X-ray Tomographic Systems for Cultural Heritage

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Science & Cultural Heritage

Application of scientific methods and technologies to Cultural Heritage study

WHAT material is it made of?

WHEN was it made?

WHERE was it made?

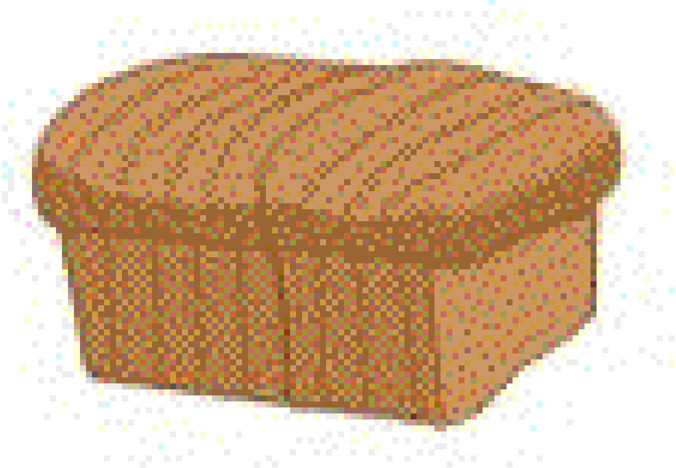
HOW was it made?

HOW can we preserve it for future generations?

X-ray Computed Tomography

X-ray Computed Tomography (CT) is a powerful non-destructive diagnostic technique, able to give morphological and physical information on the inner structure of the object studied, overcoming an important limit of radiography: the superimposition of elements belonging to different layers of the object.

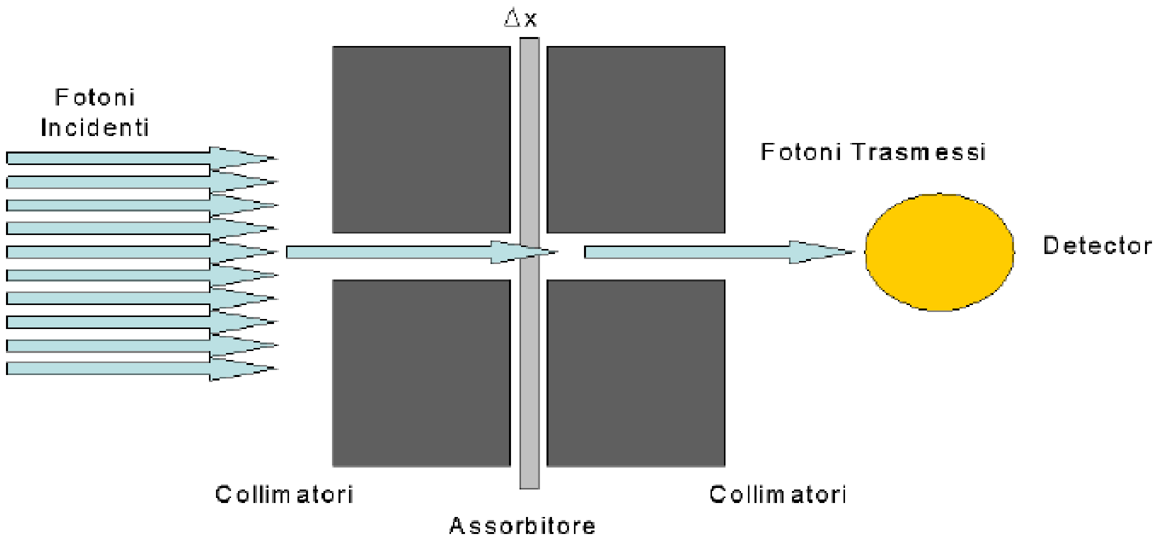
“Tomography” comes from the Greek word “tómos”, that means “section”. In fact this kind of non-destructive analysis is used to “virtually” cut an object and see inside it.



Attenuation of monochromatic X-ray photons

Beer-Lambert's law for homogeneous material and monochromatic photons:

$$I(x) = I_0 e^{-\mu x}$$



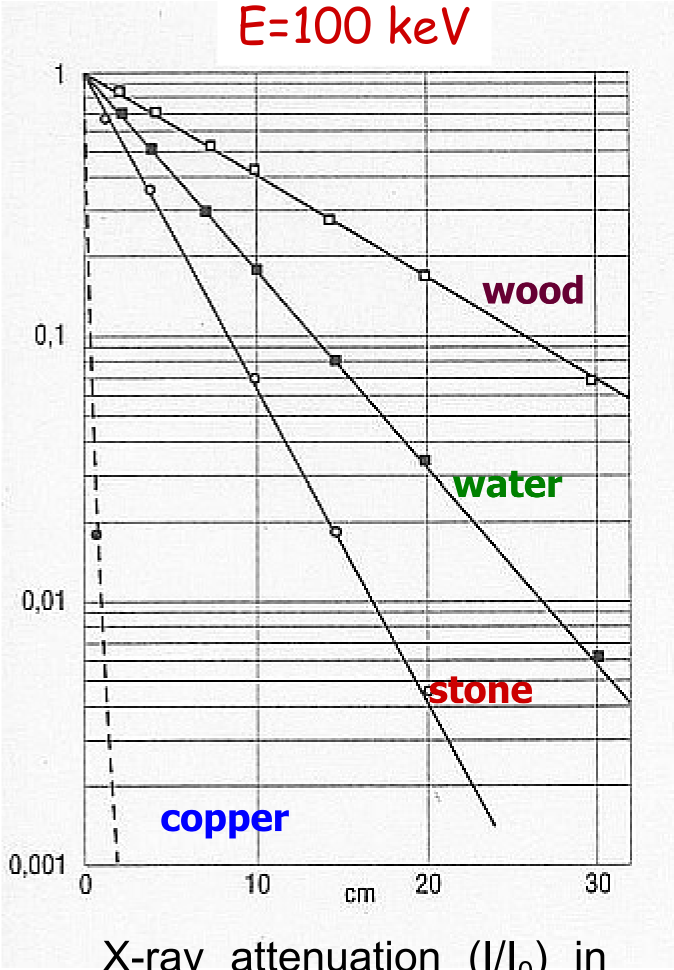
where:

- I is the number of photons reaching the detector in presence of the test material
- I_0 is the number of photons that would be detected without the test material
- μ is the linear attenuation coefficient for a homogeneous material
- x is the thickness of the test material.

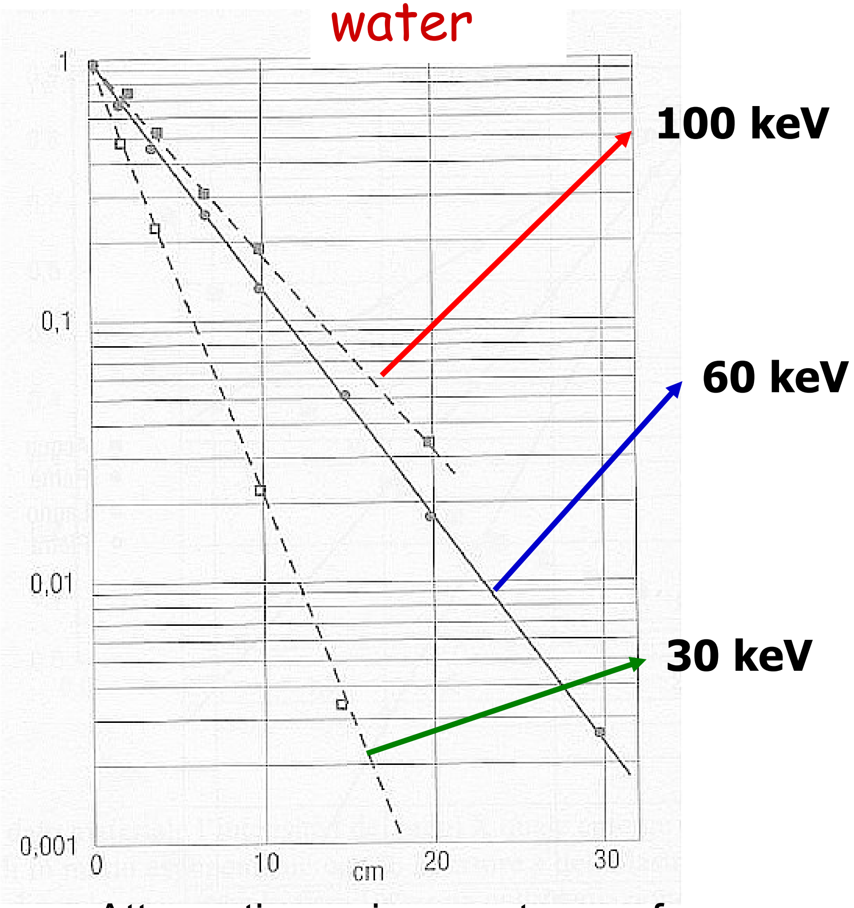
Attenuation of monochromatic X-ray photons

μ depends on:

- the atomic number of the material
- the density of the material
- the energy of the X-ray beam



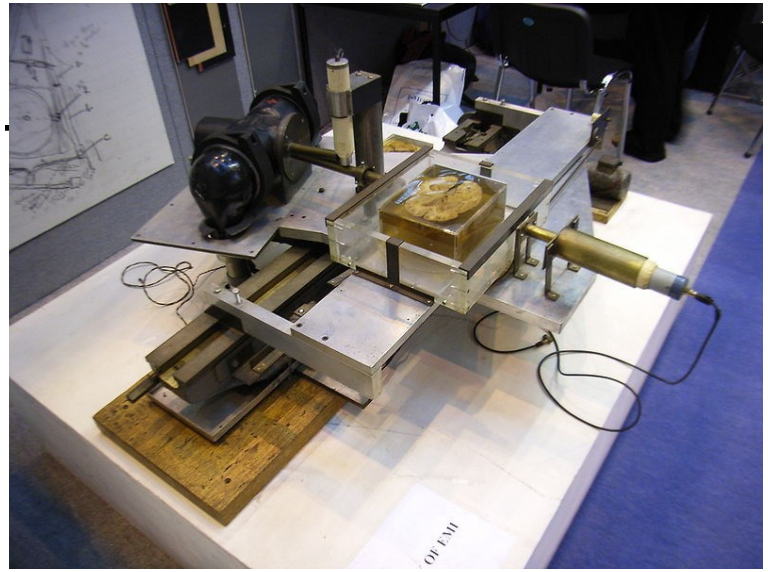
X-ray attenuation (I/I_0) in different materials.

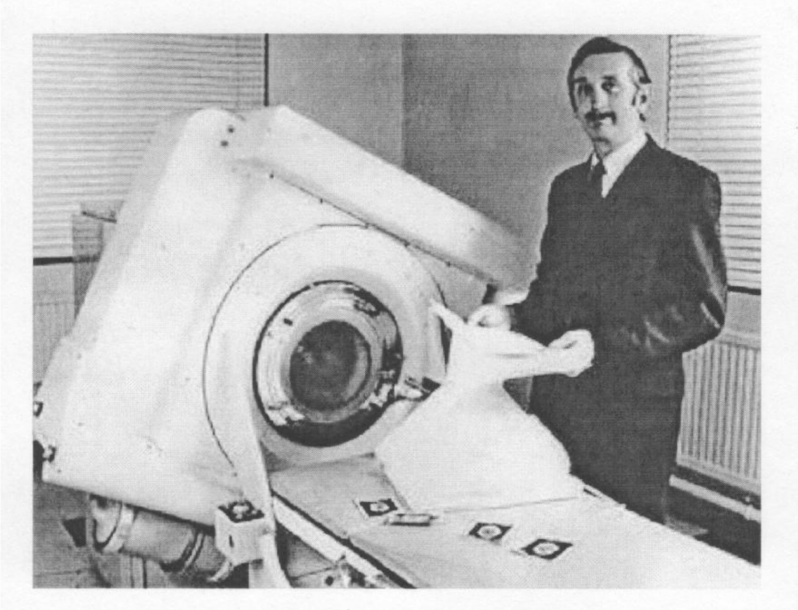


Attenuation in water of monochromatic X-rays for different X-ray energies.

The first CT scanner (1971)

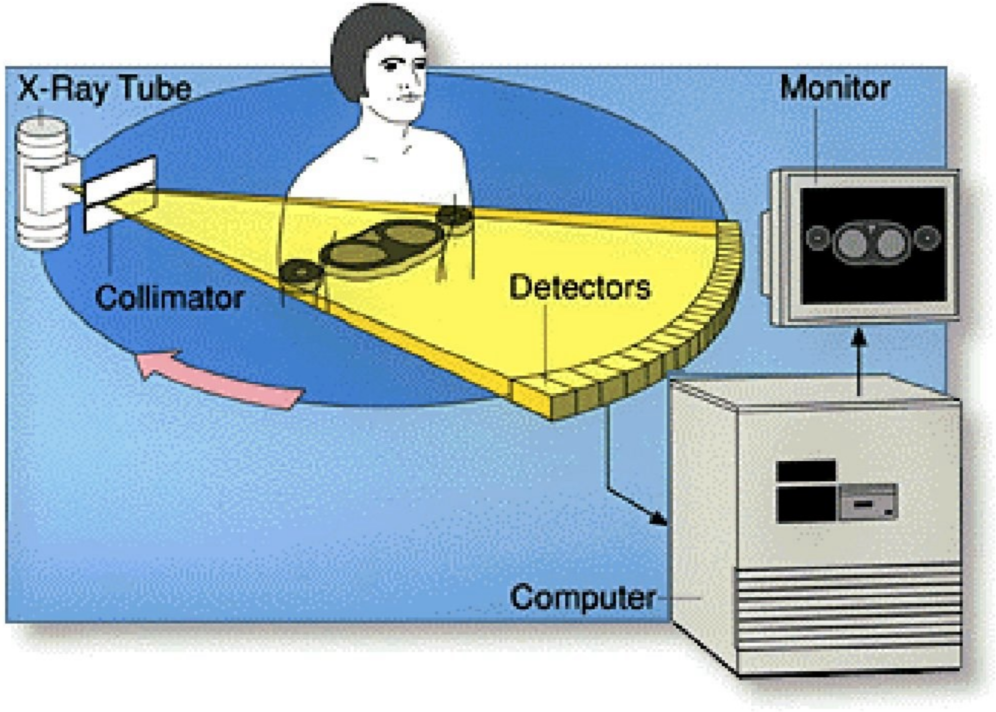
The first CT scanner for clinical use ("EMI Mark I scanner") was developed by the British engineer Godfrey Hounsfield in the research laboratories of EMI (United Kingdom) and installed in 1971 at Atkinsons Morley's Hospital in Wimbledon (London).





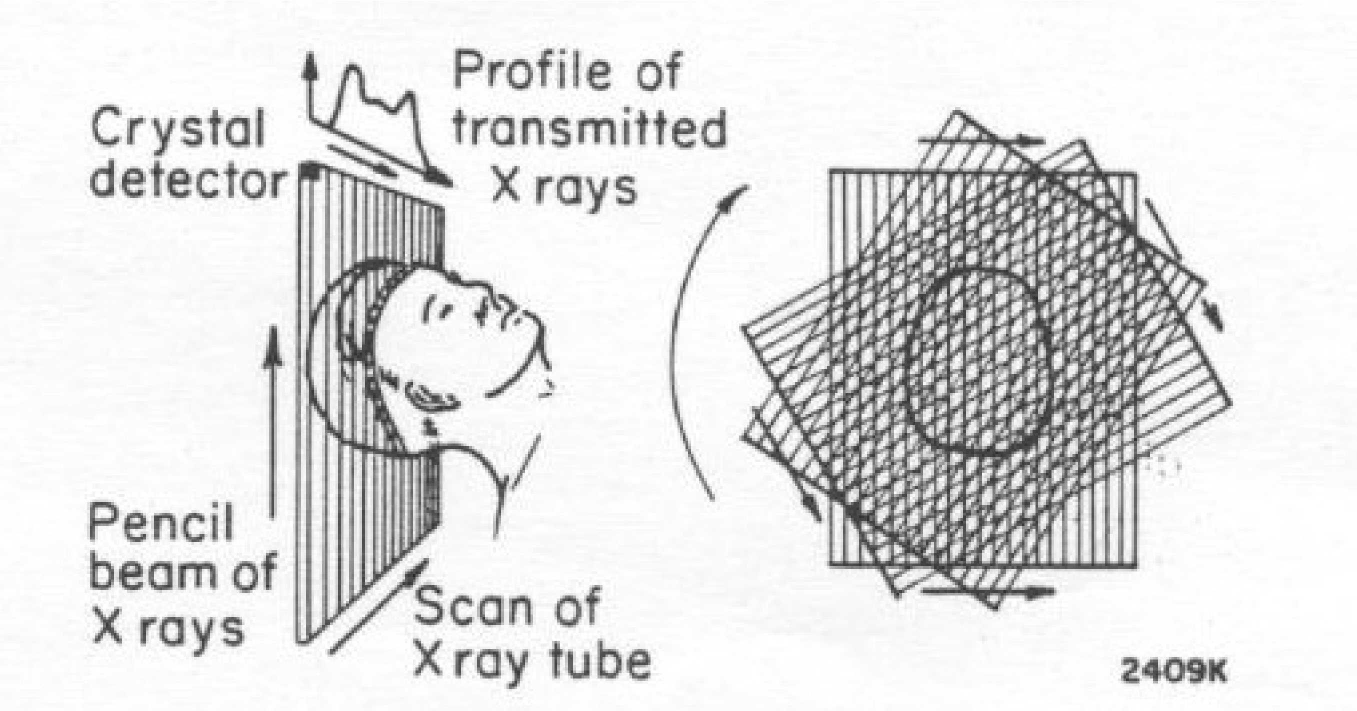
In 1979 Hounsfield shared the Nobel Prize for Medicine with the physicist Allan Cormack.

Tomographic slices



A tomographic **slice** is the image of a cross-section of the object under investigation, in which the grey-levels are proportional to the values of the linear attenuation coefficient in that section of the object.

