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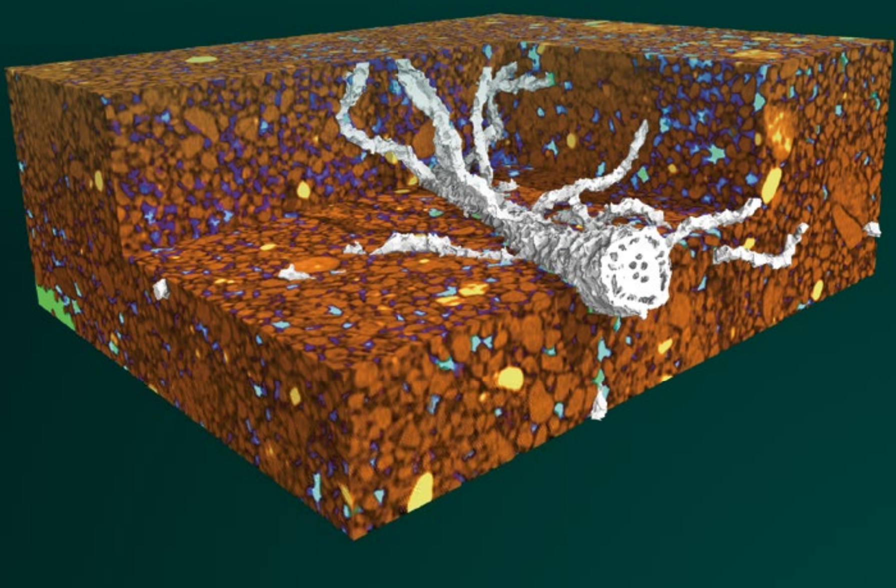
X-ray Imaging of the Soil Porous Architecture



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Foreword

Soils are literally fundamental to all human civilisations and underpin all terrestrial ecosystems. As such, their importance to the Earth system, and all life thereon and therein—including humans, of course—is paramount. Soils function by virtue of their spatial organisation, and they are arguably unique systems in terms of both the diversity of their mineral and organic constituents and in the way these are arranged in four-dimensional space (i.e. three dimensions over time) over many orders-of-magnitude. Soil structure is the term traditionally used to describe and conceptualise these spatial characteristics, but arguably *soil architecture* is a more apposite term since it explicitly integrates living entities in the framework and encourages consideration of soils as integrated ecological systems. And it is pore networks, manifest as extraordinarily complex multi-scale labyrinths, which are one of the most essential features of soil systems. This is because they represent the *inner space* of the soil system, in and through which all gases, liquids, solutes and organisms are bound, reside, move, react, transform and more besides. There is a curious irony in that these pore systems are effectively defined by where the solid phases of the soil are *absent*.

One of the major challenges in studying soil architecture, which has certainly constrained progress in these terms since the onset of pedology, as a well-found scientific discipline, is that they are (generally) friable and (certainly) opaque to the unaided human sensory experience. One can only progress so far in quantifying and understanding the origins and consequences of soil architecture by direct visual observation, nor even with light or electron microscopes and modifying geologists' or histologists' approaches based on carefully spatially-preserved thin-sections.

Enter Godfrey Hounsfield with his visionary (pun intended) invention and development of X-ray Computed Tomography in a medical context, with the emergent means to non-destructively image many of the key constituents of soil, and there was then a means to overcome what was previously considered as an intractable challenge. This opened new frontiers to explore soil systems, and over the past 40 years the tomographic tools that have evolved for application in soil science have been revolutionary. These encompass multi-disciplinary hardware, software and conceptual (i.e. modelling) engineering endeavours, allied to imaginative experimental systems. This laudable volume provides a comprehensive description and synthesis of all these aspects of the science and art of X-ray Computed Tomography as applied to soil systems. It reveals often astonishing new views of the underworld and sets the scene for the exciting future of this powerful approach to understand, and therefore effectively manage, the critical soil resources on which we depend.

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Chapter 1
40 Years of X-ray CT in Soil: Historical Context

Iain M. Young, Sacha J. Mooney, Richard J. Heck, and Stephan Peth

1.1 Introduction

In December 1973 Godfrey Hounsfield published his seminal paper on transverse axial scanning, describing a methodology that could non-destructively analyse a human head (Hounsfield, 1973). Two years previously, a patient's head had been scanned in what was the first system available to hospitals developed by Hounsfield and his research partners. Thereafter, an explosion in the use of Computed Tomography (CT) systems for medical purposes was seen in most western countries, and today Tomography systems (including MRI), in general, and CT systems, in particular, are some of the most widely used techniques in hospitals around the world. Two decades ago, a CT exam would take more than 30 minutes. Now, it is possible to collect high-resolution images in 2 seconds, along with vast improvements in detector hardware and associated software, whilst reducing any dose by up to 80%.

