X-Ray Fluorescence Imaging of the Archimedes Palimpsest:

A Technical Summary

By Uwe Bergmann

Introduction

Almost 100 years ago a big literary find in Constantinople made headlines around the world [1]. The Danish philologist Johan Ludvig Heiberg had found a 13th century Byzantine parchment prayer book that, underneath the Euchologion text, revealed copies of Archimedes' works. This famous book, known as the Archimedes Palimpsest (AP), contains Greek versions of seven texts of Archimedes copied by an unknown writer in the 10th century using iron gall ink.

Figure 1

Photos of the Archimedes Palimpsest Right: View of the Palimpsest with the Archimedes text is in the horizontal. Also shown is one of his drawings. (Christie's Images Ltd 1998)

Heiberg had discovered not only the oldest surviving manuscript containing the work of Archimedes, but a previously unknown treatise by the ancient mathematician, the missing text of ***The Method of Mechanical Theorems***. In this text Archimedes describes the use of mechanical methods to cope with infinity when determining e.g. the volume of various objects. After World War I, the AP disappeared until it resurfaced in Paris in the 1990s. In the early 20th century four of the folios, including the second page of the introduction to ***The Method*** had been over painted with gold forgeries. The AP was auctioned in 1998 and is currently on loan from the private owner at the Walters Art Museum in Baltimore. Here it is the subject of an integrated campaign of conservation, imaging, and scholarship, a project that has received extensive press coverage over the last several years including the award winning TV show "Infinite Secrets" on NOVA and BBC's flagship science program "Horizon", articles in the Washington Post, The London Times, The London Sunday Times, and the New York Times. It was found that Heiberg's understanding of e.g. ***The Method*** is incomplete and, in some cases wrong. This is partly because he was working from an incomplete set of photographs, partly because he was working with an unbound manuscript in which much of the Archimedes text was hidden, and partly because he could not use advanced imaging techniques available today. In the past years large fractions of the AP were successfully imaged using various optical techniques including magnetic resonance, confocal microscopy, and most importantly multi-spectral imaging. But even today, significant gaps remain in our knowledge of the text of Archimedes, while texts by other authors - potentially of major significance - remain yet unread. It is clear now that the optical techniques are not able to recover these missing parts. Some of the text is too faint and some is covered by the forgeries, mold stains, glue or other writings.

X-ray Fluorescence Imaging

X-rays in the multi keV range can penetrate such obstacles to reach the covered iron ink. However, small amounts of ink make it practically impossible to obtain sufficient contrast in a transmission image as used e.g. in a dental or chest x-ray, and a much better signal to noise ratio is obtained by measuring the x-ray fluorescence (XRF). This advantage has been used for a long time in both x-ray absorption spectroscopy and x-ray imaging. In XRF the incident x-ray energy is tuned above the threshold to remove an inner shell electron (7.1 keV for the Fe 1s electron) and the fluorescence radiation following the decay of the core hole is recorded with an energy sensitive e.g. Ge detector (6.4 keV for Fe Kα). To obtain an XRF image of a particular element, the object is raster scanned with a small x-ray beam and the corresponding fluorescence intensity is recorded at each point where the beam strikes the object (see Figure 2). We will use this method to image the missing text of the AP. The practical difficulty of XRF imaging is that the 2-dimensional point by point raster scan of a large area can be very time consuming. For example, a 14 cm * 17 cm folio of the AP imaged with 600 dpi (dots per inch) resolution contains ~ 1.3 * 10^7 dots, and 600 dpi is a lower resolution standard for imaging hand written text of the size contained in the AP. An exposure time of 10 milliseconds per dot corresponds to a scanning time of more than 36 hours per page, not including overhead times from readout and at the end of each line.