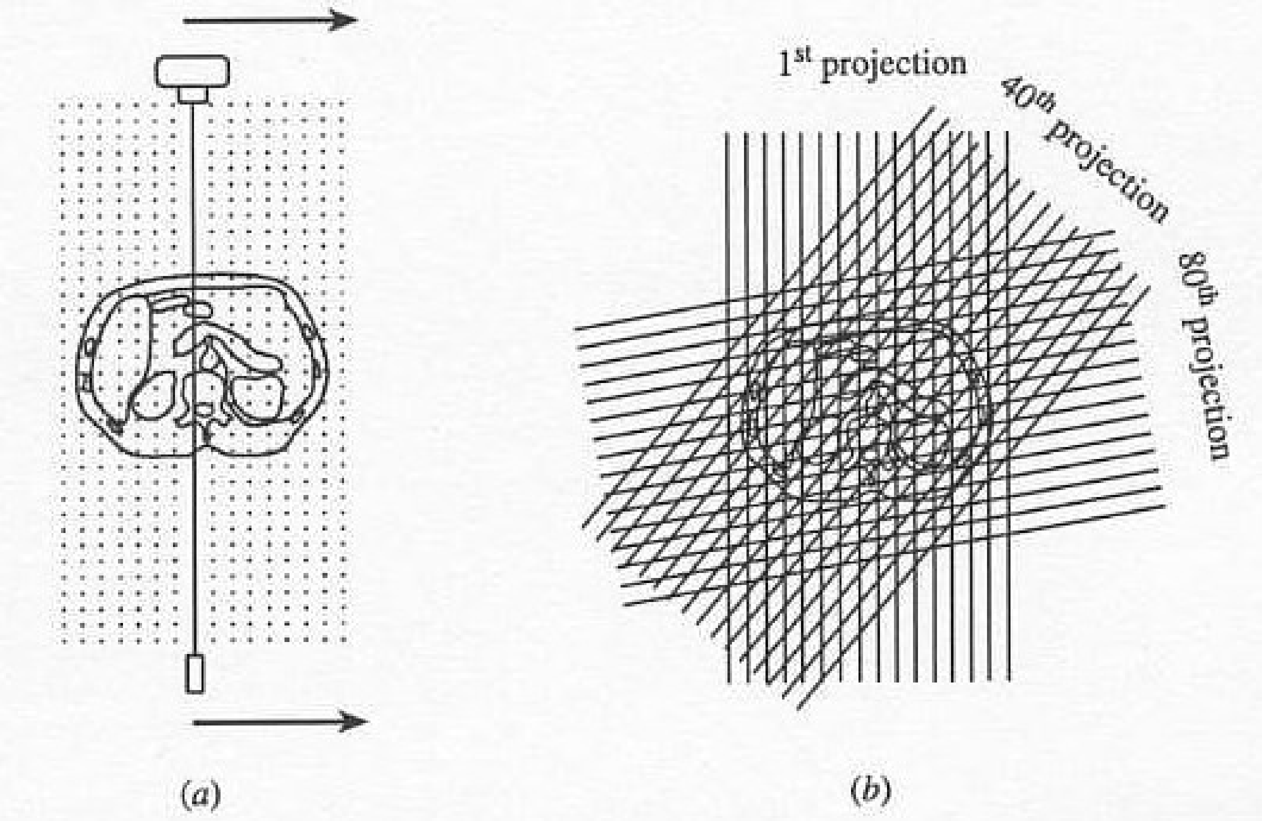
The measurement process (first generation CT scannes)



Principle of the first CT scanner, developed by Hounsfield and designed to study the human brain.

An X-ray tube emitting a pencil-like beam is coupled to a single radiation detector. The two are moved together on a carriage, so that a plane in the head is scanned by a series of parallel rays as the translation takes place. For each ray the fraction of the radiation transmitted is measured and stored in a computer.

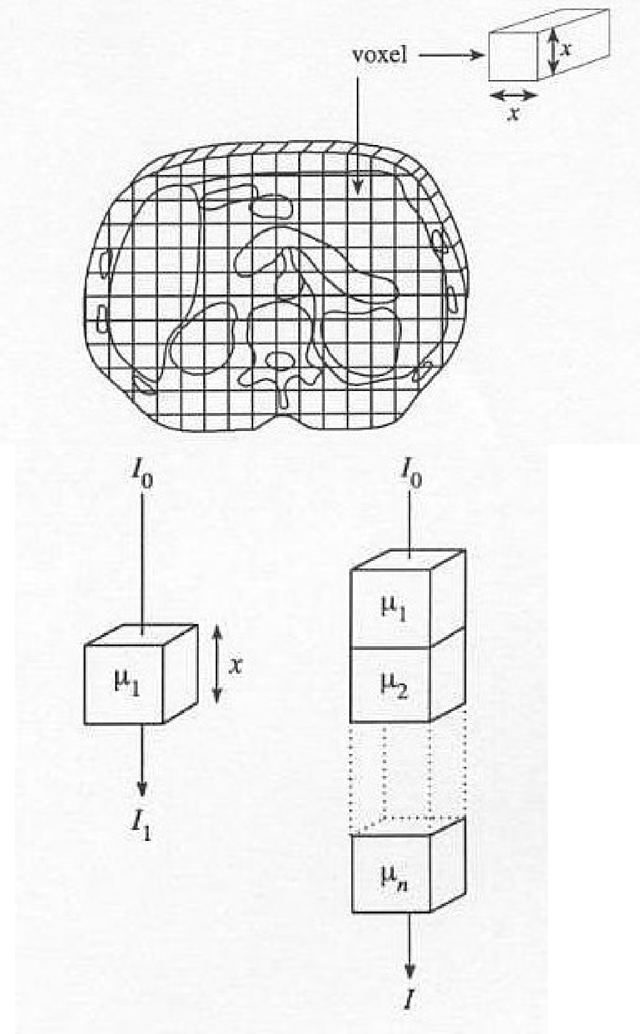
The measurement process



a) The pencil beam of X-rays is translated across the patient to acquire a projection, that is made up of a large number of pencil-beam attenuation measurements.

b) The X-ray source and the detector are rotated around the patient and a large number of projections are acquired, each one at a different angle.

The measurement process



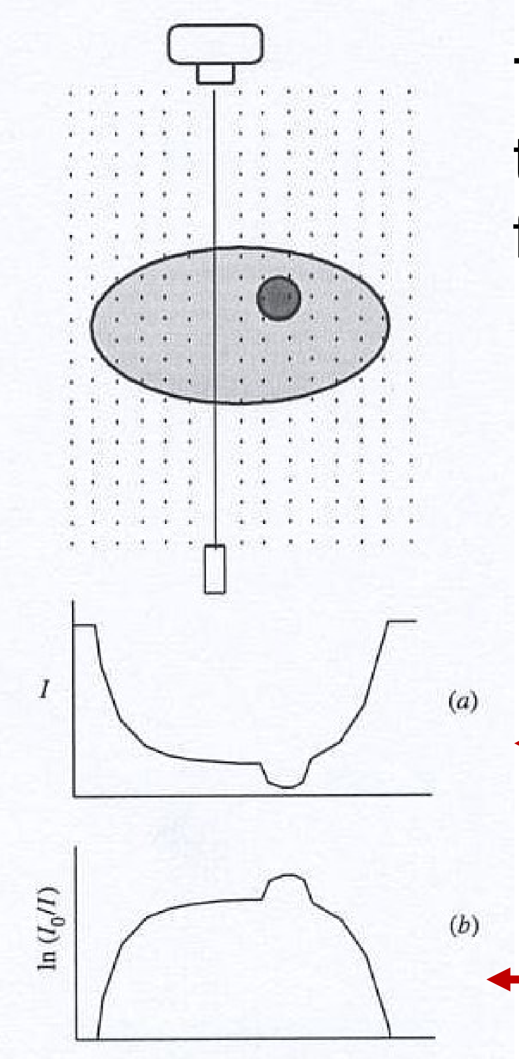
Assuming that the X-ray beam is monoenergetic and has an incident intensity I_0, then the intensity I_1 of the beam transmitted through a small volume of tissue having thickness x and attenuation coefficient μ_1 is:

$$I_1 = I_0 e^{-\mu_1 x}$$

In traversing from one side of the patient to the other, the X-ray beam will be attenuated by all the voxels through which it passes. The emerging X-ray beam will have an intensity I given by:

$$I = I_0 e^{-x\sum_{i=1}^{n}\mu_i} \Rightarrow \ln\frac{I_0}{I} = x\sum_{i=1}^{n}\mu_i$$

The measurement process

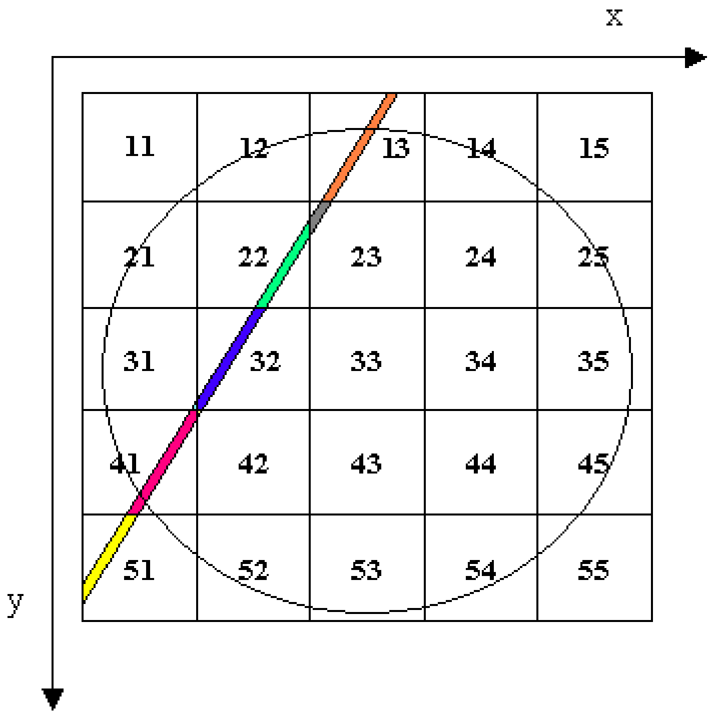


The figure shows the measured X-ray intensities and the corresponding logarithms of the intensity ratios I_0/I for one projection.

Intensity profile

Attenuation profile

The measurement process



The image shows a cross-sectional view of the object under investigation superimposed upon a rectangular matrix of pixels, which for clarity of presentation has been made very coarse.

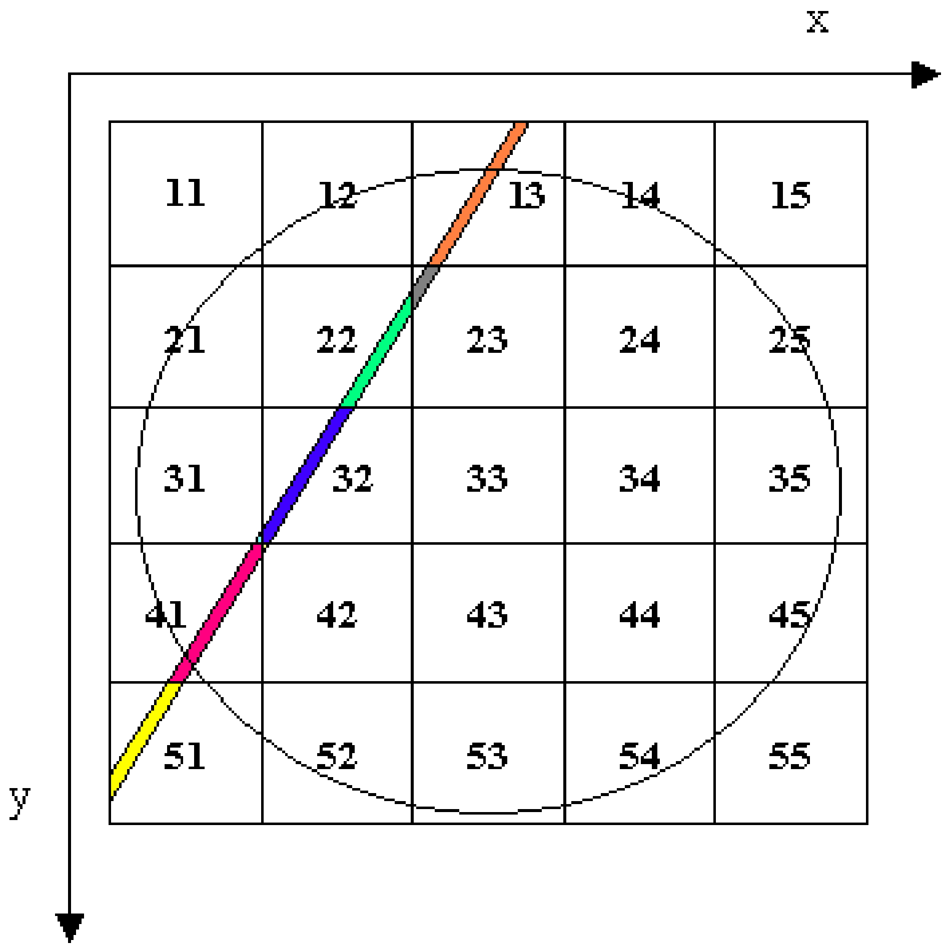
Let $\mu(x,y)$ be the average attenuation coefficient of the tissues in the pixel (x,y). The radiation transmitted It is related to the incident radiation I_0 by:

$$I_t = I_0 e^{-\sum \mu(x,y) l(x,y)}$$

$$\ln\left(\frac{I_0}{I_t}\right) = \sum \mu(x,y) l(x,y)$$

The elements of lenght *l(x,y)* are determined by the geometry of the system and hence can be calculated and stored in the computer.

The measurement process



Our problem is to determine the attenuation coefficient of the object under investigation in each picture element of the slice.

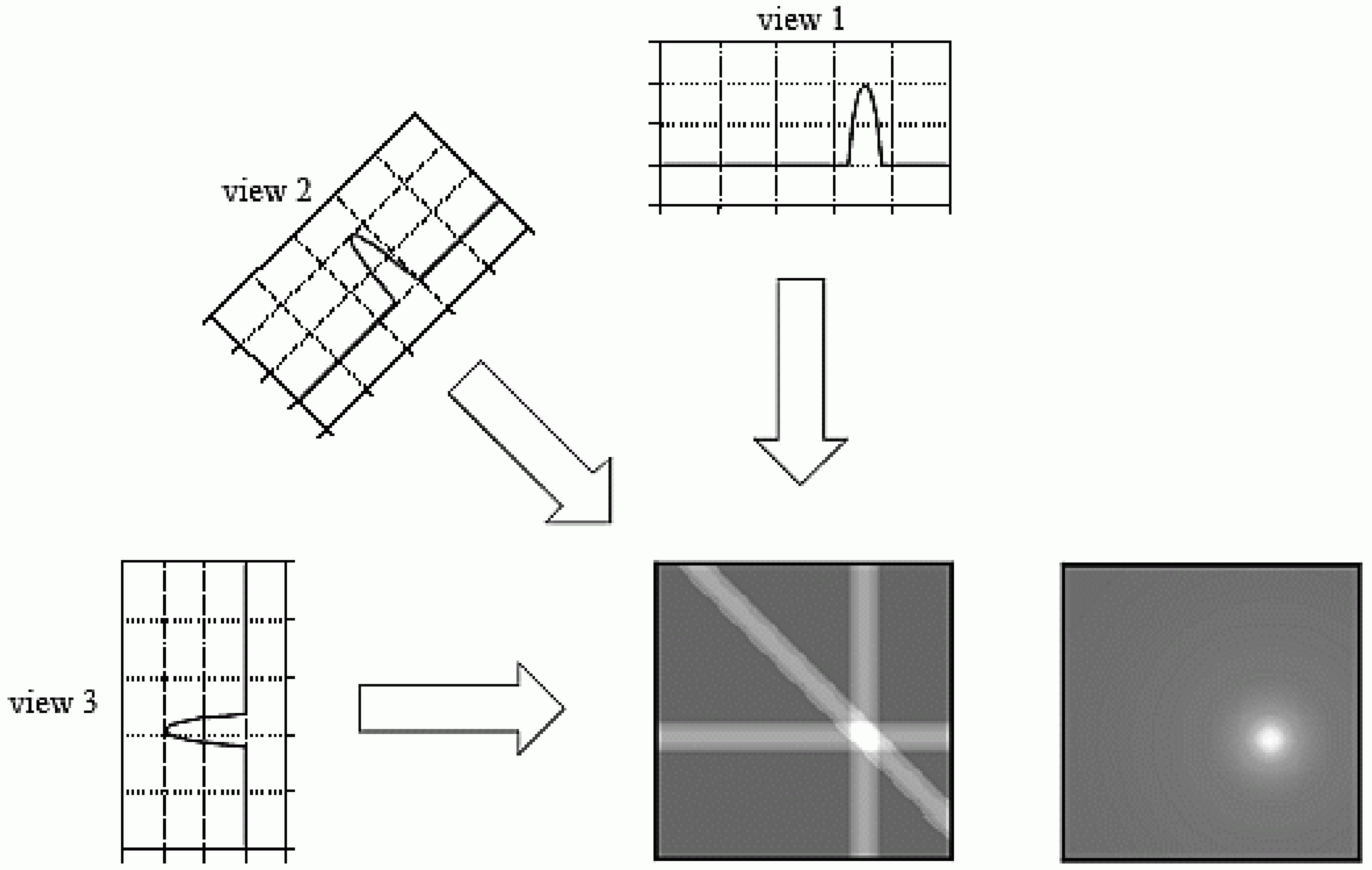
The reconstruction process creates an image that is a map of the X-ray attenuation coefficients of the object in the plane under examination.

Image reconstruction

The method used on most of the CT scanners is the method of filtered back-projection. The mathematics of filtered back-projection dates back to 1917 with the work of the Austrian mathematician Radon, who theoretically solved the problem of obtaining a section of an object using an infinite set of rays passing through it.

However, as previously stated, it was not until the 1960s that two scientists, the engineer Geoffrey Hounsfield and the physicist Allan Cormack (separately) succeeded in obtaining the section of an object experimentally.

