach is an established method for the generation of quantitative information, as for instance density $\rho$ and the effective atomic number $Z$. In NDT applications, first efforts have been made to take advantage of the dual-energy methods in order to enhance the separation of different materials to provide an insight into their physical and chemical characteristics. The idea is the following: Two data sets are acquired with different effective energies at the exact same positions and afterwards reconstructed. Various spectra are realized by using different pre-filters and tube voltages while keeping all remaining parameters unchanged. Additionally we plan to use linearization to enhance image quality.
The resulting grey values in the 3D dataset are scaled attenuation coefficients and can therefore be associated with attenuation coefficients of the materials at the different energies by reversing the scaling. The set of attenuation coefficients $\mu_1$ and $\mu_2$ at those two energies span a vector-space which obviously can also be represented by other bases. The original base formed by the attenuation coefficients is transformed into another base, as $\rho$ and $Z$ will form one:

$$\begin{pmatrix} \mu_1(\rho, Z) \\ \mu_2(\rho, Z) \end{pmatrix} \rightarrow \begin{pmatrix} \rho(\mu_1, \mu_2) \\ Z(\mu_1, \mu_2) \end{pmatrix}, \qquad (3)$$

This base transform is performed by means of the function $F(Z)$ as defined in [3]. Then, after the change of basis, the pairs of attenuation coefficients $\mu_1$ and $\mu_2$, and hence the respective pairs of grey values can be replaced by pairs of $\rho$ and $Z$ of quantitative information. This method is supposed to easily provide quantitative information about different materials. Especially dust and ashes do not generate as much contrast against water as air does. Therefore those inclusions will be hard to find. We expect that the dual-energy method will provide more quantitative information about those materials.

## 4. Evaluation methods

Due to the object size and related geometric possibilities only the inner part of the ice core can be displayed and reconstructed in a high resolution of up to 3.5 µm voxel size. Nevertheless we want to obtain global information about the ice core and hence about climatic situations in according time periods. Therefore in case of porous ice the high-precision results of the inner parts of the ice cores are extrapolated on the whole reconstructed volume. The high resolution measurement enables precise conclusions about the physical volume of single pores and furthermore allows calculations of a statistic distribution of the pores' volumes in the inner part of the core. The lower resolution scan gives information about the number of pores and their local distribution. Combining theses two, we can draw conclusions about the mean porosity and the porosity distribution in the entire volume.

In the case of firn ice, pores can naturally not be separated and only a mean porosity per slice is calculated. The measurement of the firn ice cores consist of two steps:

1) Calibration: A calibration measurement with an ideal phantom without any porosity is made: This measurement will be made with a low spatial resolution (i.e. appropriate detector binning is used) since only mean values of each layer are of interest. A reconstructed volume and a single projection image will be used afterwards. Using this calibration, a lookup-table (LUT) will be generated that allows applying a linearization of the measured data.
2) Measurement: A Helical-CT measurement is carried out with the same low spatial resolution as the calibration. Subsequently a correction of scattered radiation is applied and the grey values are linearized by the LUT generated during calibration. After the 3D reconstruction, the grey values will yield attenuation coefficients comparable to each other. Hence, the obtained mean attenuation coefficients can be compared directly with the mean attenuation coefficients of the reconstructed phantom. Density and thus also porosity of the firn core can be calculated slice by slice.

A detailed description of the firn ice porosity measurement can be found in the distinct contribution "Porosity Determination in Firn Ice Cores Using Quantitative Computed Tomography Methods" of this conference.

## 5. Measurement conditions

As the ice cores are stored in an environment of -15°C, the measurements must be done under comparable circumstances. The CT system is integrated into a climatic chamber and the whole system is cooled down to the required temperature. Obviously challenges arise regarding the operation of the system and the choice of components and accessories. As shown in Figure 5, the X-Ray components are equipped with a climatic shielding and an internal heating in order to protect the components from the extreme temperatures. The additional beam hardening caused by the carbon fibre reinforced plastic and any internal structures of the material are corrected during measurement. Cables that are generally used at room temperature may crack and finally fail when being subjected to such low temperatures. All cables therefore have to be specified for operation and movement at temperatures well below 0 °C and must always be handled with care.

Another big challenge is the amount of generated data: A high-resolution scan over the full length would lead to a reconstructed volume of 80,000 slices with a height of 12.5 µm each. A size of 8000 x 8000 pixels per slice leads to an amount of approximately 9.5 TB of disk space needed to save the complete data set. If additionally the projection data are stored on disk, another 7.5 TB of disk space are required. In order to be able to handle the vast amount of data, the volume is reconstructed, processed and analysed block-wise.