In 1979, Hounsfield and Allan Cormack won the Nobel Prize in Physiology and Medicine "*for the development of computer assisted tomography*". Less than 3 years

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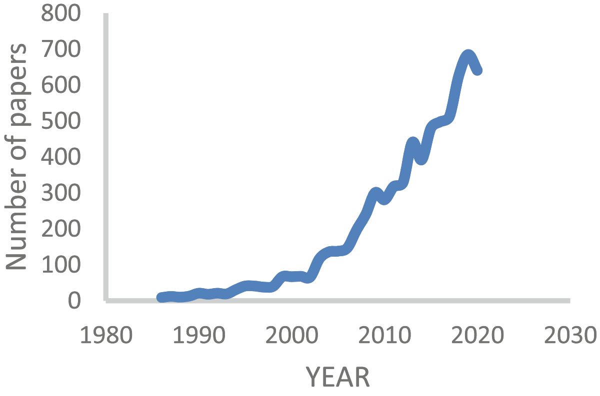

Fig. 1.1 Publications using X-ray CT in the soil sciences

later, in a short technical note, the first X-ray microtomography system (μCT) produced an image of the internal structure of a snail's shell (Elliott and Dover, 1982), with a 15 μm spatial resolution, opening up the possibility of relatively inexpensive (at least compared to medical CT systems) lab-based scanners for a wide range of medical and non-medical applications.

Petrovic et al. (1982), in a first for soil science, using a fourth generation medical CT system, successfully quantified bulk density changes in soil, and a year later in Perth, Western Australia, using a bespoke laboratory gamma-ray system, Hainsworth and Aylmore (1983) determined the spatial distribution of water in a soil column. A new dawn in investigative technology had arrived for soil scientists who could now observe structural elements of soil in a non-destructive fashion.

Figure 1.1 shows the published papers (using Scopus and the search terms "tomography and soil or plant"—28th Jan 2021). A slow rise in publications between 1986–1995 (195 publications) through to 672 papers published between 1996–2000, with an obvious upswing in 2003. Between 2016–2020 we see an exponential rise in publications (2963). This is probably related to an increase in the development and accessibility of benchtop high-resolution X-ray CT systems (hereafter referred to as X-ray CT), with much of this development driven by the oil, mining and engineering industries interests in porous media.

Whilst many of the challenges of using an X-ray CT for soil systems research map onto those of other systems, soil brings peculiar and complex problems not seen in any other opaque architectures, including the human body. Many such examples are presented in this book. It is important to recognise, for instance, that the use of CT for medical purposes is generally focussed on divergence from the norm in human bodies. So, abnormalities such as bone fractures, emergence of dense tumours or changes in the density of lungs are daily occurrences and most medical systems are driven to produce clearer and faster images for such architectures, with the lowest radiation doses possible. Often these features are readily detectable both in terms of contrast and resolution. Similarly, in engineering where defects in prescribed designs are an important focus. However, in soil, where compositional and spatiotemporal heterogeneities are inherent across multiple scales, where complex geometries of structures exist over space and time, in generally unsaturated conditions within complex organo-mineral constructs that shrink and swell, change is a constant. It is, however, within this complex architecture of soil that the many macro-, meso- and micro-communities live and imprint their own activity, requiring accurate observations and analysis, that present us with problems that are of many orders of magnitude more difficult to deal with.

As hardware has advanced, so has associated software. Due to the complexity of soil however, the problems of image processing and analysis of the soil-plant-microbe complex remain a great challenge (Chaps. 4 and 5). Whilst much has been achieved, the reality is that the problems related, for example, to the segmentation of unsaturated organo-mineral complexes, that comprise soil, have so far not been solved to the extent that automated processes can be used across soil types and X-ray CT hardware. Much improvement has been made, however, to isolate and quantify root systems (see Chap. 9) in various soil textures despite limits of spatial resolutions and some progress has been made observing organic matter in soil (Chap. 10). The greatest progress has been made in the analysis of soil porosity (Chaps. 6, 7, 8), and associated metrics (see Feeney et al., 2006). This has advanced to the extent that we can now scan an undisturbed soil core and from the captured 3-D architecture simulate water flow, retention and gas flow. The linkages of model simulations and 3-D pore space architecture are highlights of the advancement of the use of X-ray CT in soils (Chap. 11).