Image reconstruction: simple back-projection

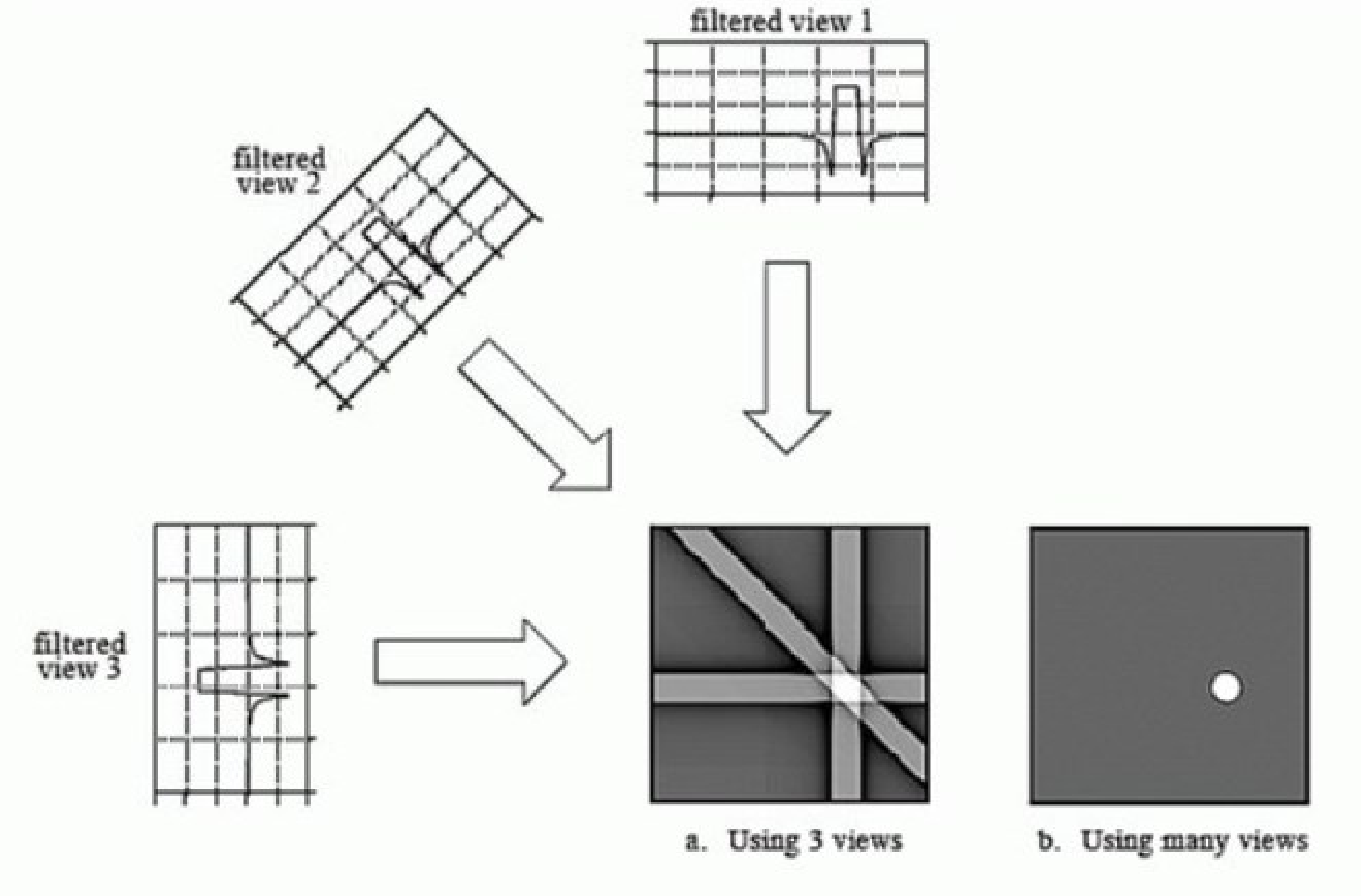


a. Using 3 views

b. Using many views

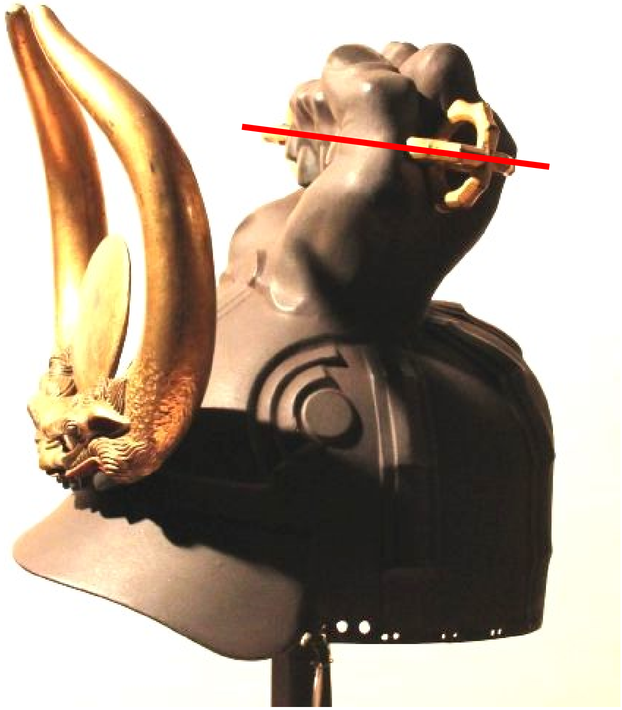
Back-projection reconstructs an image by taking each view and smeraing it along the path it was originally acquired. The resulting image is a blurry version of the correct image.

Image reconstruction: filtered back-projection

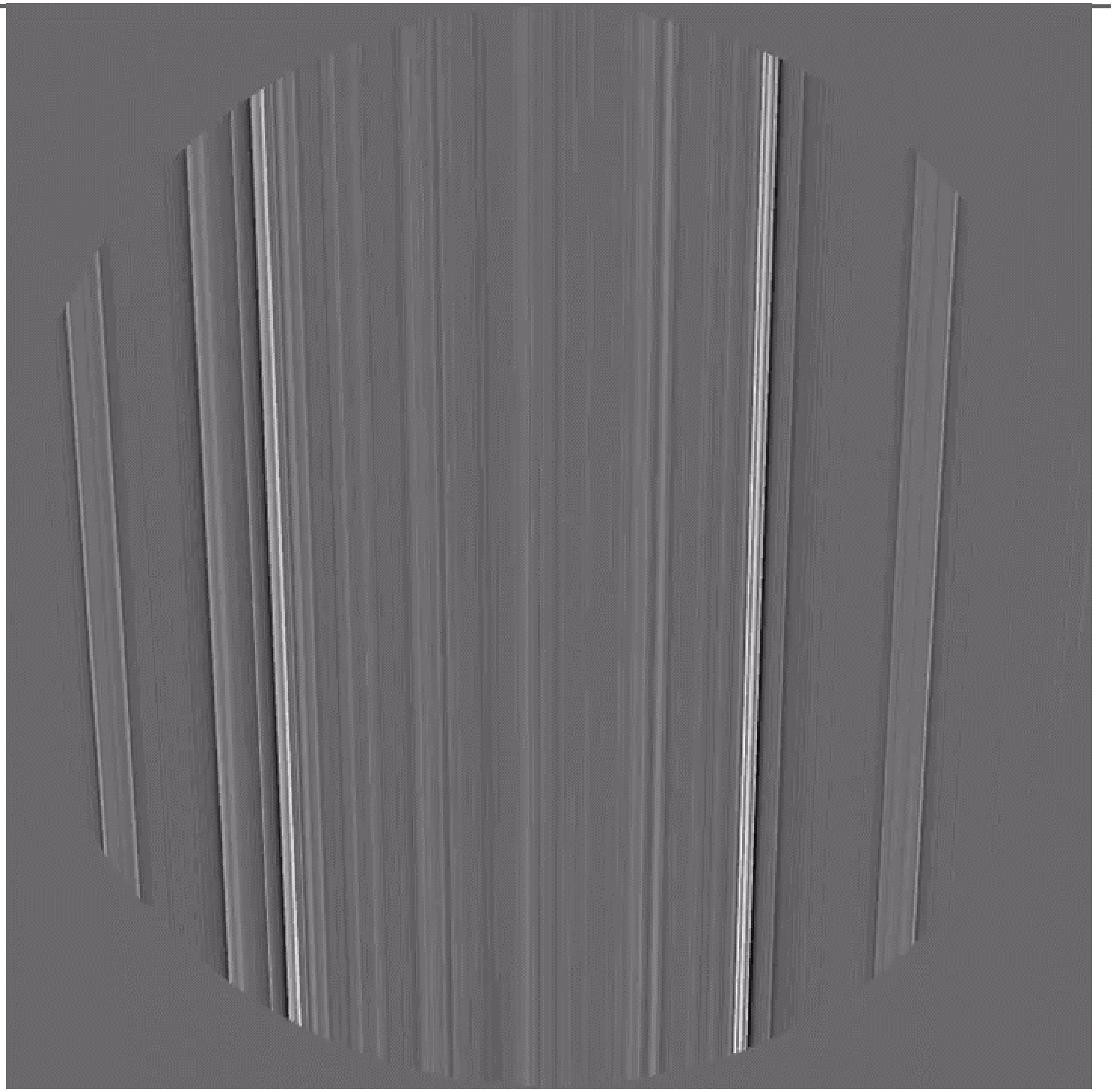


The image reconstruction process of the FBP algorithm. Each set of projection data, taken at different angles, undergoes convolution filtering before back-projection. This removes the blurring that would result from simple back-projection without filtering.

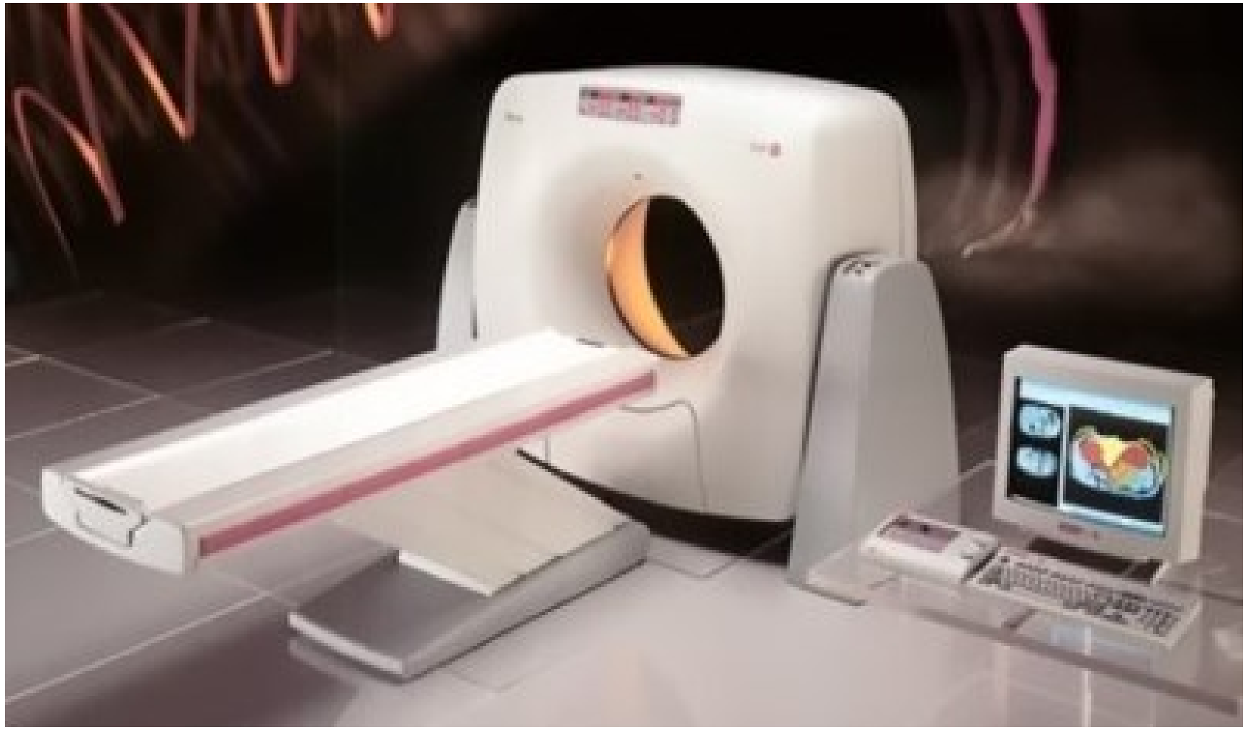
Filtered Back-Projection



Japanese helmet fromn the Stibbert Museum (Florence).



Components of a CT scanner



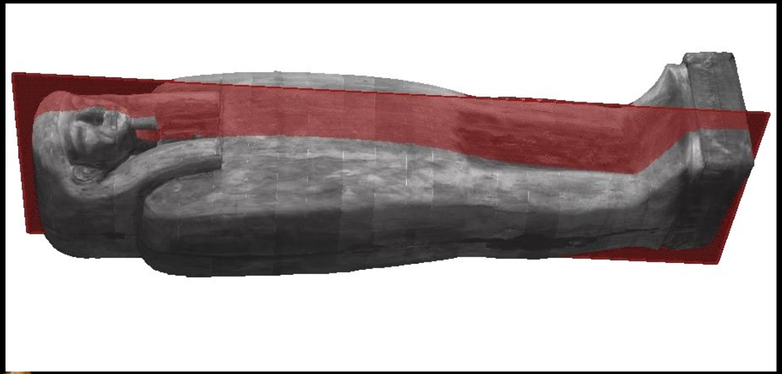
Computed Tomography implies

1. **a radiation source**
2. **a detection system**
3. **mechanics**
4. **control software**
5. **reconstruction and rendering software**

X-ray CT & Cultural Heritage

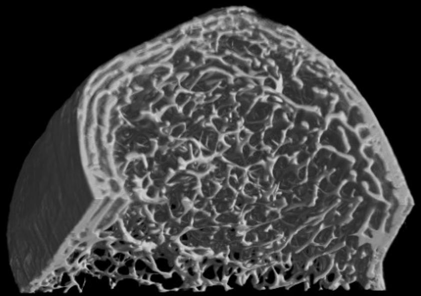
DIFFERENT SIZE

- m



- cm

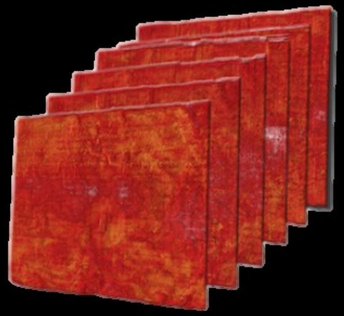
- mm

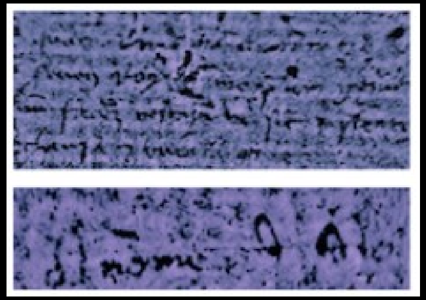


Increasing size

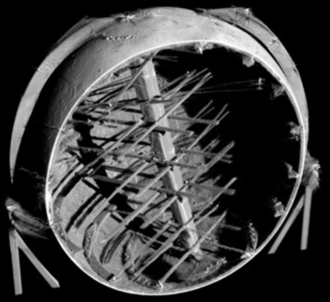
X-ray CT & Cultural Heritage

- Paper
  - Low energy

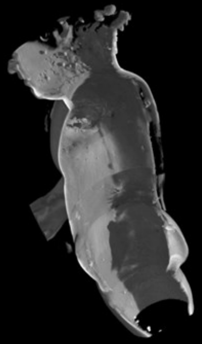


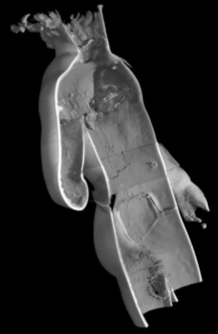


- Wood
  - Medium energy



- Stone
  Metals
  - High energy





Increasing energy

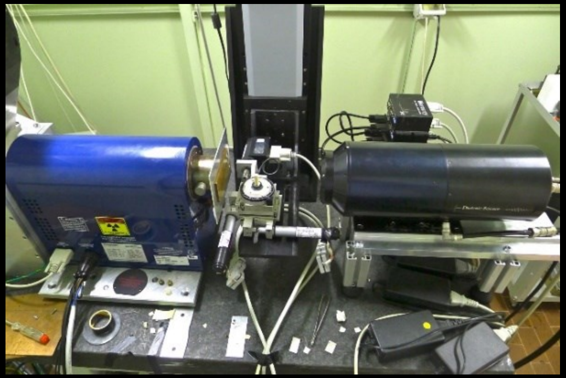
X-ray CT & Cultural Heritage

It is difficult to move the works of art from the place where they are kept.

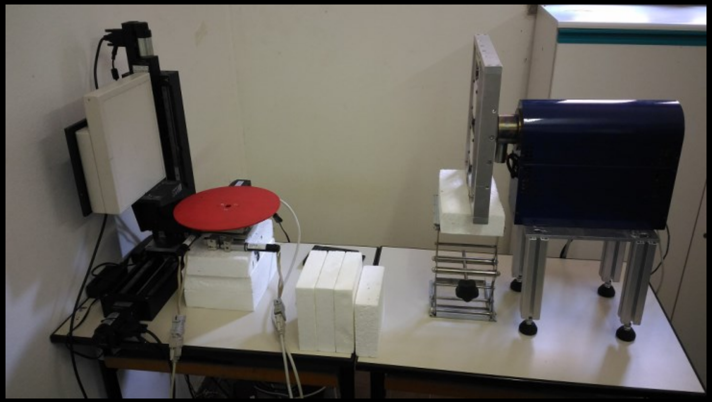
Therefore it is important to develop equipment that is easy to move, specifically designed for Cultural Heritage analysis on-site.

In the recent past, our research group developed a number of acquisition systems for Digital Radiography and Computed Tomography. We have performed high resolution micro-CT of small objects (voxel size of few microns) and CT of large works of art (up to 2 m of size), using different kinds of X-ray sources and different setups, in order to meet the different needs of various case studies.