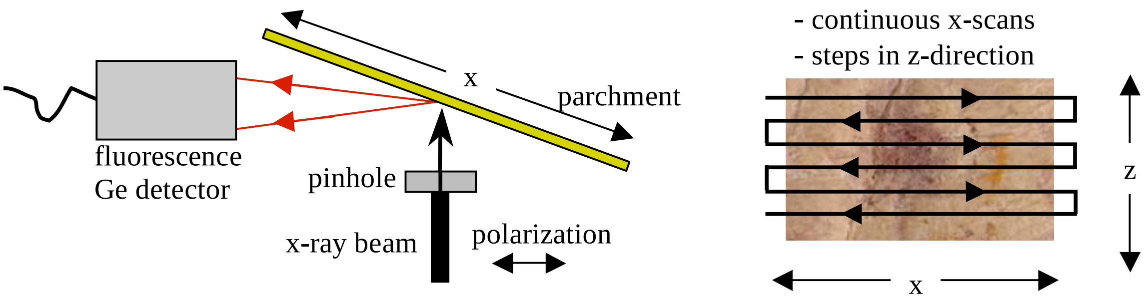

Figure 2 Schematic experimental setup. Left: Top view. The pinhole close to the palimpsest and an upstream collimating slit (not shown) ensure the well defined beam at sample. Right: front view showing the scanning procedure. At the end of each x line, a pneumatic shutter is inserted to protect the parchment.

It is thus obvious that efficient and effective XRF imaging of large areas such as a palimpsest folio requires a) a very intense x-ray beam to obtain a fluorescence signal with sufficient statistics in a short time, and b) a procedure where the data are read "on the fly" in order to avoid overhead time. A synchrotron based x-ray beam is ideally suited to perform such work. Besides the large flux it can be collimated and it is tunable and polarized. For our initial work we have used the SSRL wiggler beamline 6-2 operating with a collimating mirror followed by a multilayer monochromator (10^{-2} resolution) and a torroidal focusing mirror. This is currently the most intense source at SSRL in this energy range. The initial work showed that the XRF technique adds unique new capabilities to read this important document. In fact, we were able to, e.g., unveil text from underneath the forgeries (see Fig.2). The work has already received an enormous interest and has been extensively covered in the press and media [2].

In this setup at beamline 6-2 the maximal 8 keV flux through a 50 μm diameter pinhole is ~ 3*10^{11} photons/sec (cps) at 100 mA ring current. In order to obtain good collimation an upstream slit was inserted 35 cm in front of the 50 μm diameter pinhole which was ~ 3.5 cm in front of the AP (see Fig xx). Collimation is particularly important for pages that are undulated, because during the scan, they are not at a constant distance to the pinhole.

To ensure that the intense x-ray beam does not damage the AP we performed tests on a 19th century parchment. Collagen fibers extracted from the x-ray exposed parchment were tested at the Canadian Conservation Institute in Ottawa. A dose corresponding to 10^{10} photons (8 keV) per 50 μm diameter beam size was determined as safe. During our initial imaging the x-ray intensity was selected around 2 * 10^{10} cps and the parchment was scanned with a speed corresponding to an exposure time of 12.7 ms per 40 μm. Hence, the dose on the parchment was ~ 40 times less than the safe dose. At the end of each line and during the time to move up to the next line a pneumatic shutter was inserted to block the beam. This procedure ensures that the parchment is only exposed when moving. A 13-element germanium detector (Canberra) placed along the polarization of the incident x-rays (to minimize scattering) is used to record the Fe Kα fluorescence. The gated Fe signals (0.125 μsec amplifier shaping time) from all 13 channels were added in a fan in multiplexer and fed into the hex scale counter. Typical Fe Kα count rates were 2-5 * 10^4 cps background (probably from the Fe distributed over the parchment when the Archimedes text was partly erased) to ~1-5 * 10^5 cps on the writings up to 1.4* 10^6 cps on some parts of the forgeries that contain Fe paint on folio 81R. (The incident x-ray intensity was adjusted in order to keep the Ge detector from saturating.) Data for each pixel were recorded on the fly every 10 ms with an additional dead time for readout of 2.7 ms. The typical image size was 20 * 40 mm^2, and images were then patched together. Considering the overlap of adjacent images and the time per pixel, this amounts to a time of ~ 30 hours to image half of a folio from one side. Figure 3 shows a photo of folio 81R and the iron x-ray map of part of the folio. Clearly, text not visible on the photo can be seen on the x-ray image. This text is currently being deciphered by Reviel Netz.