This book deals with the great challenges of using X-ray CT for soils and looks in detail at the recent developments in X-ray CT applications in soil research. The associated opportunities and problems are described, from a range of researchers covering different fields, including tips on the best way forward (Chaps. 3 and 4) and, in some cases, differing views on the same subject; and provides practical approaches to some limiting problems in using and/or choosing hardware systems (Chap. 2). We hope that this book will be of interest to the soil scientists undertaking their first forays into the world of imaging 3-D soil microstructure, as well as the experienced user looking for special applications and practical solutions for μCT acquisition and image analysis.

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Chapter 2
Practicalities of X-ray CT Scanning for the Soil Sciences

Andrew Ramsey

2.1 Introduction

What better application can there be of X-ray CT than to study the heterogeneous structure of soil? What more friable, fragile structure can there be but that of soil, so sensitive to the slightest touch? Yet, accurately visualising the structure of soil is so vital to understanding the passage of nutrients and water through it and the microbes residing in it. What other technique could resolve the complex three-dimensional (3-D) features without affecting them?

X-ray CT is a promising method of examining the 3-D structure of soil since it is completely non-destructive and typically requires no special preparation of samples. An X-ray CT system can image samples from a few particles of soil (~1mm) up to a large core of soil of 20–30 cm diameter and 100 cm long. The resolution will vary, being far higher for the smaller samples and lower for the larger samples. It will typically be the diameter of the sample divided by a few thousand. The very highest resolution that can be expected is around 1 μm (although some new systems state possibilities beyond this).

X-ray CT volumes are generated from a set of projection images, so the amount of information in them is limited by the number of pixels across the detector. It is important though to make sure that the X-ray source is small enough that fine details are not blurred over more than one pixel and that the mechanics of the sample manipulation does not introduce motion blur into the reconstruction. There is a distinction between the voxel size, which is typically the effective pixel size at the position of the sample (only affected by the number of pixels across the detector and the geometric magnification), and the spatial resolution which gives the finest details separable (resolvable) in the CT volumes. This latter measure depends also upon the

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sharpness of the projection images and the stability and accuracy of the sample manipulation stage as well as knowledge of the position and alignment of the X-ray source, stage and detector.

X-ray CT produces a full 3-D map of the internal structure of a specimen by measuring the X-ray linear attenuation coefficient at each 3-D point in a small-pitch volumetric grid. The pitch of the grid can go as low as 1 μm but is defined by the size of the sample divided by the number of pixels across the detector, being typically in the 10s of μm range, depending on the sample size (larger for larger samples). The volumetric grid can be thought of as the 3-D analogue of a 2-D pixel grid in a digital image and in fact the volume grid elements are known as "voxels". The X-ray linear attenuation at each voxel is calculated from the millions of total attenuation measurements, one in each pixel of every projection radiograph collected at hundreds or thousands of projection angles. Since the linear attenuation is proportional to the electron density in the sample, then the CT results show a good indication of material density changes, as well as being affected by chemical changes, allowing different materials to be discriminated.

2.2 Manufacturers of μCT Systems

With so many manufacturers and designs of X-ray CT systems available (some example X-ray CT system cabinets are shown in Fig. 2.1), how can you choose the right one for your application? Below is a (non-exhaustive) list of current X-ray CT system manufacturers, though it is inevitable that new ones will appear within a year or two:

- *Bruker* (originally *SkyScan* of Belgium), based in Mass., USA: mainly suited to small samples. https://www.bruker.com/en/products-and-solutions/microscopes/3d-x-ray-microscopes.html.
- *Diondo*—based in Hattingen, Germany (formerly owned by Yxlon). www.diondo.com.
- *Nikon Metrology*–originally X-Tek Systems (UK), bought by Nikon Corporation of Japan, HQ in Belgium, manufacturing a range of cabinet sizes and now collaborating with US-based *Avonix Imaging Inc.* of Minnesota, USA for larger enclosures. www.nikonmetrology.com.
- *North Star Imaging (NSI)*—in Minnesota, USA, owned by ITW of Chicago, manufacturing a wide range of system sizes. www.4nsi.com.
- *Rayscan Technologies*—Germany. https://www.rayscan.eu/.
- *Rigaku*—Japan. Use both sealed and open-tube (rotating target) sources. imaging.rigaku.com.
- *Scanco Medical*—Switzerland. CT systems using sealed sources designed mainly for small life sciences samples. www.scanco.ch.
- *Shimadzu*—Japan. Both sealed and open-tube microfocus CT systems. www.shimadzu.com.