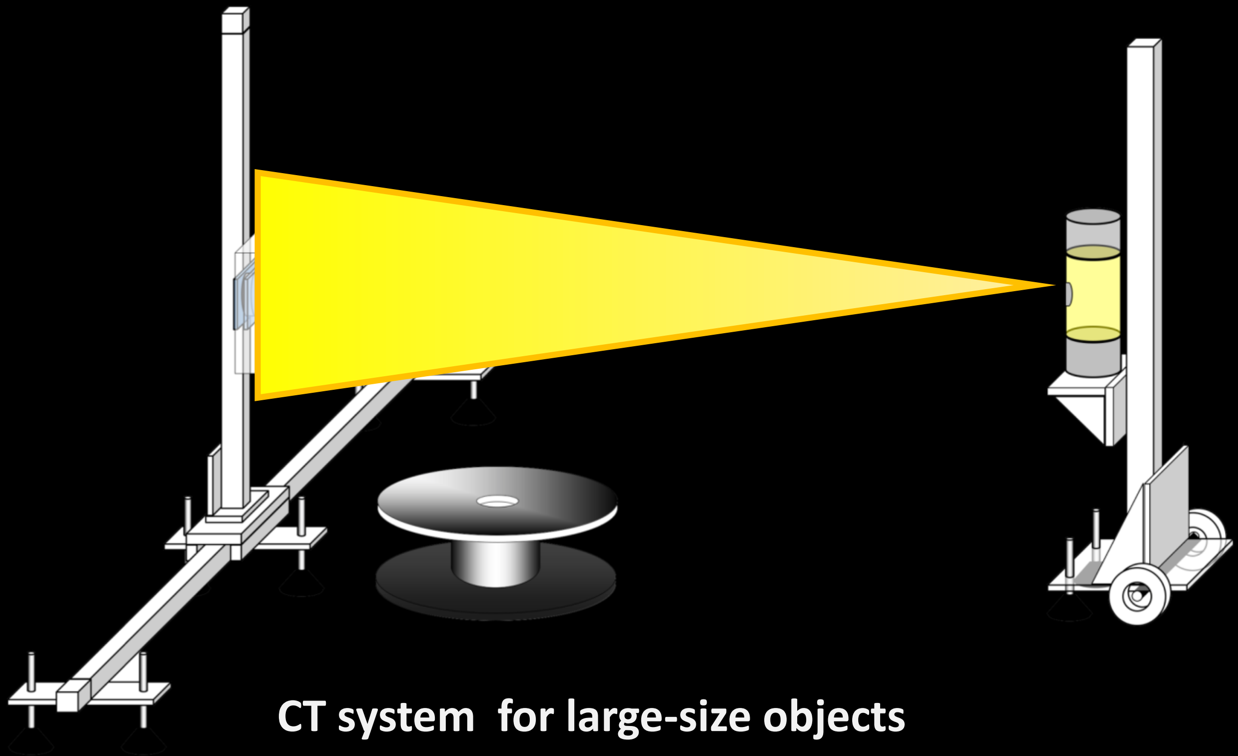
X-ray CT & Cultural Heritage



Micro-CT

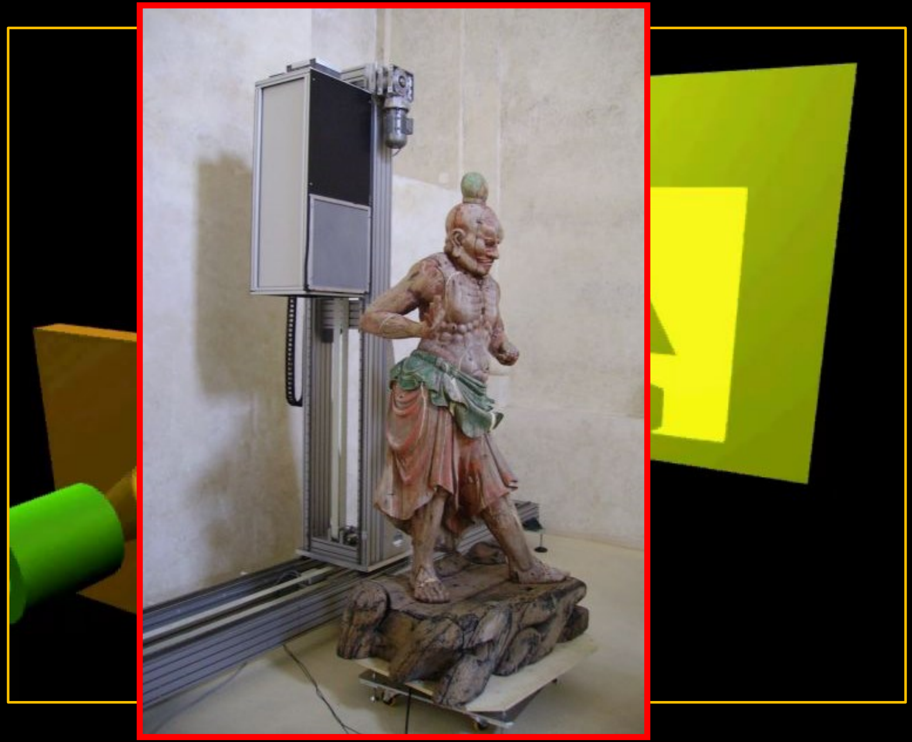


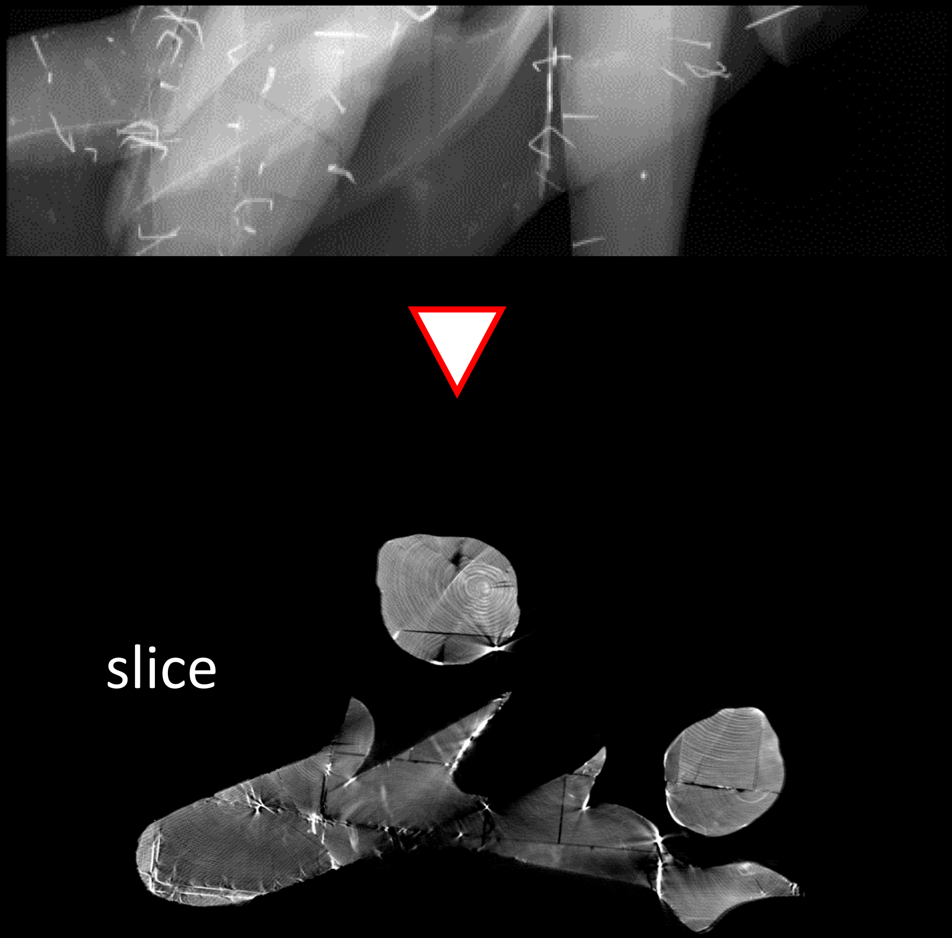
CT system for medium-size objects



CT system for large-size objects

X-ray CT & Cultural Heritage





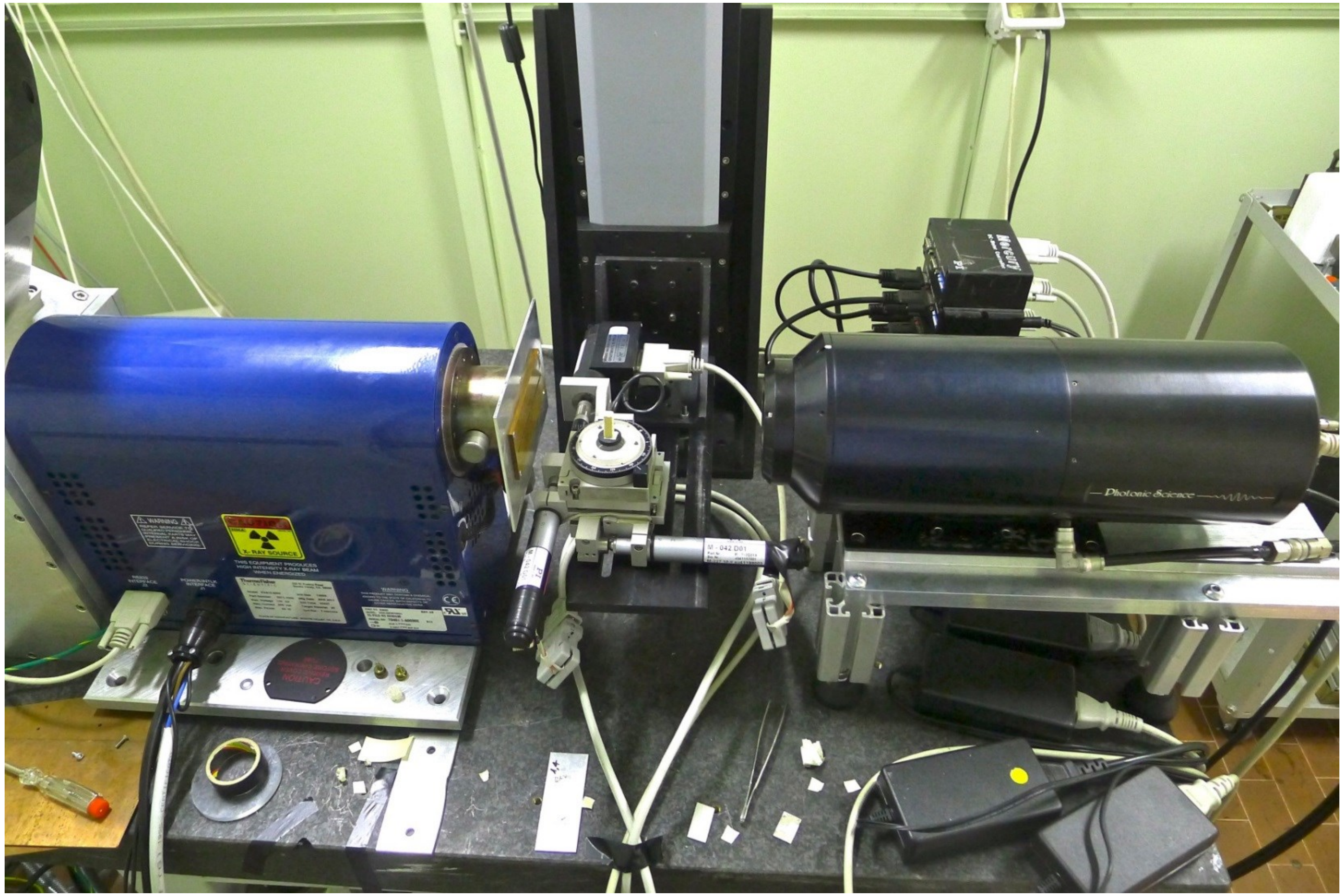
slice

rendering 3D

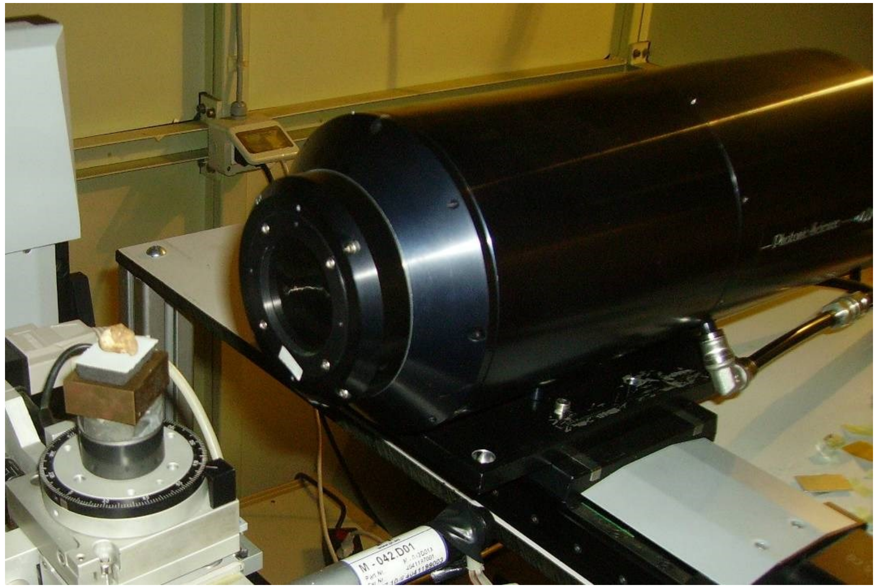
Examples of case-studies

Micro-CT analysis of small samples

Micro-CT system



Micro-CT system



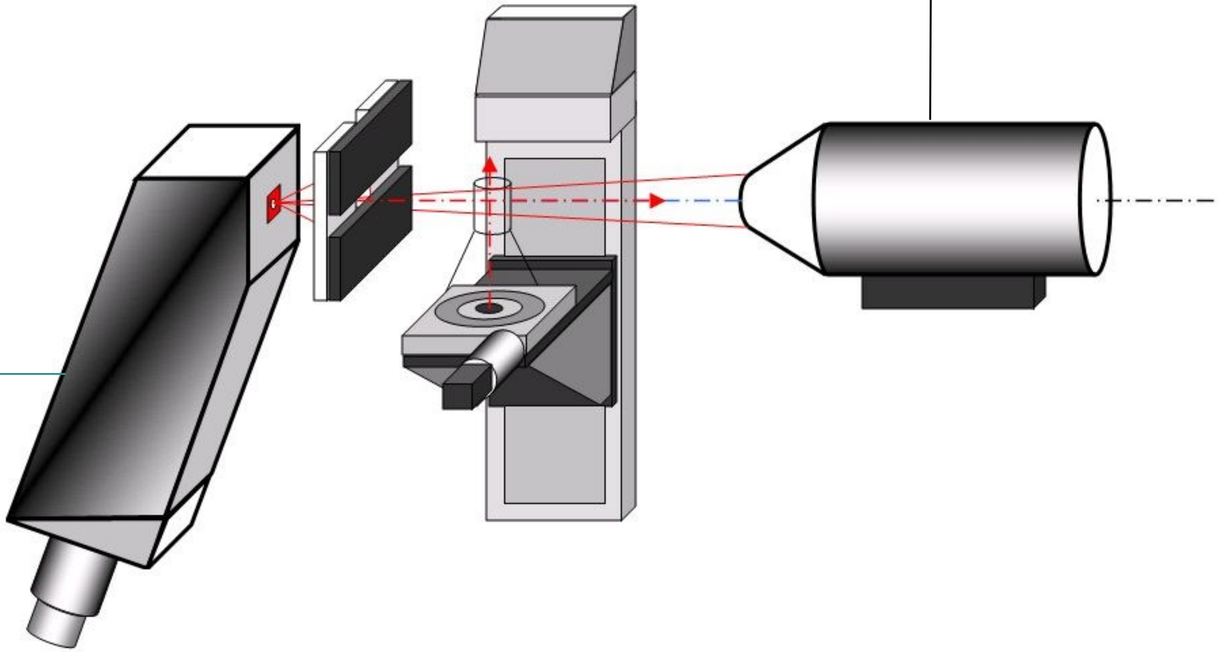
X-ray detector

Photonics Science liquid cooled camera CCD Kodak sensor
4008x2672 pixels; pixel size: 9 μm; FOV = 36 x 24 mm^2
GOS scintillator with 1:1 fiber optics plate

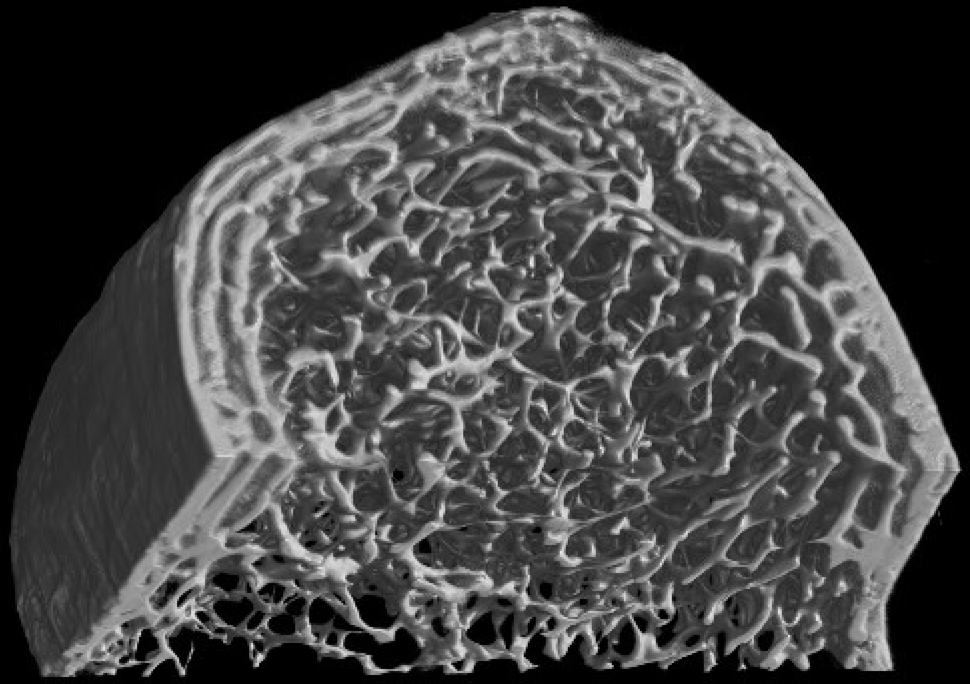
Microfocus X-ray tube

KEVEX PXS10

- 45-130 kV
- 0.5 mA
- 53° beam angle
- 7-100 μm focal spot

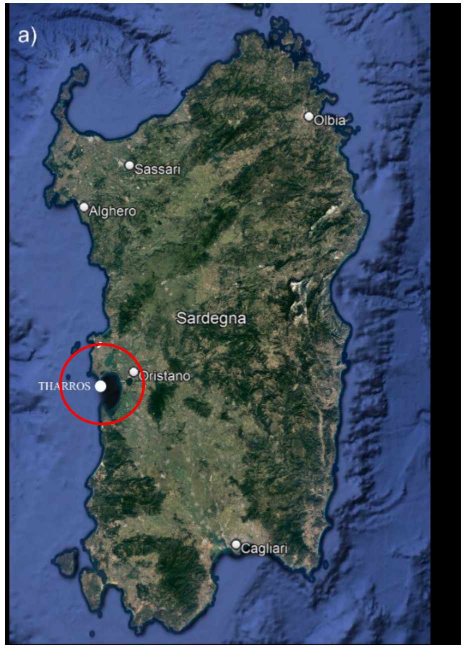


Analysis of human skeletal remains

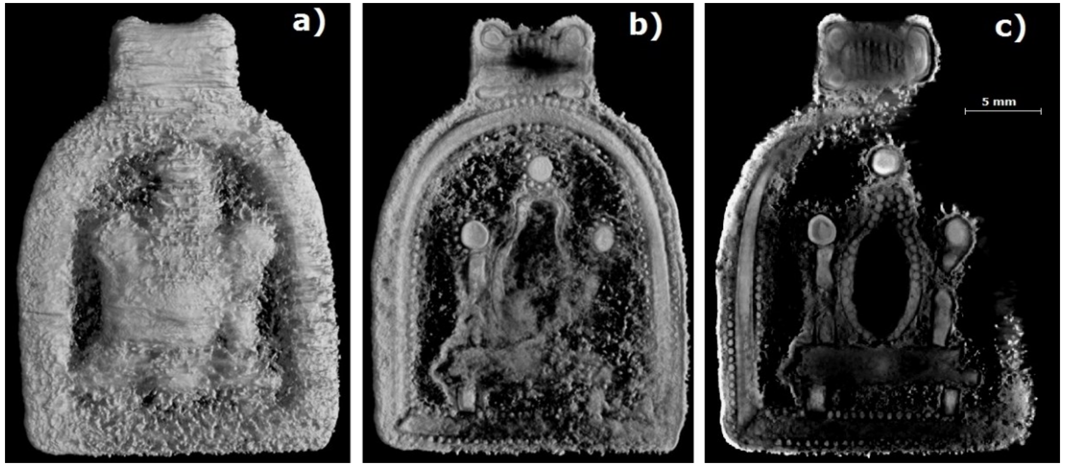


Trabecular microstructure of a child bone from the Anthropology Museum of UNIBO (voxel size: 10 μm).