Figure 3 Left: photo of folio 81R of the Archimedes Palimpsest. The gold painting of the evangelist is a 20th century forgery. Right: Grey scale XRF image of the iron Kα signal of the lower left part of folio 81R. Archimedes text is horizontal, Euchologion text vertical.

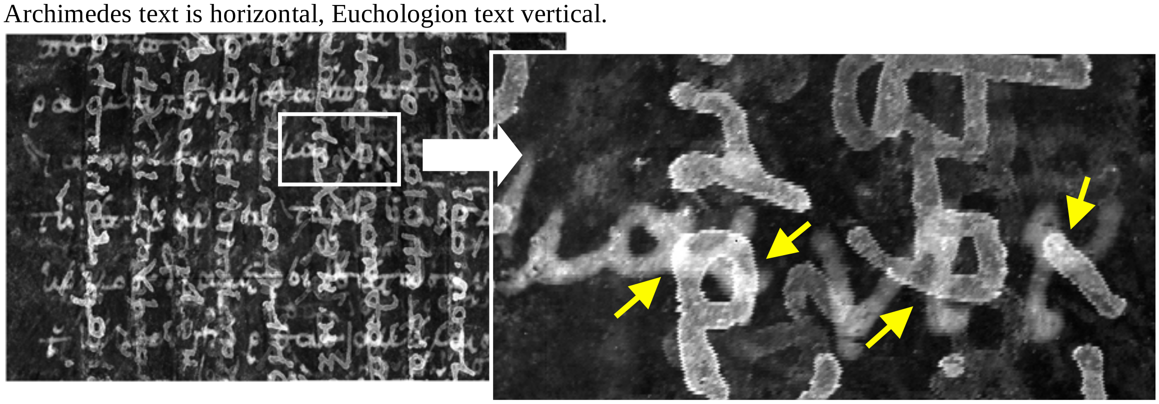

Figure 4 Left: Fe Ka XRF image of part of folio 163V. Right: Magnification of the area inside the box. Yellow arrows indicate examples of areas with overlapping texts.

Besides uncovering text underneath the four pages that contain the forgeries, we also propose to image Archimedes text under various other obstructions including grime and wax accrued over centuries. Critical is the first folio of the Palimpsest. Netz has identified this as a unique and previously unrecognized page of *On Floating Bodies* in Greek, but he has made very little headway using the optical images that have been made so far.

Another example of using XRF to potentially facilitate the reading of Archimedes text is shown in Figure 4. Here the Fe Kα XRF image of an excerpt of folio 163V is shown (the grey scale is inversed compared to the previous image). The Euchologion text is again shown in the vertical and the Archimedes text in the horizontal. On the right of the figure, which shows a magnified portion of the x-ray image, it can be seen that in the overlapping areas of the text the fluorescence signals of both writings add up, producing a stronger XRF signal. Hence, one can see whether there are Archimedes characters or fractions thereof underneath the Euchologion text or not. This is generally not possible with imaging methods relying on visible and UV light where the top layer of text is often opaque.

The XRF method also adds a complication to the imaging. Because the x-rays penetrate through the parchment, writings on both sides of each folio are imaged. Therefore up to four texts can overlap in the iron map, making the reading more difficult. We have addressed this problem by making use of the different intensities from text of front versus back. An algorithm devised by Keith Knox of the Boeing Corporation, which takes advantage of the difference in contrast between images taken from the front and back of the same area of a leaf, can distinguish the two sides and makes it possible to display both sides in different false colors. Figure 5 shows an example of a small excerpt of folio 163V.