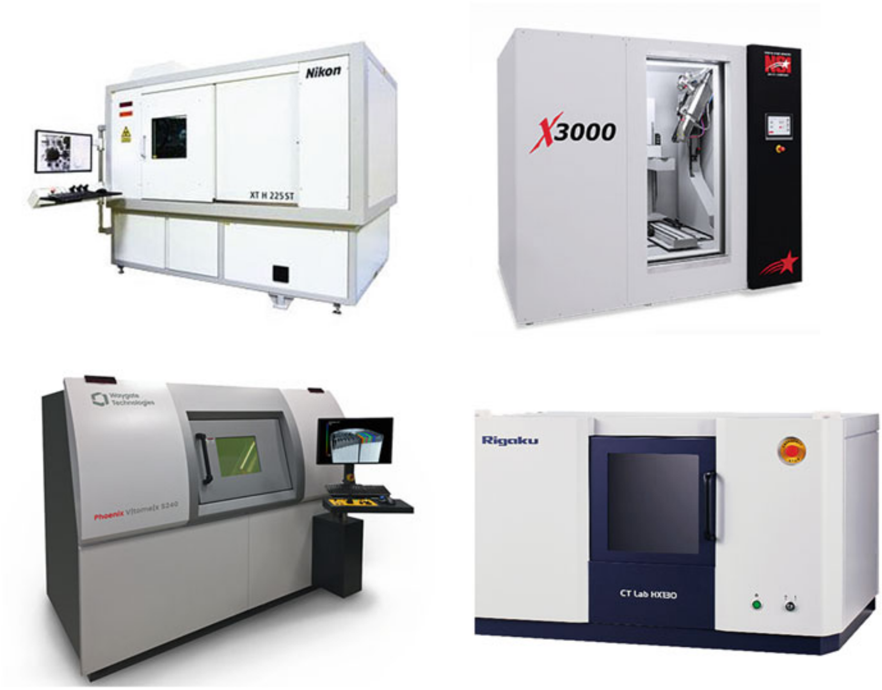

Fig. 2.1 Top-left: A Nikon Metrology XTH225ST cabinet; Top-right: An NSI X3000 cabinet. Bottom-right: A Waygate v|tome|x 225 kV system; Bottom-right: A Rigaku CT Lab HX cabinet. [Image ©Rigaku Corporation. Used by permission]

- *ThermoFisher Scientific*—makers of *HeliScan,* designed for small rock cores. www.thermofisher.com.
- *VJ Technologies*—New York, USA. www.vjt.com.
- *Waygate*—originally "*Phoenix|x-ray*", bought by GE, then Baker Hughes, based in Germany. https://www.bakerhughesds.com/.
- *Yxlon*—also in Germany (grew out of Philips X-ray). www.yxlon.com.
- *Zeiss* (both the Metrotom and Xradia product ranges)—Germany: Zeiss's measurement reputation married with Xradia's nanofocus technology. https://www.zeiss.com/metrology/products/systems/computed-tomography.html.
- *ProCon*—Germany. https://procon-x-ray.com.

Note that some of these are measurement companies relatively new to X-ray technologies; others have decades of X-ray imaging experience. Rather than discussing the range of systems from each of these companies, we note the characteristics of systems that make them suitable for inspecting soil samples. Is it better to buy a system with a high-resolution detector or a high-resolution source, or both? How does an open-tube X-ray source compare with a closed-tube source? How accurate does the sample manipulator need to be? Is helical scanning better than circular scanning?

All CT systems have an X-ray source, a sample manipulator and an X-ray detector. Industrial systems rotate the sample while keeping the source and detector static (the converse to medical system, as the need to keep a patient still rather than being rotated through 360° is not there). For helical scans, the sample is translated vertically during the rotation to form a helical path.

2.3 X-ray Sources

There is one characteristic of an X-ray source that will greatly affect the quality of the CT results and the running costs of the system. X-ray tubes come in two types: open and closed. Closed tubes are evacuated and sealed once for their lifetime. This has the advantage that the filament never needs to be replaced and often lasts a few years (typically between 3 and 7 years depending on the dose output). Once it blows though, a new X-ray tube insert is required which greatly adds to the running costs of the system. Open tubes maintain their vacuum using a constantly running vacuum pump (typically a high-speed turbo-molecular pump backed by a backing pump). The filaments in these tubes last typically a couple of months and then need replacing, a procedure which usually takes less than an hour can be easily done by operators and costs typically a few tens of dollars. The open tubes themselves can last decades.

If the electron beam, in an X-ray tube, is focused onto the target, the tube is said to be a microfocus tube, with a spot size of typically less than 10 μm. If it is not focused, the spot size may be much larger and high-resolution images can only be obtained by acquiring low-magnification images of samples placed close to a high-resolution detector. These are known as minifocus tubes. Most, but not all, closed tubes are minifocus tubes.