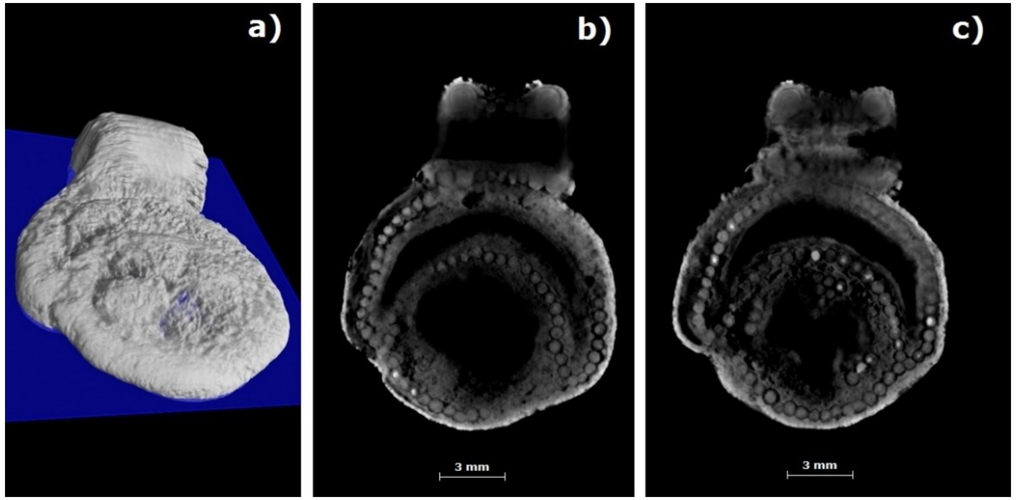
Micro-CT analysis of silver jewelry (7th-6th century BCE)



PUNIC NECROPOLIS OF THARROS – CAPO SAN MARCO (SARDINIA, ITALY)



X-ray CT images of a curved pendant:
a) 3D rendering;
b) internal section;
c) coronal slice, showing details of granulation and filigree decorations.

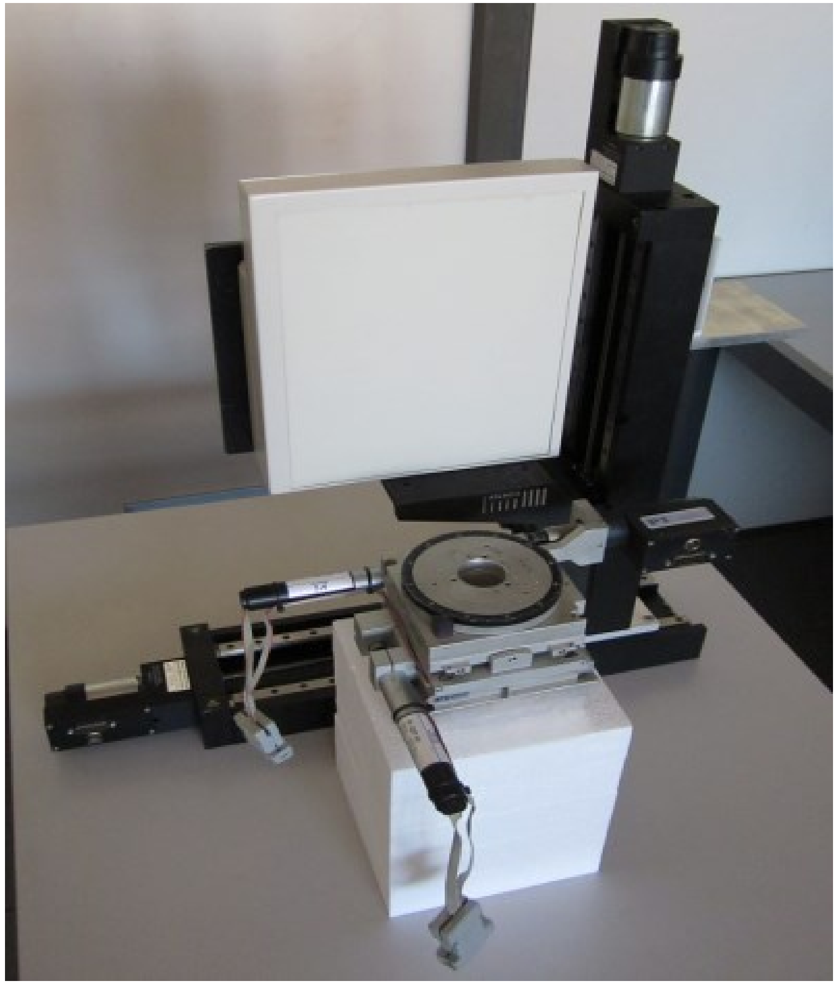


X-ray CT images of a circular pendant:
a) coronal plane sectioning the 3D rendering;
b) crescent moon decoration;
c) star decoration.

Examples of case-studies

Analysis of medium-size artefacts

CT system for medium sized-object



CT system for medium sized-object

Vertical axis

Physik Instrumente (PI)

Model: M413.3PD

Range: 30 cm

Step: 1/10 micron

Flat panel

Varian

Model: PS2520D

Pixel: 127 micron

Area: 25 cm x 20 cm

Vertical axis

Physik Instrumente (PI)

Model: M413.3PD

CT analysis of Egyptian animal mummies

CT analysis of 4 animal mummies from the Archaeological Museum of Bologna.

CT analysis of Egyptian animal mummies

Mummy of a cat
cm. 28

Unknown provenance
Ptolemaic - Roman period
Palagi Collection, EG 2039

Cat mummies represented a very common votive offering to Bastet, a goddess with a feline head.

CT analysis of Egyptian animal mummies

Cat mummy (EG 2039)

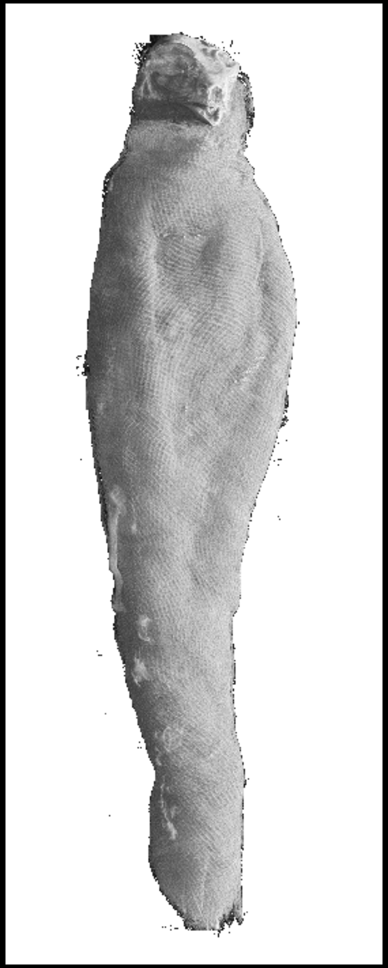
CT analysis of animal mummies

Hawk mummy wrapped in linen bandages
cm. 28 x 6,5

Unknown provenance
Late Period-Ptolemaic Period
Palagi Collection, EG 2050

The falcon-like god Horus, closely related to the concept of royalty, is one of the most important deities for the ancient Egyptians.

This hawk mummy, covered only by a few layers of bandages that leave the head uncovered, appears intact.



CT analysis of Egyptian animal mummies

CT analysis of Egyptian animal mummies

CT analysis of Egyptian animal mummies

37 x 10 x 19.5 cm

Cat-shaped wooden coffin (Egyptian Collection of the Archaeological Museum of Bologna).

The Lilibeo Project

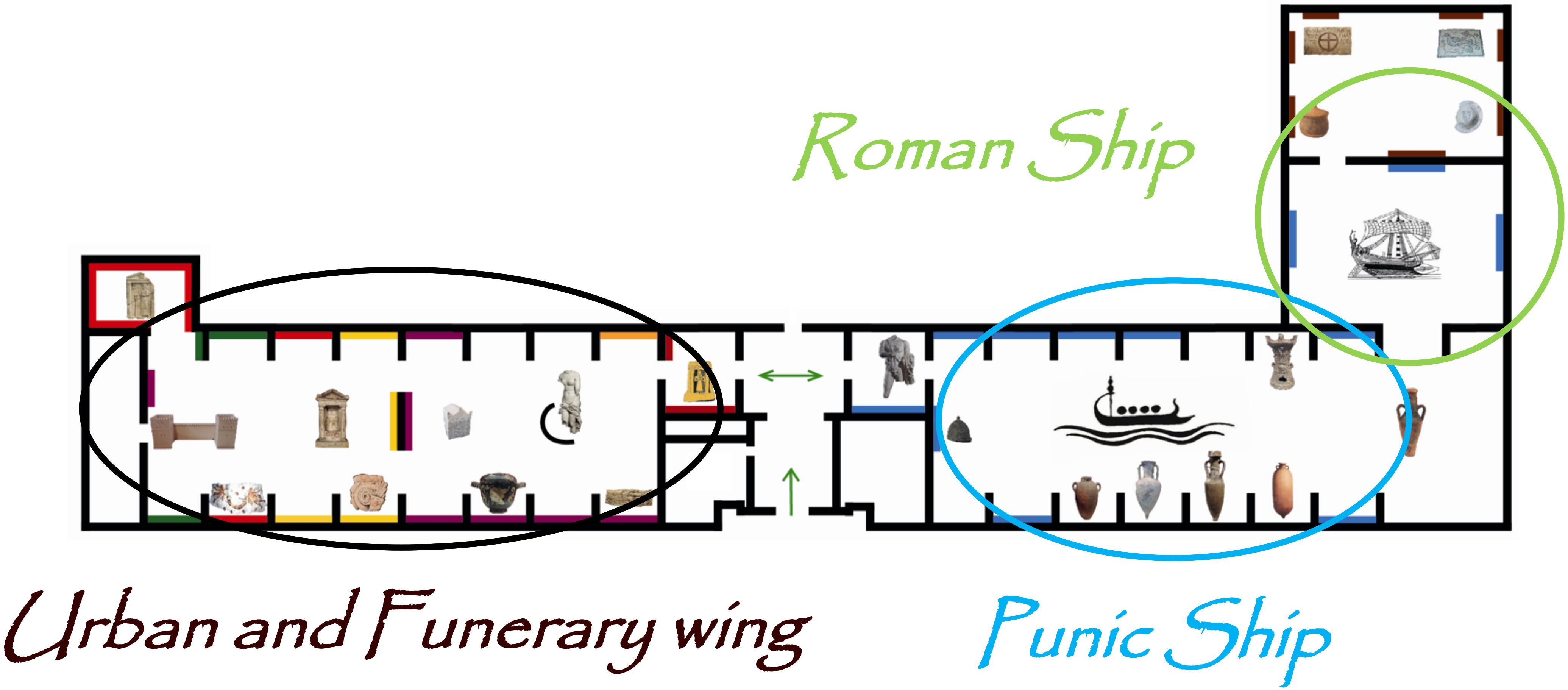
PARTNERS:

- Centro Fermi
- Bologna University & INFN
- Tor Vergata University
- Scuola Normale Superiore
- University of Geneve
- Trapani and Marsala Regional Pole for Cultural Sites
- Regional Archaeological Museum «Lilibeo» (Marsala)

AIM OF THE PROJECT:

To study, through non-invasive methodologies, the characteristics of some finds preserved at the Lilybaeum Museum.

The Lilibeo Project



CT analysis on-site

BABY-BOTTLES AND RATTLES




PLASTIC VASES

3th century B.C.



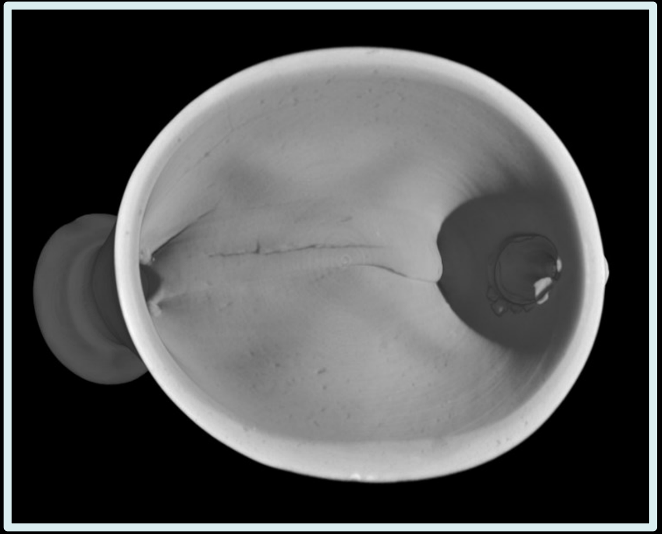
CT analysis on-site

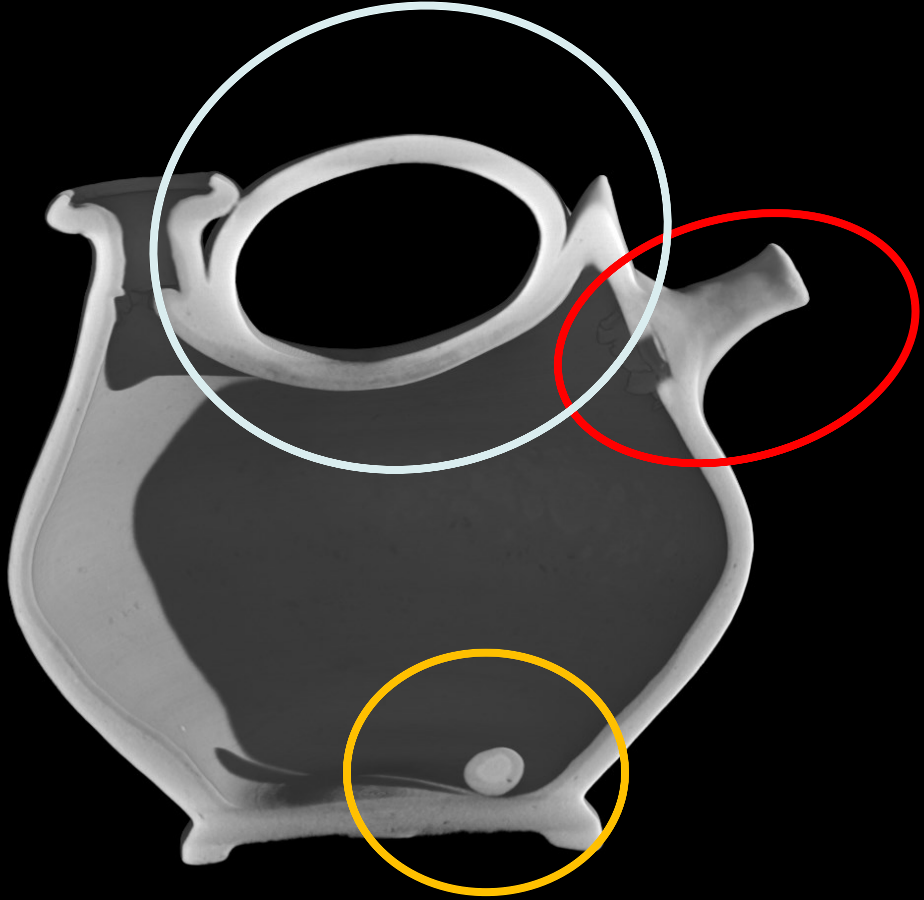
Black-glass aryballos (30×23×41 mm), late 4th – 3rd century B.C.

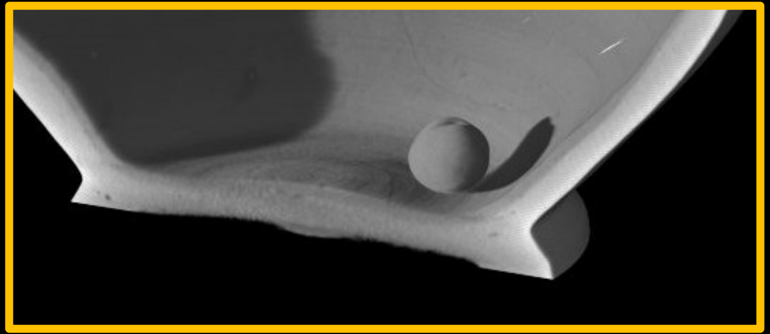
Polychrome glass alabastron (23×24×87 mm), late 4th – 3rd century B.C.

Blown glass balsamarium (height: 90mm), 1st century A.D.