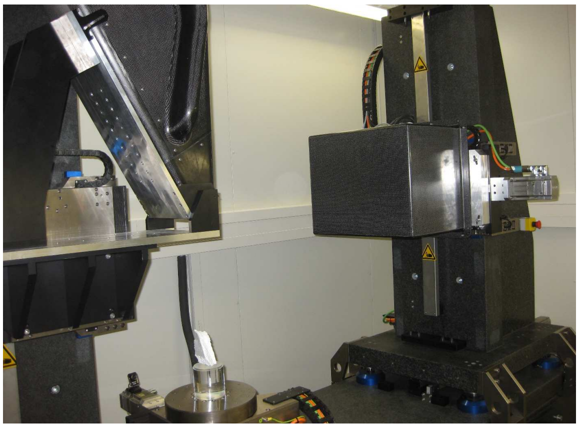

**Figure 5: Climatic shielding for X-Ray components. Those shieldings protect the X-Ray components from extreme temperatures. Artefacts in the images resulting from the shielding must be corrected.**

Reconstruction algorithms are executed on graphic boards which allow a significant speed enhancement. In fact calculation time of the back projection could be reduced by a factor of 14, while the performance of the whole reconstruction algorithm was enhanced by a factor of 7, which can be explained by memory management and data transfer. Moreover the amount of data influences the speed of reconstruction. If the data to be processed can be stored in the memory of the graphic board completely, the data can be accessed much faster and a considerable speed enhancement can be achieved. To save disk space, the reconstructed volumes are saved in compressed format on disk.

In spite of the reconstruction algorithms running on graphic boards, still reconstruction is expected to take several days up to weeks due to the very large number of slices to be reconstructed. Also image acquisition is expected to take several hours, depending on the region to be reconstructed and integration time of the detector. Therefore one has to face the risk that the X-Ray tube may not emit radiation at a constant dose over the complete measurement time. Also, one possible risk is that problems with the PC system could occur during a measurement. To overcome those risks, we developed continuable procedures for image acquisition, volume reconstruction and image analysis. Those procedures are able to continue aborted measurements. They cope with missing radiation and rebooting PCs without having to start the measurement from the beginning.

A number of as much as ten PCs each with two quad core Xeon 2.26 GHz CPUs, 48 GB RAM and a 1.8 GB Nvidia 295 GT graphic board are used for reconstruction. Each of them is equipped with a 2 TB hard disk drive for data storage only. Another PC with two quad core Xeon 2.26 GHz CPUs, 48 GB RAM operates the entire system and controls the measurement procedures. This PC is equipped with 30 TB of freely usable space on a hard disk drive.

## 6. Results and outlook

At the time of report submission deadline, the climatic chamber had not been installed properly, such that measurements of ice cores have not been made yet. Additionally the reconstruction PC system has not yet been fully installed. As a consequence only measurements at room temperature with low spatial resolution could be made so far.
In order to test the measurement and reconstruction procedures we used a wooden pale of 1 m length with a diameter of approximately 8 cm. Figure 6 shows one reconstructed slice of the test object. This measurement was done at 120 kV tube voltage with 400 projections. A horizontal and vertical detector binning by a factor of 8 was used at a magnification of approximately 3. Annual rings and a disruption can clearly be seen. Additionally areas of locally higher density can be identified.

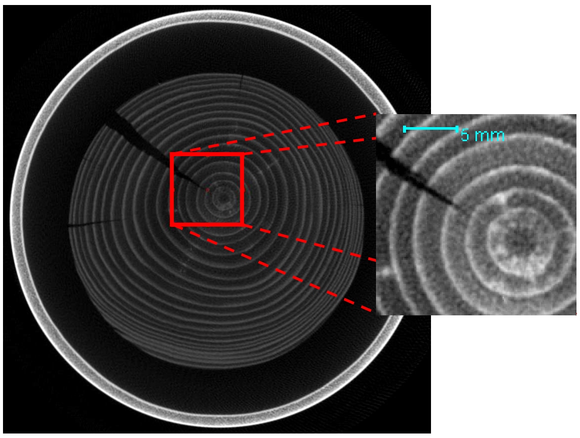


**Figure 6: Reconstructed slice of a wooden pale with a diameter of approximately 7 cm. The pale is positioned in a pipe made of plastics. The measurement was done with a detector binning by a factor of 8 and a resulting voxel size of approximately 132 µm.**

Further steps in the development of this CT system are the operation at the required low temperatures and at full spatial resolution.
Also speed enhancement is to be expected. Reconstruction algorithms on graphic boards are still under optimization. Work is in progress in order to optimally use the network facilities and furthermore the memory of the graphic boars is to be used in an optimal way.
The spatial resolution is expected as follows: with a detector pixel size of 50 µm and a maximum magnification of more than 14, the maximum spatial resolution is 3.5 µm voxel size. This resolution can be achieved in the inner part of the reconstructed ice core. For the outer parts of the core, a magnification of less than 4 must be used in order to image the entire diameter of the core on the detector. Hence, a minimum voxel size of 12.5 µm will be achieved in the outer regions of the core.

**References and further reading**


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