X-ray tubes are also characterised by their penetrating power, determined by their maximum voltage (measured in kiloVolts, or kV) and by their maximum power in Watts, which determines the number of X-ray photon they can produce. X-rays up to 225 keV can easily pass-through soil samples up to 100 mm (4 inches) in diameter. These sources often have the smallest spot sizes and are mostly microfocus.

It is worth asking the manufacturer about maintaining an open tube; some tube materials require monthly deep cleaning, while others need only an occasional wipe with an alcohol-soaked cloth. It is also worth asking about the cycle time of sources: can the source, for example, work 24/7 thus allowing for batch scanning of more samples overnight. It is advisable, regardless of system purchased, to take out maintenance cover, with local expertise (through training by the manufacturer) also being present. Well-maintained systems are often in use more than a decade after purchase.

2.4 Detectors

Most X-ray detectors work by converting the X-rays into visible light using a fluorescent material layer (known as a scintillator) in front of a large array of photodiodes, which convert the visible light into electronic charge that can be read by the digitiser. Some detectors directly capture X-ray photons. While such detectors are generally more sensitive than standard detectors, they are often much more expensive (Fig. 2.2).

Following the merger of PerkinElmer and Varian a couple of years ago, Varex Imaging Inc. has become the world's largest manufacturer of X-ray sensitive flat panel detectors (Fig. 2.2). A few other companies make competitive detectors, such as iRay, Hamamatsu and Detection Technologies Inc., but these have yet to make their way into mainstream CT systems. Waygate (being ex-GE themselves) uses a detector created by GE which is claimed to be both high-resolution and high efficiency (in terms of converting X-ray photons to electrical signals).

2.5 Obtaining High-Resolution Images

Increasing the image resolution can lead to a whole new level of detail being visible, as seen in Fig. 2.3. It is often debated as to whether it is quicker to obtain high-resolution CT data using a high-resolution detector or a high-resolution X-ray source. A detector is deemed to be high-resolution if its pixels are smaller than 150 μm. It is worth noting that the efficiency of capture of X-rays by detector pixels is proportional to the area of the pixel and so to the square of the quoted pixel size. Furthermore, smaller pixels require thinner scintillators, to prevent the spread of visible light over several pixels, and so many more X-rays pass straight through the

Fig. 2.2 Left: Varex 4343 (2880 × 2880 150 μm pixels); Right: Varex 2520DX (1900 × 1600 127 μm pixels). ©Varex Imaging. Used by permission

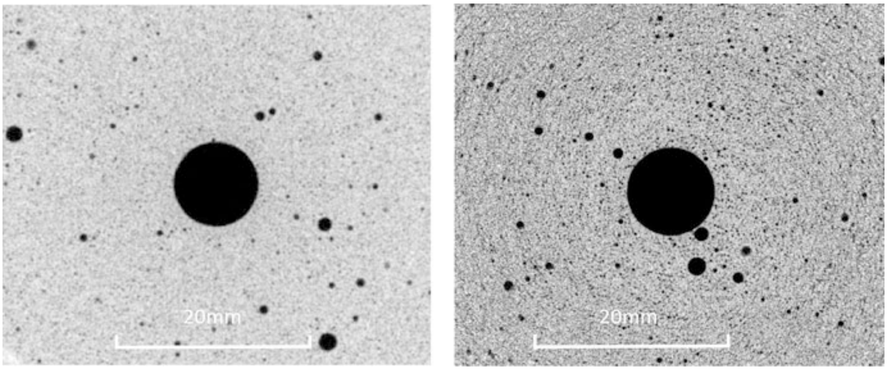

Fig. 2.3 Increasing the image resolution can lead to a whole new level of detail being visible, as seen in these images of a grinding wheel using (left) an image intensifier and (right) a Varex 1620 flat panel. [Images courtesy of Nikon Metrology UK Ltd.]

scintillator without being detected. This typically makes the efficiency of capture of X-rays by a detector inversely proportional to the cube of the quoted pixel size.

An X-ray source is considered microfocus if its spot size is less than around 100 μm. At higher magnifications the size of the X-ray spot becomes the limit on the spatial resolution that can be obtained. Since microfocus X-ray sources must limit their power at small spot sizes, or expand their spot size to prevent target damage, the scan times are often assumed to be longer. But the power of a small X-ray spot is proportional only to the spot size itself, and so doubling the resolution needs only twice the scan time instead of the eight times required when the detector resolution is doubled.