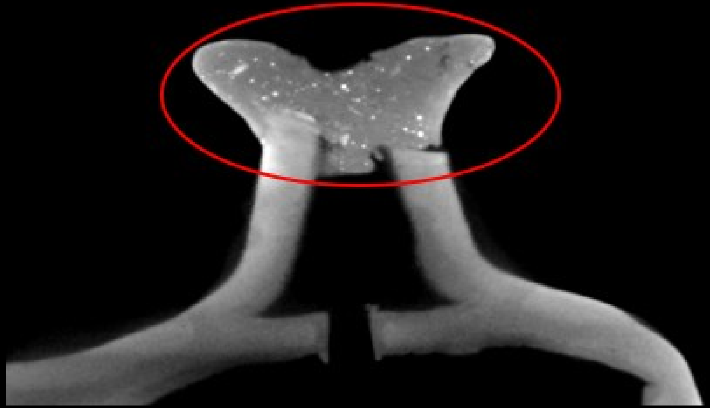
CT analysis on-site

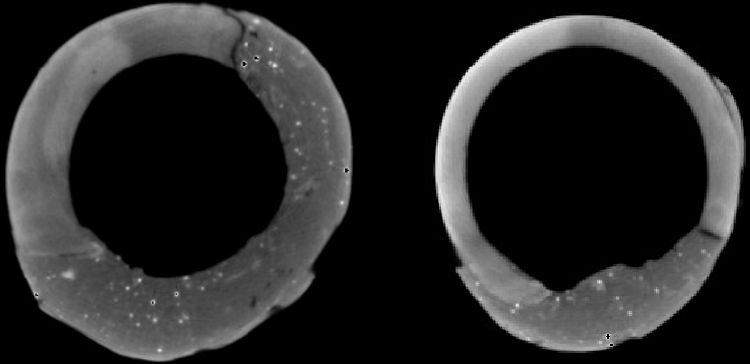






CT analysis on-site





Axial slices

CT analysis on-site

CT analysis on-site

Polychrome glass alabastron

Examples of case-studies

CT analysis of large artefacts

The Coronelli's celestial globe at Marciana Library

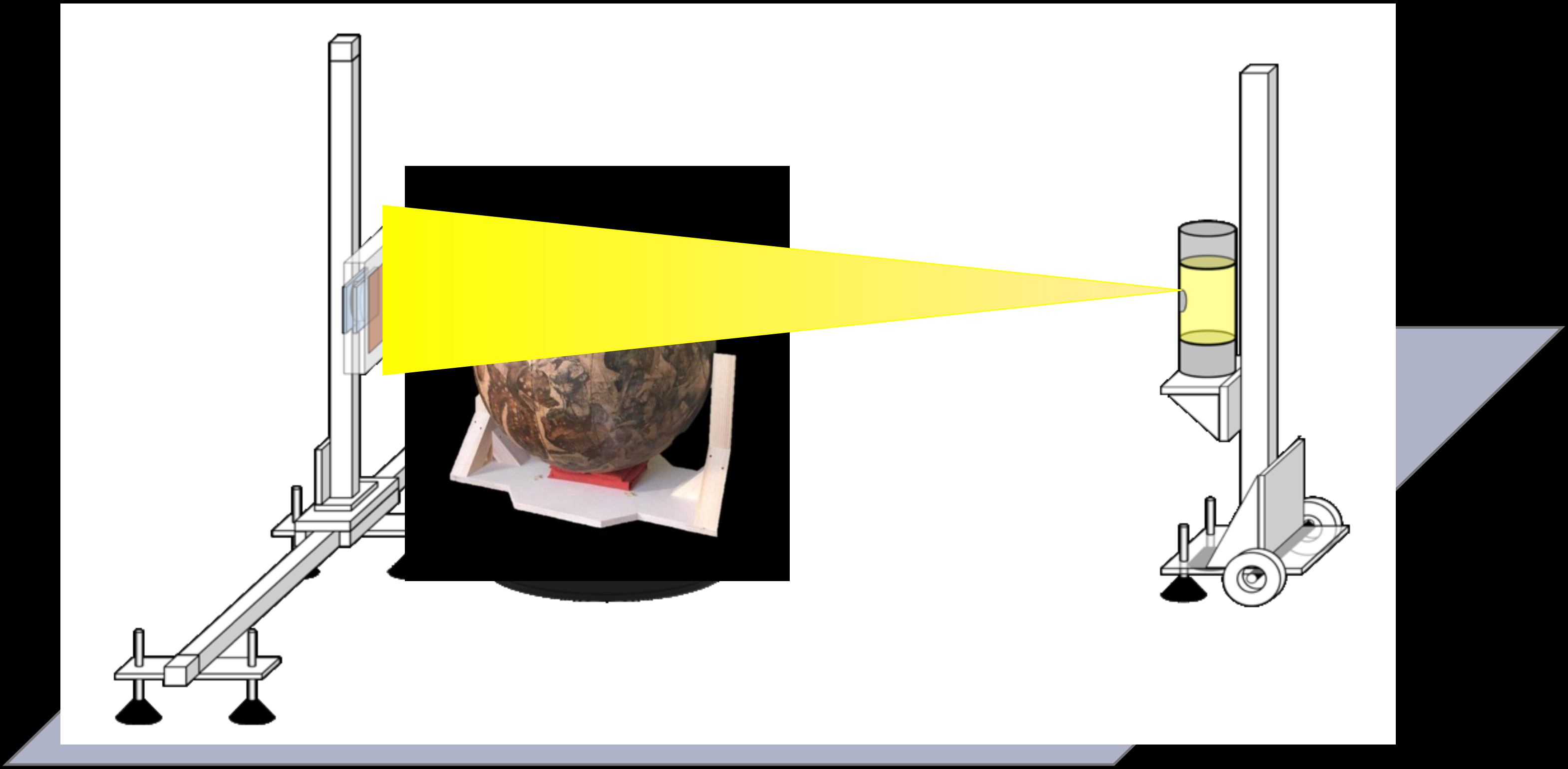
Vincenzo Coronelli
(1650-1718)

Pair of terrestrial and celestial globes by Coronelli
Marciana National Library (Venice)

Transfer of the CT system on site

Marciana National Library in Venice

On-site experimental set-up



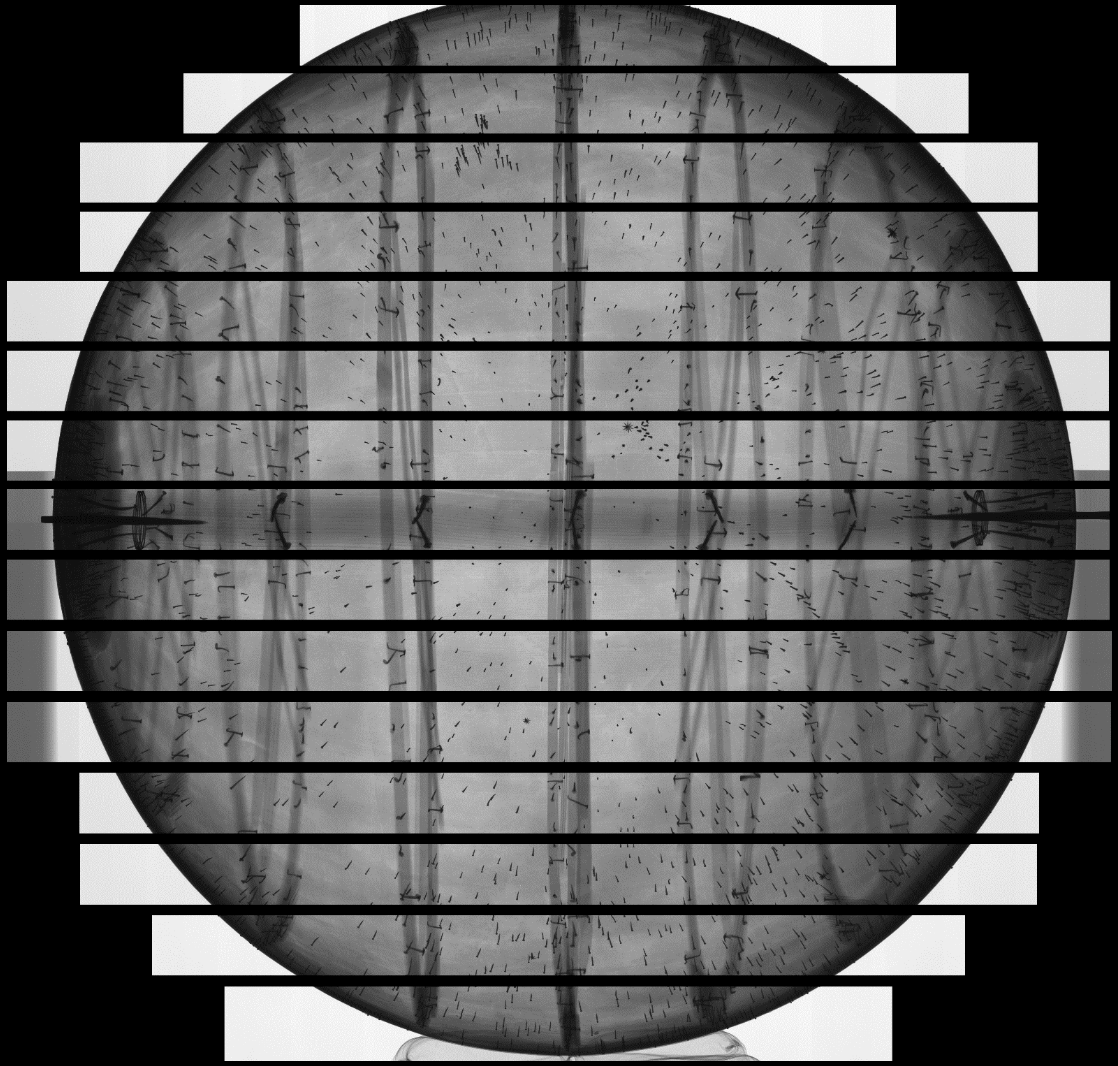
Flat Panel Detector

C10900D – Hamamatsu –
- Solid State Detector + CsI:TI scintillator
- 12 x 12 cm^2
- 100 μm pixel

X-Ray Tube

SMART EVO 200 D – Yxlon –
- 50-200 kV
- 0.5 – 6 mA
- 1 mm focal spot

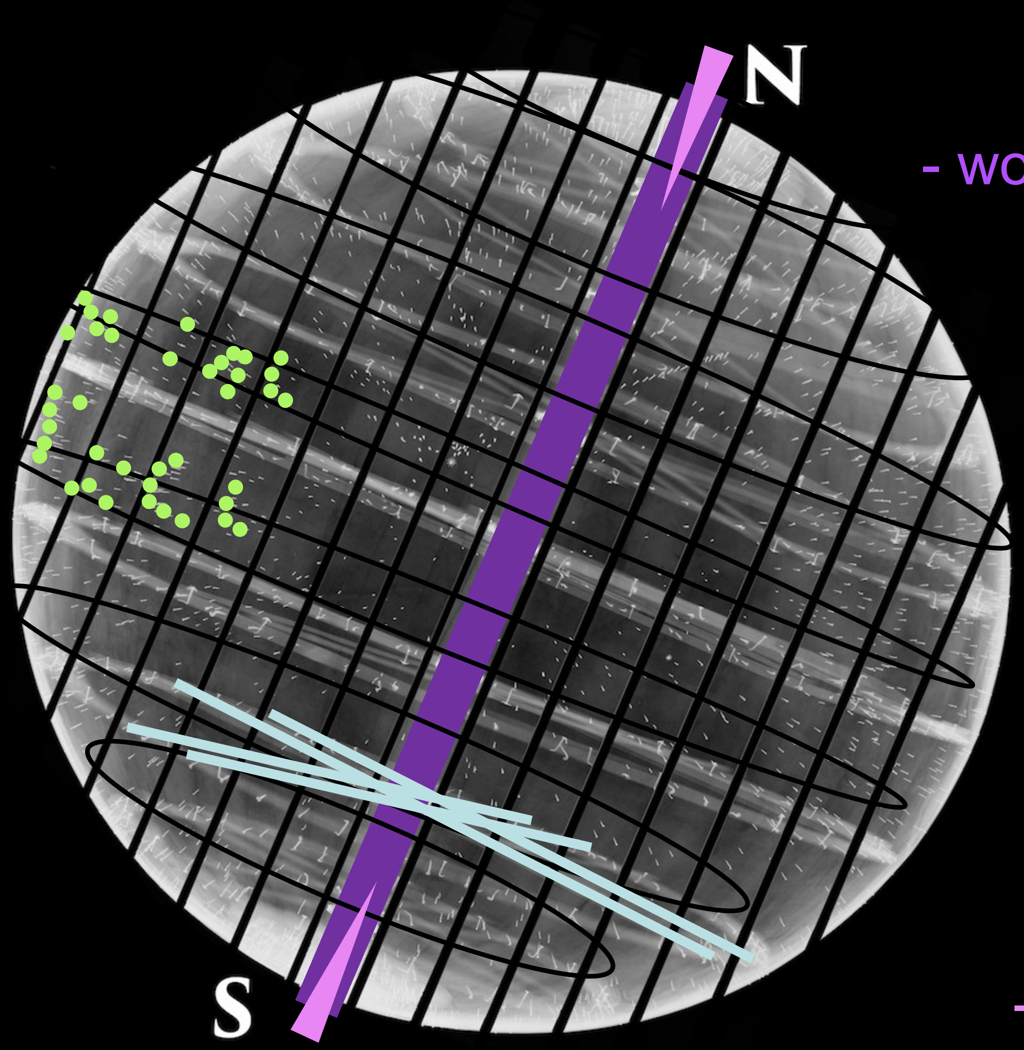
CT analysis of the globe



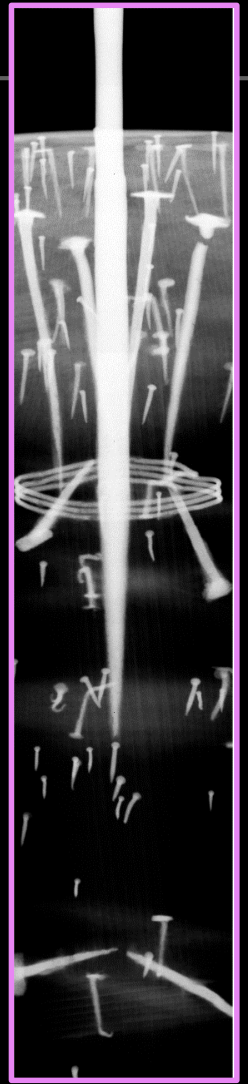
Tile scanning

- ≈ 200 detector positions
- 3 minutes for each one
- 10 hours
- 180000 partial radiographs

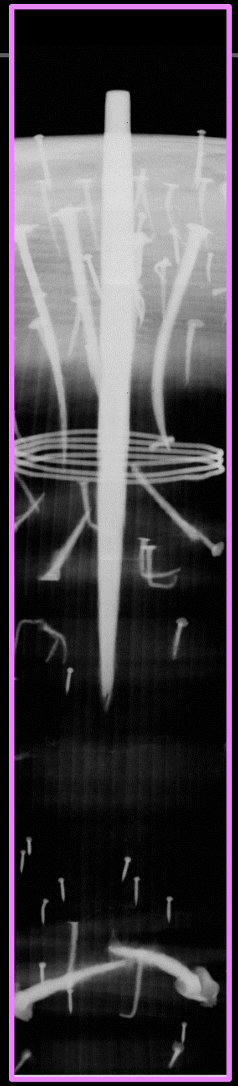
Results of the CT analysis



- wooden polar axis
- 7 internal circles
- 7 groups of 4 perpendicular wooden boards
- Metal nails
- 2 polar pivots