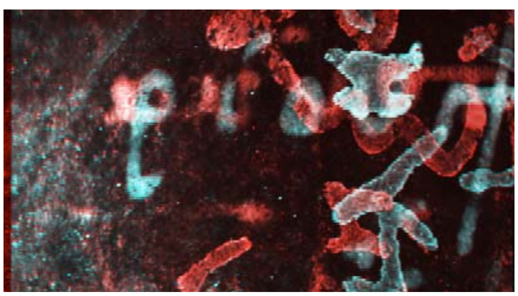

Figure 5

False color x-ray image from folio 163V. Writings on the front side are displayed in cyan, whereas writings on the backside (i.e. on folio 163R) are displayed in red.

We are currently also working on a way to distinguish the Euchologion from the Archimedes text. We know that potassium and sulfur are present in the Euchologion ink but not in the Archimedes ink. This might help us to subtract the unwanted text when imaging the Archimedes writings. Approximately 20% of the potassium Kα fluorescence (3.3 keV) will penetrate the ~ 8 cm distance of air between parchment and detector. Sulfur is another possible candidate, but it would require a different sample environment. We are currently contemplating such a setup.

Finally, it should be pointed is out that the AP contains other works besides those of Archimedes. There is an unknown text on folio 80 that is not written with Fe gall ink, and there are five leaves containing text by Hypereides (c. 390-322 BC). Hyperides was a fourth century B.C. orator, and a friend of Demosthenes. Scraps of his important work are found on papyri, but this is a new and major find. It is the only example of Hyperides work that has been discovered in a manuscript book. We will investigate if XRF can be helpful to uncover some of these writings. In summary, we think that proposed work will make an important contribution to a better understanding of one of the greatest minds of all times. It can also have a significant impact on the ability of reading obstructed and damaged documents throughout the history of mankind.

Time line of proposed research

The Walters Art Museum has a stringent time line to finish the imaging and conservation by mid 2007. Shortly thereafter the complete text of the AP will be made available to the public, and there will be an exhibition of the results and the imaging program. We are currently working on a different readout system with which we should be able to reduce the scanning time to ~ 12 hours (compared to the currently 30 hours) for half of a folio or, correspondingly, 48 hours for a folio imaged from both sides. These estimates use a resolution of ~40 μm corresponding to 600 dpi (dots per inch). We possibly want to image some fractions of the text at 1200 dpi resolution which will take four times longer. This depends on the particular part of writings to be imaged. In order to accomplish the XRF imaging on the AP We plan to image the following folios:

Folios 21r, 57r, 64v, 81r

Folios 135/138, 144/5, 173/6, 174/5 (Hypereides text)

Folios 73/80, 120/121 unknown text

Folios 1/2, 157/60, 158/9 and small, critical, areas of 17v, 28r, 50r, 56v, 87r, 105r, 127r, 130v, 163r, 165, 166, 172-177 (unreadable text due to faintness, obstruction, mold, others)

Some of the text e.g. folios 73/80 will require longer imaging times in order to acquire sufficient statistics. We estimate a factor 3-5 slower imaging speed for these parts. In addition we estimate approximately 6-9 shifts per beam time for setup, R&D (e.g. looking for different elements to image) and unexpected problems. Considering these parameters we expect that approximately three 10 day imaging sessions per year will be required. Beamline 6-2 is best suited for the work because the multi-layer can provide the highest flux density at SSRL in the 6-10 keV range. Furthermore the beamline is specialized to do lower energy work such as potassium and possibly sulfur.

Resources

Uwe Bergmann and Martin George as well as the other SSRL and SLAC staff and equipment involved in the proposal are funded through SSRL core funds from the DOE, Office of Basic Energy Sciences.

The manuscript is privately owned, and the project on the palimpsest privately funded. Enough funding has been secured by the project director to bring the manuscript and the necessary people with the required skills to image the manuscript at the beamline.

References:

1) e.g. New York Times, July 16th 1907
2) e.g. Nature, 435, 257, (2005), news@nature 05/18/2005, Associated Press 05/21/2005. TV: CNN, ABC Channel 7, NBC Channel 11. Radio: ‘The naked scientists’ BBC, Radio Free Europe 05/18/05, Deutsche Welle, Greece.