Some manufacturers have techniques for increasing the detector resolution by moving the detector within the enclosure (such as NSI's *matriX* or Nikon's *PanelShift*), or by making sub-pixel movements and interlacing image pixels (such as NSI's *subpiX* or Nikon's *PixelPush*) (see Fig. 2.4).

2.6 Image Quality

The quality of an image is often measured by its spatial resolution (the ability to resolve separate but neighbouring features) and its signal-to-noise ratio (SNR). The higher the spatial resolution, the smaller features can be seen in the images. However, it is important that the signal-to-noise ratio is kept high to prevent small features disappearing into the background noise. Background noise, which can be seen as speckle on the projection images, is due to a different number of X-rays being in each consecutive image due to the random nature of X-ray production in the target. The SNR of X-ray images, like those produced by any random process, is proportional to the square root of the signal, which in turn is proportional to the number of X-rays imaged. This latter is proportional to the X-ray beam current

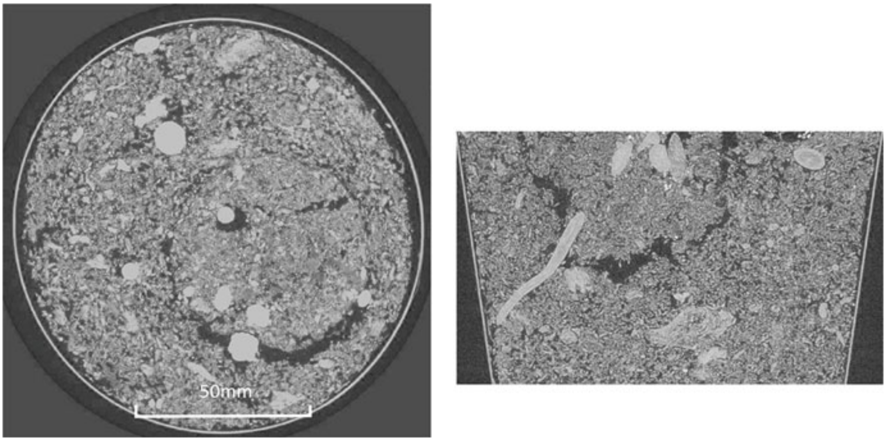

Fig. 2.4 Horizontal (left) and vertical (right) CT slices through a recently repotted plant pot showing roots (brighter) and air spaces in the soil. [Images © Nikon Metrology UK Ltd.]

(usually measured in microAmps (μA) or milliAmps (mA) – 1000 μA = 1 mA) and the efficiency of the detector as well as the scan time. To double the SNR, it is necessary to quadruple the signal. For small samples in which the beam current cannot be increased to avoid broadening the focal spot too much and losing spatial resolution, the only way to increase the signal is to lengthen the scan time. For individual images this is usually not a problem, but when a CT scan already takes tens of minutes, this can lead to unfeasibly long scan times. There is anecdotal evidence of the ends of plant roots being blurred due to long scans, i.e. they grew longer during the scan!

2.7 Sample Manipulator

The accurate manipulation of the sample during a CT scan is crucial to obtaining high-resolution CT volumes. Inaccuracy in the sample movement will blur the features in the high-resolution radiographs. For example, a precession of 100 μradians will cause a movement of 100 μm at a metre which is 10 μm 100 mm above the turntable bearings. This will prevent CT images having better resolution than, say, 20 μm at that level; which is worse higher up. Putting your sample on a pillar to raise it in front of a high source will similarly degrade your spatial resolution. Turntable runout, the slop in bearings, will cause similar blurring but this blurring will remain constant throughout the height of the sample.

A system in which the detector can be moved towards the source can save valuable scan time. If the sample is not so small that it needs the maximum system resolution, then it can be moved towards the source and the detector brought closer. Since the X-ray flux is proportional to the square of the source-to-detector distance,