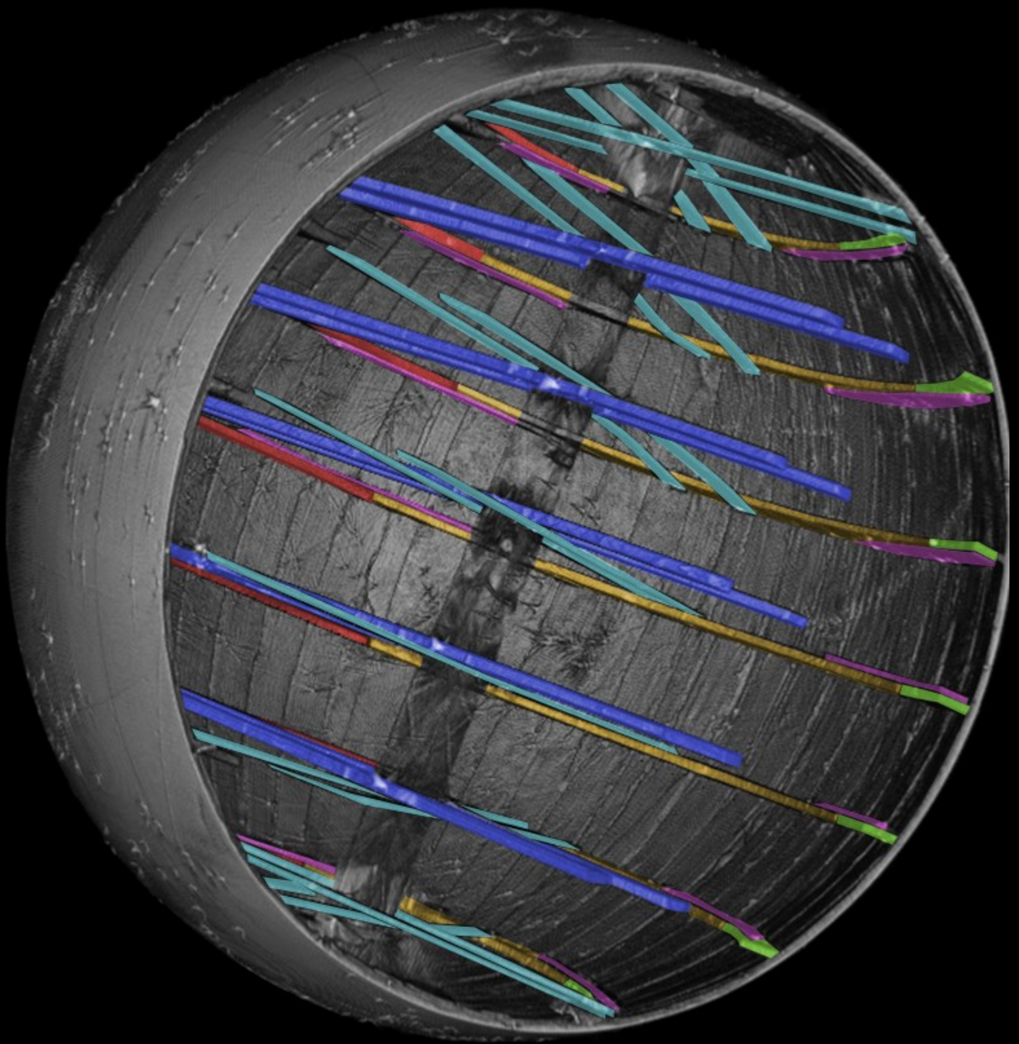


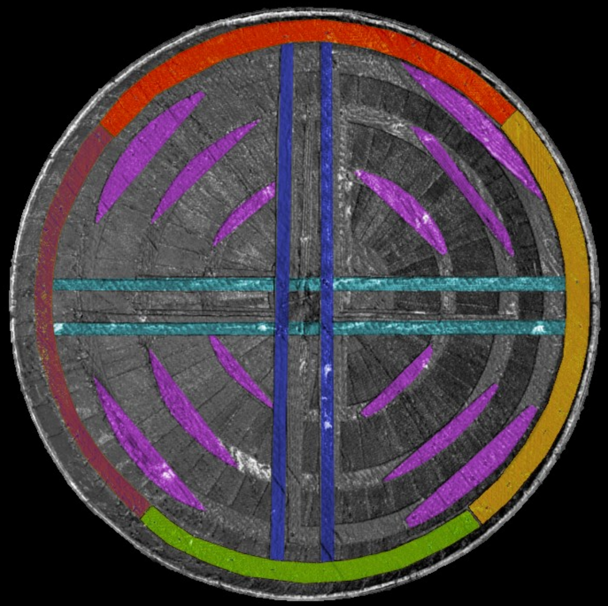
North Pole



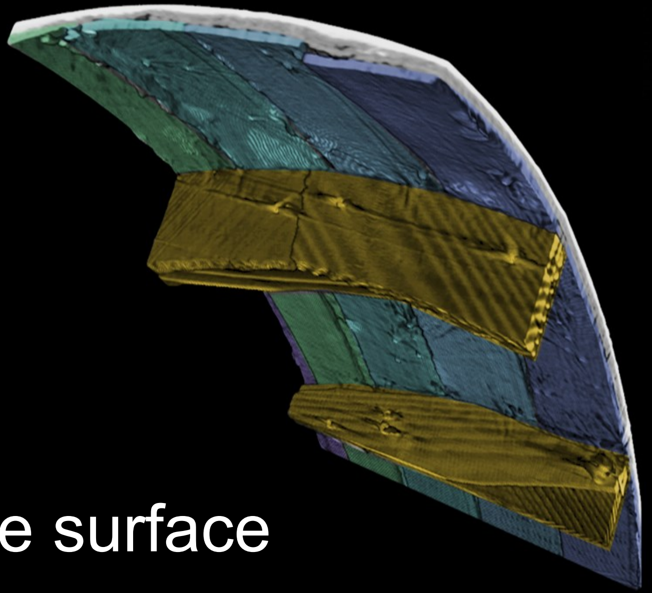
South Pole

Structural elements of the globe





Elements of the inner structure



Wooden elements on the surface

The African wooden statue at Pigorini Museum

African wooden statue kept at the *Luigi Pigorini Museum of Prehistory and Ethnography* in Rome.

It represents an anthropomorphic idol believed to have magical power.

It is carved from a single piece of wood and has a lot of metal nails in the torso for a votive function.

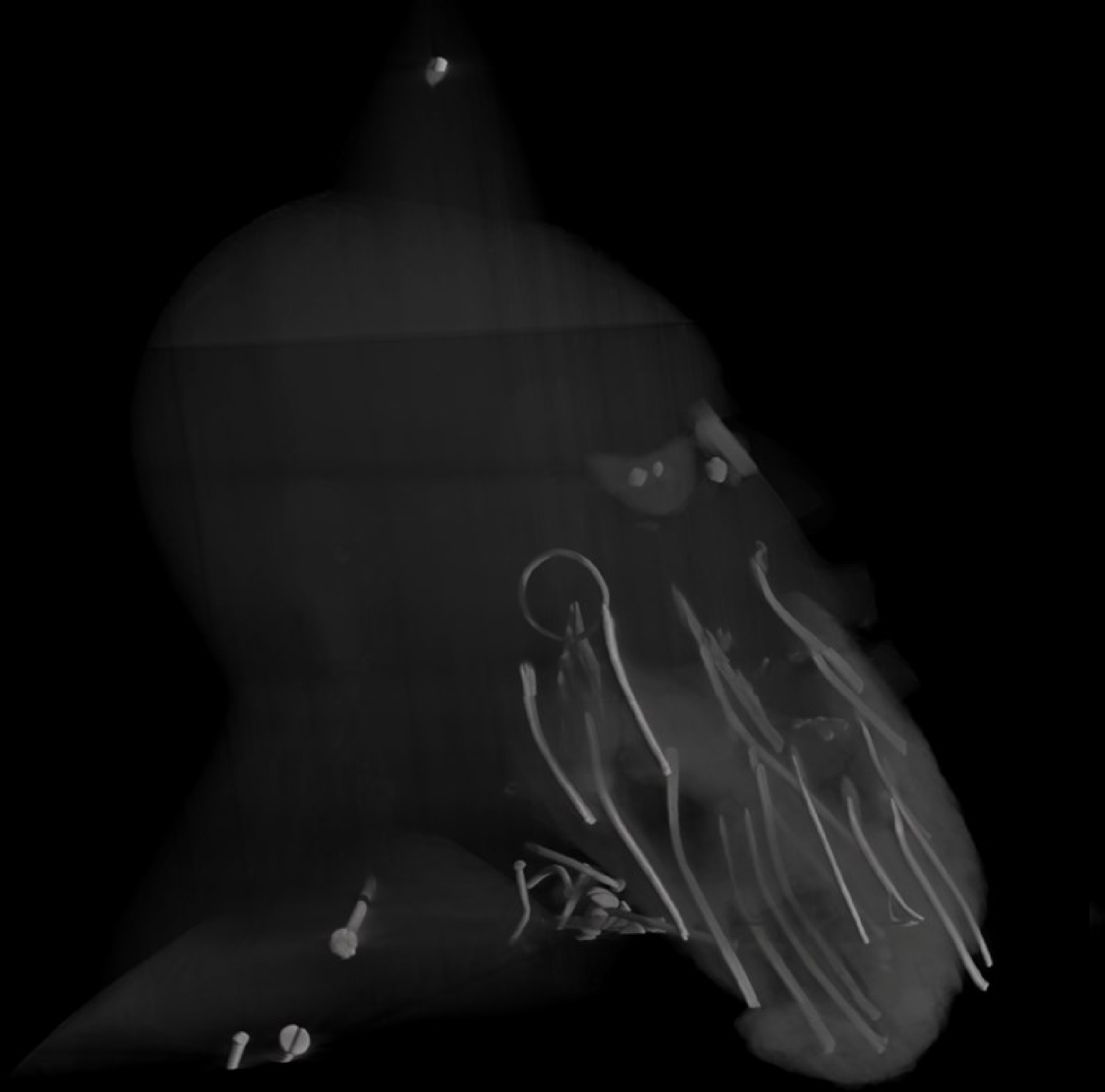
Height: 120 cm
Second half of the 19th century

The African wooden statue at Pigorini Museum

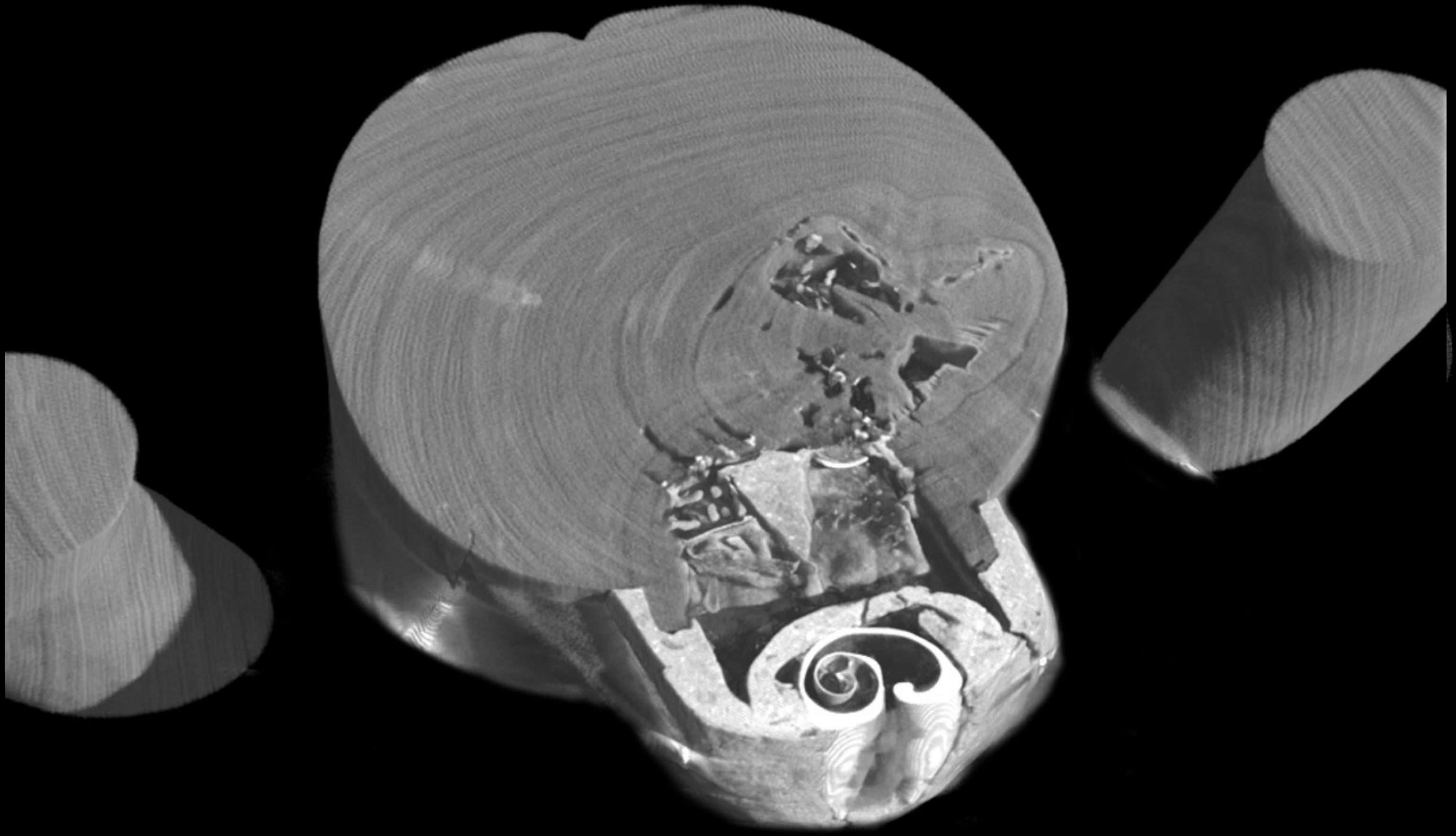
In 2014 the *Metropolitan Museum* of New York asked the Pigorini Museum for the loan of this statue for an exhibition on African Art.

Conservators at the Pigorini Museum were concerned about some parts of the statue they considered fragile and critical, thus potentially subject to fracture and detachment especially during trasport from Rome to New York.

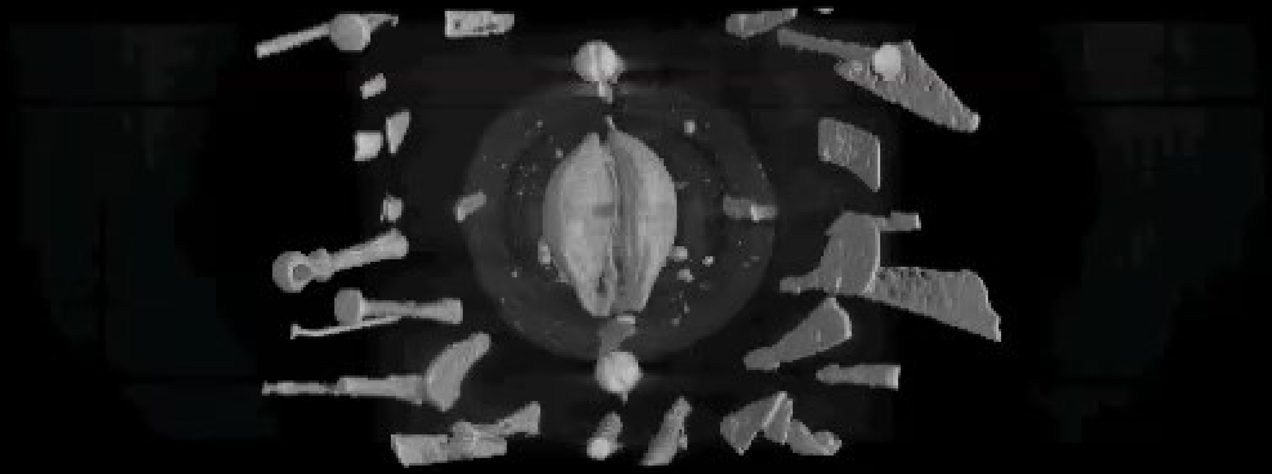
Details of the beard and of the so-called power-pocket in the abdomen of the statue: it consists of a bolus supporting a large shell and hiding an inner cavity with magical objects (herbs, stones, shells, etc.).
They have been shaped with a moldable material consisting of an oleo-resin mixed with kaolin, quartz and vegetable matter.



A double line of metal pins deeply embedded into the wood offers firm support for the beard.

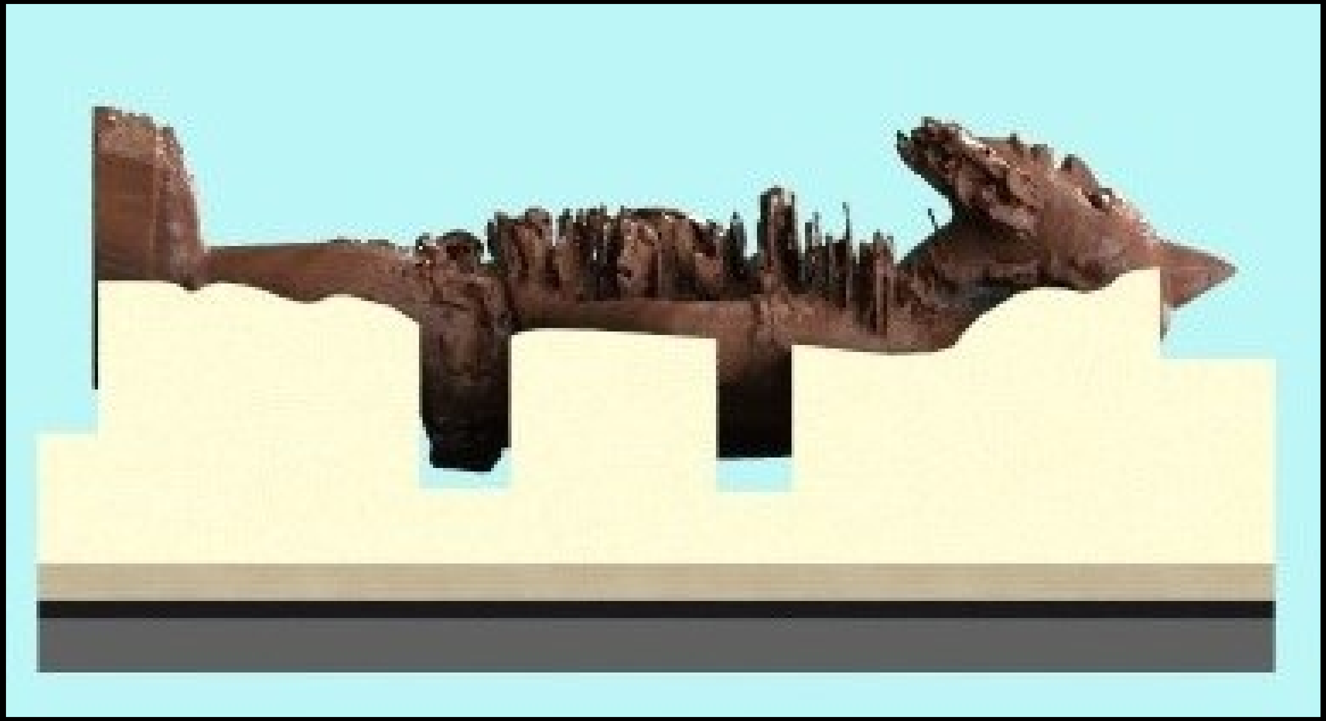


Axial section of the abdomen showing the inner cavity behind the bolus.



Four metal pins enclose the bolus of the so-called «power pocket».

A polygon mesh of the surface obtained from the 3D volume allowed the scientists at the Metropolitan Museum of Art to design and build a custom-made crate with a molded interior for the safe transportation of the statue.



The terrestrial globe by Egnazio Danti

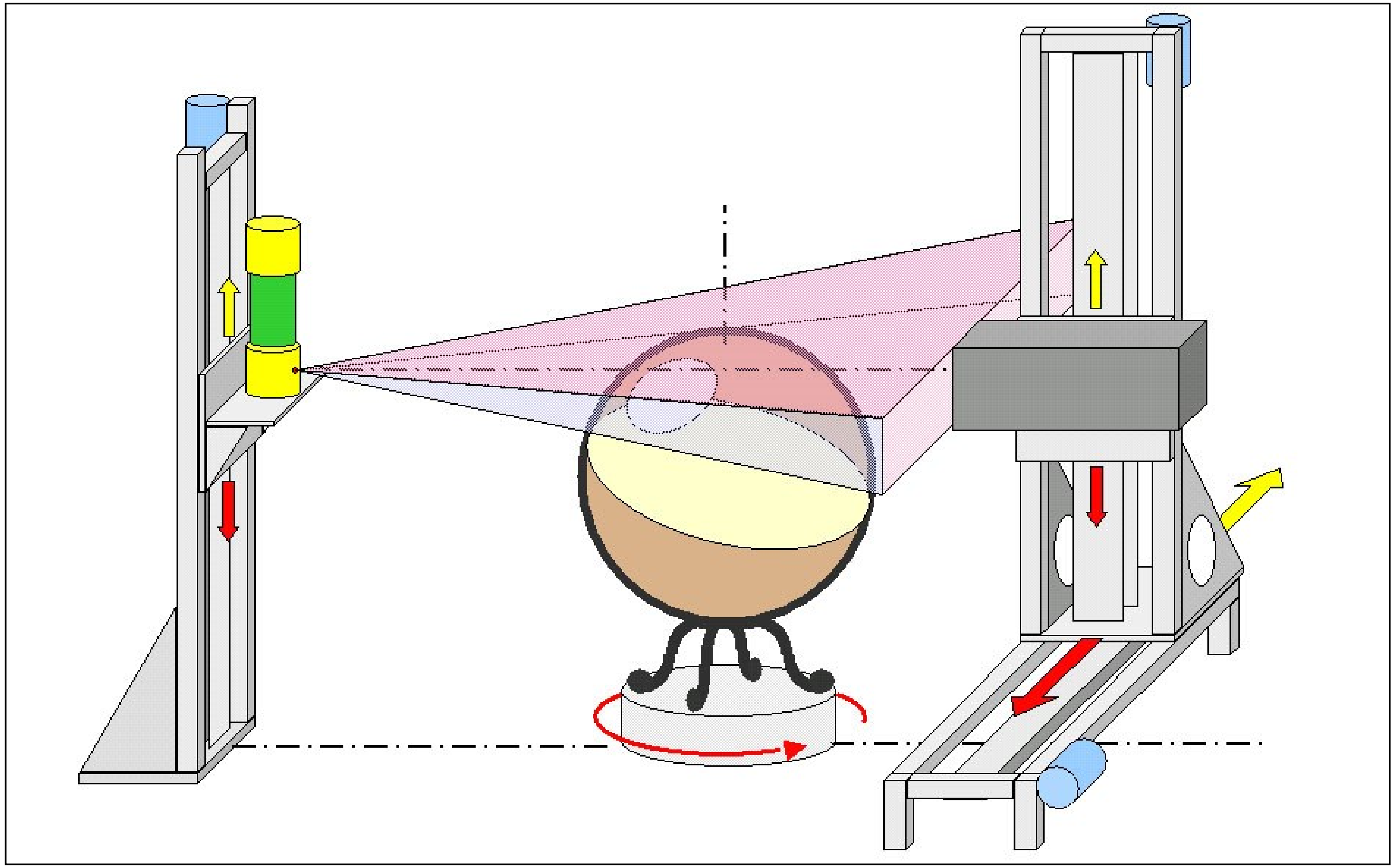
X-ray Computed Tomography of the ancient globe by Egnazio Danti at Palazzo Vecchio – Florence (2004)

The Municipality of Florence decided to set up an important diagnostic campaign for this masterpiece. Besides the cleaning of the surface, which had become brown, the project also involved an exploration of the nature and condition of its inner structure. It was therefore decided to perform a CT scan.

The terrestrial globe by Egnazio Danti

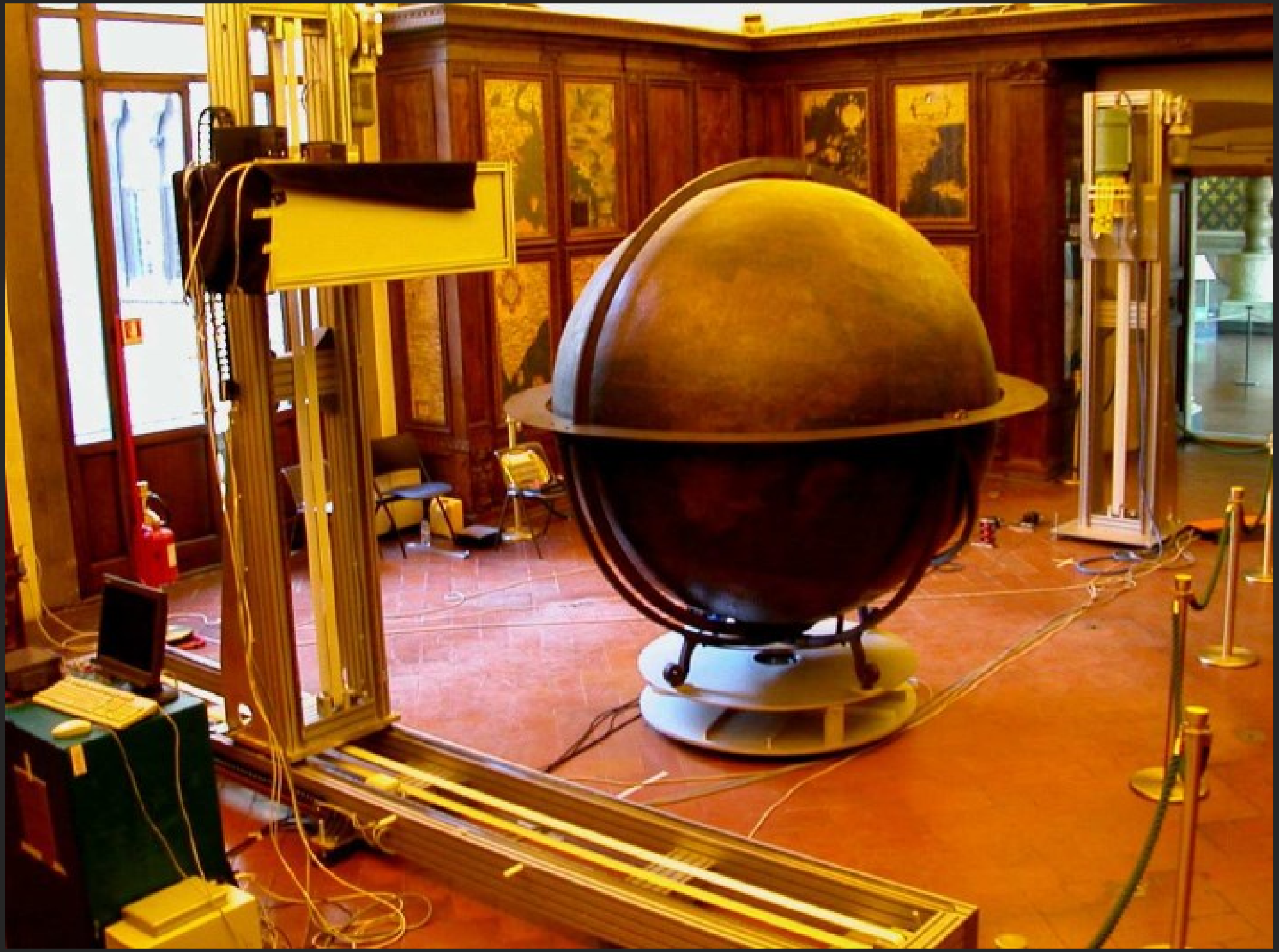
The Map room ("Sala delle Carte geografiche") within Palazzo Vecchio, with the ancient large globe created by Egnazio Danti around 1567, on assignment of Cosimo I de' Medici, duke of Florence.

The experimental set-up



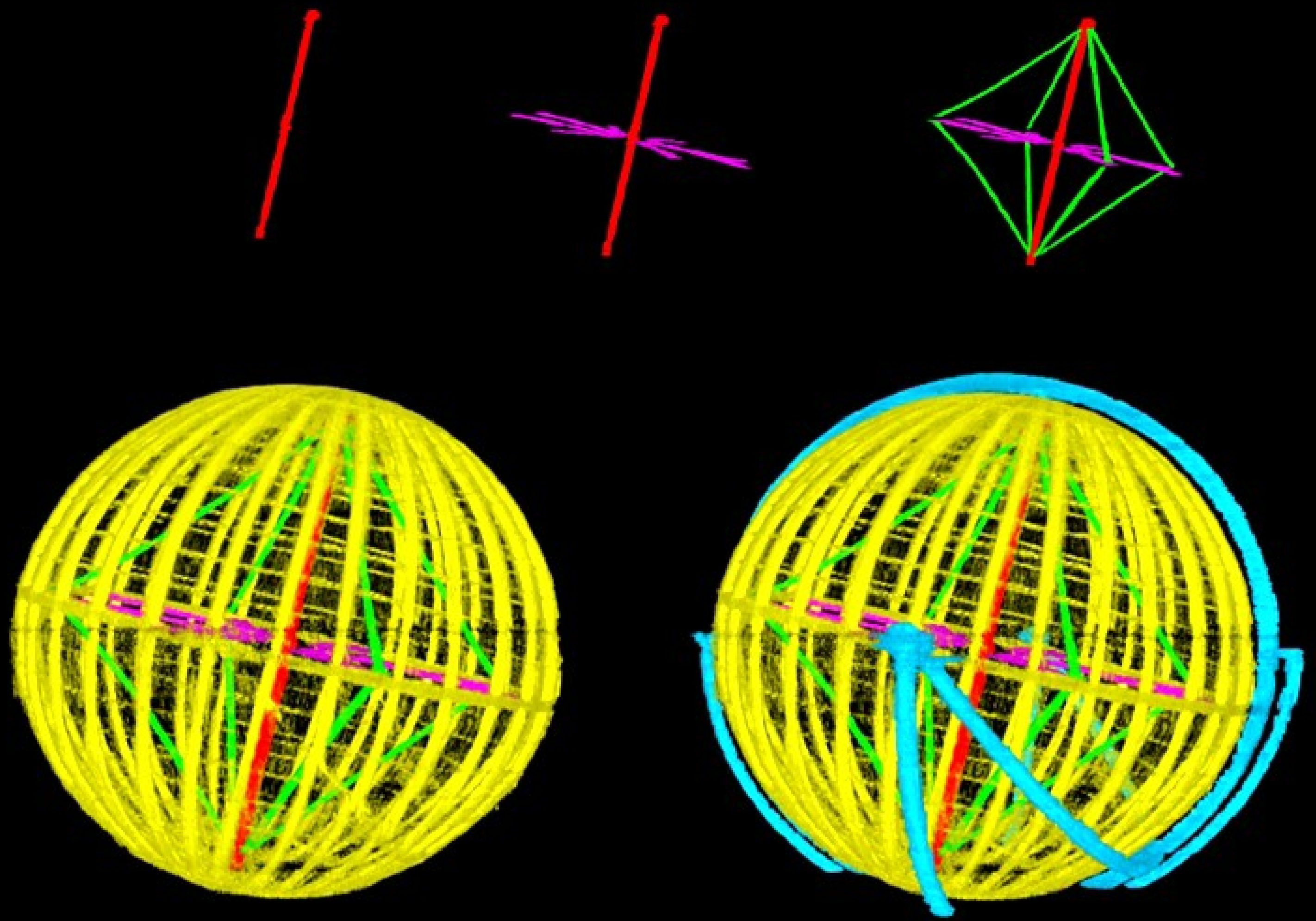
On the left: the X-ray tube; in the middle: the globe on the turntable; on the right: the detector and the translation axes (31000 radiographs).

The terrestrial globe by Egnazio Danti

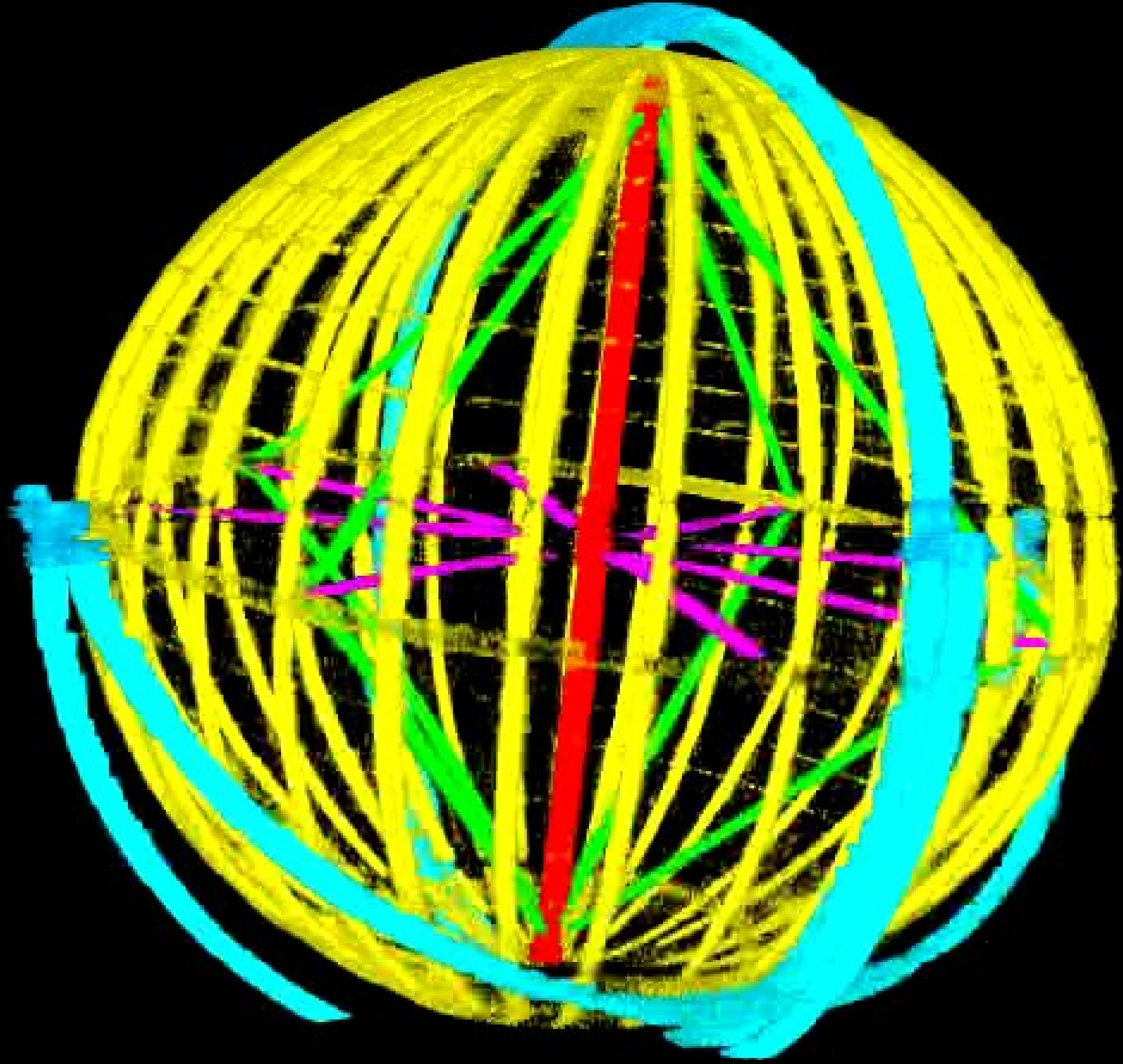


Picture of the experimental set-up: the detector on the moving axes on the left, the globe on the rotating platform in the middle, and the tube on the vertical moving axis on the right.

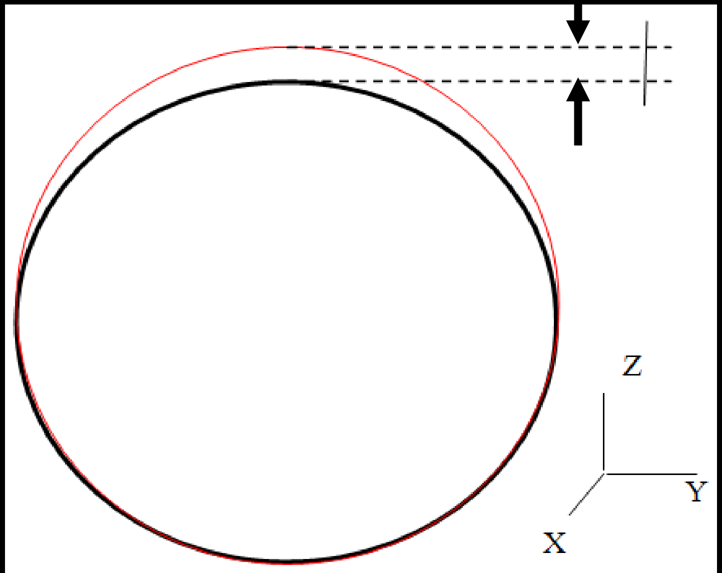
The terrestrial globe by Egnazio Danti



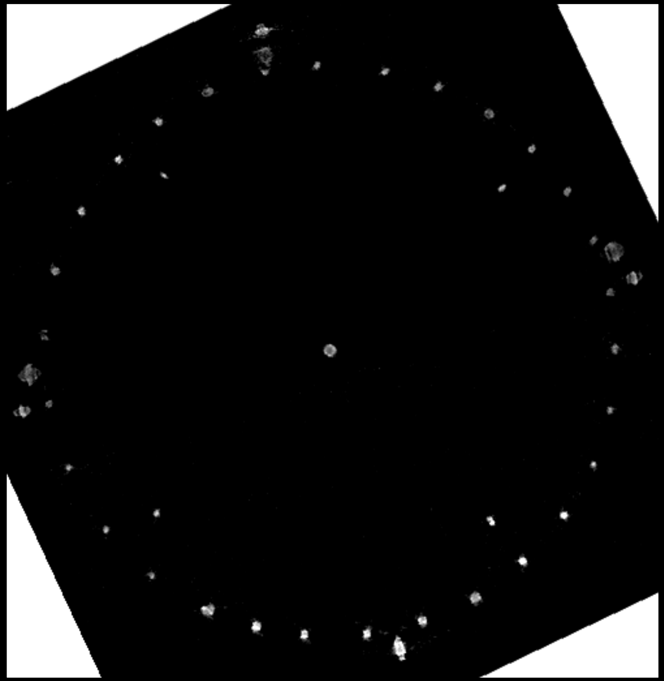
Rendering of the 3D volume obtained by the CT reconstruction. It is clearly possible to see the entire inner structure, consisting of a central axis, 8 equatorial bars, 8 bars as 2 tetrahedrons and 30 meridians.



The terrestrial globe by Egnazio Danti

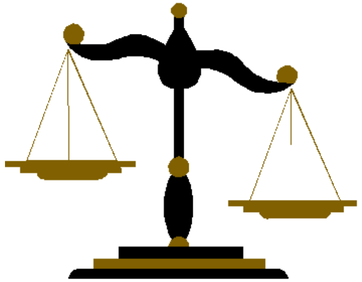


The globe is no more a perfect sphere; it collapsed about 10 cm



30 meridians, each 12° far

The globe is made mainly by iron



Calculated weight of iron:

TOTAL: ~608 Kg

INTERNAL: ~350 Kg

Conclusions

- CT is a versatile technique that can be applied to a variety of objects of different size and made of different materials.
- The availability of mobile CT systems expands the number of case studies in which tomography can be applied.
- Moreover, it gives us the possibility to work in close contact with restorers and conservators in the place where archaeological findings and works of art are located.

Thank you for your attention!

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