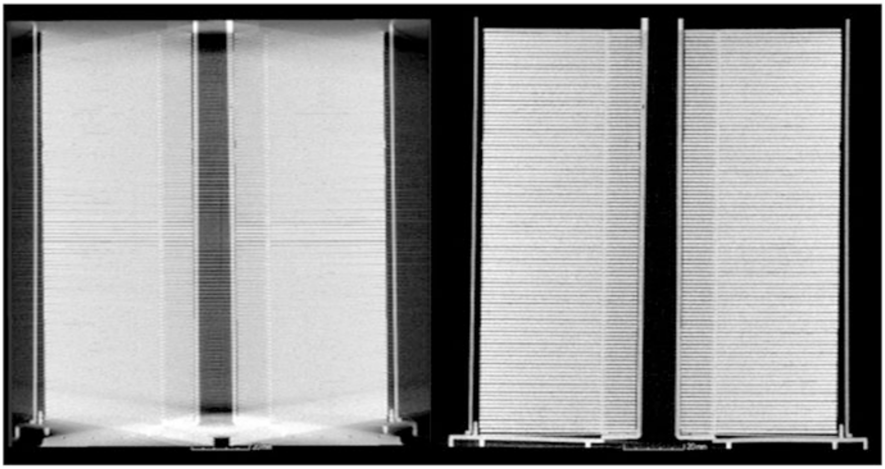

Fig. 2.5 A comparison of circular CT (left) with helical CT (right) of a stack of DVDs showing how helical CT has better vertical spatial resolution throughout the CT volume away from the central slice. This is only true when the manipulator is well-aligned

bringing the detector only 30% closer to the source will double the brightness of the images and thus halve the scan time needed to get the same signal-to-noise ratio. This can lead to larger cone-beam angles and therefore greater cone-beam artefacts in non-helical scans.

Helical CT, in which the sample is moved vertically during the sample rotation to create a helical path requires more stringent manipulator alignment than purely circular CT in which the sample is simply rotated. The rotation axis must be aligned with the vertical movement axis and must be straight. Done well, helical CT though can remove cone-beam artefacts from constantly looking up at the top of the sample and down at the bottom. These artefacts, while clearly visible at the top and bottom of the CT volume are in fact present throughout except in the central slice and will degrade the vertical spatial resolution (see Fig. 2.5).

It is worth noting that a helical scan can lead to a higher-resolution CT volume than a single circular scan, especially of a tall object, since the sample can be magnified until its width almost fills the image rather than its taller height. Of course, several circular sub-scans could be performed but these will need to be stitched together using the regions where the cone-beam artefacts are greatest.

In a helical CT scan, the sample must be moved from completely below the detector to completely above it. The cabinet height often limits the height of samples which can be scanned using the technique. One method of obviating this is to crop the detector vertically for these scans which allows taller samples to be scanned, albeit more slowly due to the more rotations needed. A fixed turntable and movable source and detector combination, as provided in some CT systems, allows the helical scanning of taller samples.

2.8 Configurations

2.8.1 Cabinet or Enclosure?

In practice, most soil samples are not too large (<30 cm cube) and so will comfortably fit into a one-piece cabinet. Most will not require X-ray sources above 225 kV which helps keep the cost of an X-ray CT system down, which is often a major factor in choosing a system.

2.8.2 CT Scanning Methods

There are a few different methods of capturing CT data:

- Circular scans—these use a simple geometry since they only need a single rotation in one position.
- Helical scans—allow taller samples to be scanned in one volume; the manipulator needs to move a long way vertically, or the source and detector move instead.
- 2-D fan-beam scanning—this is a very slow method used for highly-scattering samples; it is not usually needed for soil as scatter is not such a problem.
- Dual energy scans—allow for chemical discrimination by comparing the results of scans using different X-ray energies.
- 4-D CT—time series 3-D CT scans; or continuous scanning to characterise dynamic processes e.g. infiltration.

2.8.3 Software

The software provided with a CT system is usually the operator's only interaction with the system and can make or break the choice of system. There are several software features which are considered highly desirable:

- General appearance of the user interface: How cluttered is the interface? How many features can a user interact with? How easy it is to scan several samples with similar settings? How difficult is it to set up a new sample?
- What options are available for different types of scans? Most systems provide circular cone-beam scans, reconstructed using the standard FDK algorithm (Feldkamp et al., 1984). However, helical CT allows for high-resolution scans of tall samples and the removal of cone-beam and ring artefacts (Katsevich et al., 2004).
- The ability to batch scan allows several samples to be scanned, without operator intervention, say overnight.
- Programmable software allows for custom scan methods and third-party hardware (like robotic sample handlers). With carefully designed sample holders, the sample manipulator itself, in conjunction with a sample shelf inside the cabinet,

can act as a cost-effective though slightly slower sample loader. The programmability can range from a few simple macros to full open architecture so that software engineers can write programs to control not only the X-ray CT system but of course third-party hardware like robots, or third-party software such as databases.

- 4-D CT—both time-lapse CT scans and continuous capture in which the spatial resolution can be played off against the extra time resolution for those events which happen quickly, or extra spatial resolution can be obtained during those periods of slow change (Parmesh, 2018).

2.9 Overcoming CT Artefacts

CT artefacts are unwanted features in the data not relating to real features in the sample and come in many forms. Ring artefacts are bright and/or dark rings around the sample rotation axis that often connect features which the operator desires to segment, or separate, such as particles of soil. Rings are caused by non-linear behaviour of individual pixels in a detector that have not been identified as “bad pixels” (i.e. a dead transistor in a detector) in and interpolated over. Since they do not move as the sample is rotated, they form rings in the CT volume. A single bad pixel, differing greatly in intensity from its neighbours, can produce three adjacent rings due to the filter in the filtered back-projection reconstruction algorithm [3]. A jump in sensitivity of adjacent pixels can cause two rings (for the same reason). It is rare to get a single ring.

Ring artefacts can be supressed during scanning by, for example, moving the sample or detector sideways by random amounts and subsequent correcting by shifting the image sideways by a fractional pixel amount. They can also be removed afterwards by post-processing algorithms acting on the CT volumes.

Beam hardening artefacts occur when particles in the soil filter an otherwise unfiltered X-ray beam and cause parts of the volume to be imaged with only higher energy X-rays instead of the full beam spectrum. They can complicate the grey-value thresholding of soil particles because the threshold needs to vary across the sample, being lower in the centre. It is worth noting that the voltage selected in the software is the electron beam acceleration voltage and not the energy of most of the X-rays, which is much lower and of a wide range of energies. Dense particles will filter the lower energies out of the beam leaving only more highly penetrating X-rays, making those parts of the sample appear less absorbing of X-rays and of a lower density. Placing a filter, for example, in front of the X-ray source removes those low energy X-rays from the beam and improves the CT images (Fig. 2.6), at the expense of a longer scan time. The images from the unfiltered beam are brighter but only because they contain many low energy X-rays which cannot penetrate the sample. These low energy X-rays are best removed from the equation. It is worth remembering that the mean energy of the X-ray beam is controlled much more by the thickness of filter in front of the source than by the acceleration energy of the electrons selected.

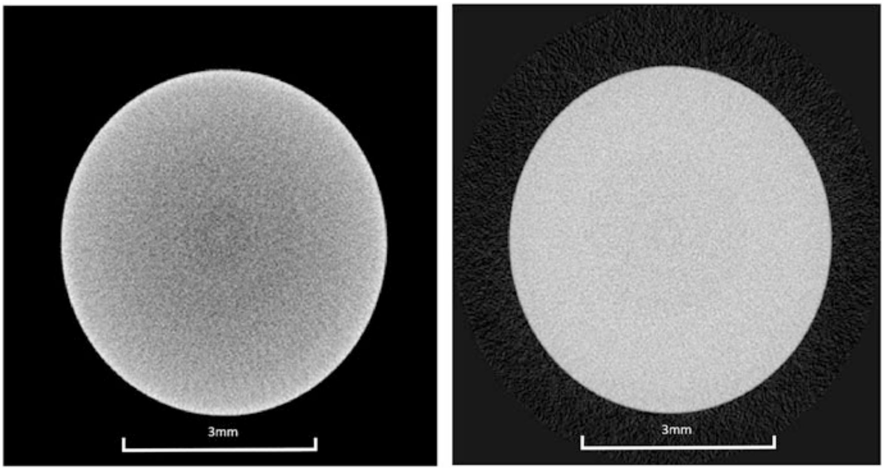

Fig. 2.6 Left: Beam hardening in a steel rod lowering the apparent density of the centre of the sample; Right: Beam hardening removed by filtering the X-ray beam and/or by software correction. [Image courtesy of Nikon Metrology UK Ltd.]

Beam hardening artefacts can also be suppressed using corrections during reconstruction. These work best when there is only one material in the sample, so often a combination of source filtering and software correction is used (see Chap. 4).

2.10 Evaluating a Potential X-Ray CT System

The best way to evaluate a potential X-ray CT system is to have the manufacturer scan some of your samples. Preferably use the same sample for all supplies under consideration for comparison purposes. For soils, a resin impregnated sample is often a good choice as it is structurally stable, presents the same challenges for all systems, and once you define the scanning characteristics you want (fast scan vs. slow, etc.), will provide the best comparison possible.

Samples to be scanned should range from the largest sample you will need to scan, down to individual soil aggregate, only few millimetres across to give a breadth of the possibilities from the instrument (Fig. 2.7). The sharpness of the images should be evaluated considering the smallest features you expect to see/segment in samples of a certain size, bearing in mind that the resolution is generally higher for smaller samples as they can be imaged at higher magnifications. Zoom in until individual voxels can be seen. The ability to scan small regions of larger samples can be very useful but is not offered by all systems. Look out for sharpening filters being used to artificially increase the resolution: such filters also increase the noise and therefore do not increase the ability to distinguish small features of interest from background noise. Noise suppression filters may also be used to reduce the