Sapienza University of Rome

ARCHMAT

(ERASMUS MUNDUS MASTER IN ARCHaeological MATerials Science)

Multi-Analysis of the Wood Painting "Polyptych of the Virgin"

by Antonio Vivarini and Stefano da Sant'Agnese

in Church of San Zaccaria

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Contents

1. Introduction

The Polyptych of the Virgin studied by this thesis, is composed of five tempera paintings. They're painted by two different artists, Antonio Vivarini and Stefano da Sant'Agnese. Currently, this Polyptych of the Virgin has been commissioned by ICR for restoration.

In so far, there have been no attempts to analyze this "Polyptych of the Virgin." Therefore, the scientific results can help understand the artist's techniques and the material used to understand the paintings better.

In this thesis, the objects will be studied mainly by image analysis (IR\UV\radiographic) and in-situ XRF analytical. Specifically, the following questions were asked:

1. Draft drawings or modifications in these five wooden paintings.
2. Interventions of paintings in the past.
3. The chemical composition of some pigments used in these paintings.

In this type of research, a complete IR image needs to be stitched together from multiple partial images, usually done manually. On the one hand, this approach should minimize the number of partial photos, which will reduce the fineness of the photos to a certain extent; On the other hand, it is extremely time-consuming. A major challenge in this experiment is that we need to collect IR images of five paintings, which will involve a large number of partial pictures. Manually stitching pictures is almost hard to do. So, this research will try to find a suitable method of automatically stitching IR images. In order to improve the resolution of the image, show as many details as possible, and improve work efficiency at the same time.

The focus of this research is not only to improve the scientific information of this object, it is also essential to provide more effective information for the work of the restorers and by understanding the needs of the restoration process, carrying out targeted testing, and integrating scientific analysis for restoration, instead of just providing scientific data.

This research is carried out simultaneously with the restoration work, which could provide a significant opportunity to establish a close connection between restoration work and scientific analysis to use the information and technology held by both parties effectively.

2. Materials and Methodology

2.1.   Materials

2.1.1.   Church of San Zaccaria

Church of San Zaccaria is located in central Venice. "It was originally a monastery built in the 7th century, established by St Magnus. Rebuilt in 811 during the reign of Doge Angelo's participation, it was completed in 829. In the same year, the body of St.Mark was brought to the lagoon's new capital."(Aikéma, 2000)

The monastery went through a major fire in 1106, and reconstruction began in the same year.

From 1456 to1458 the construction of the second church began from scratch, adjacent to the pre-existing church, just renovated and decorated: today's church of San Zaccaria, Antonio Gambello was the original architect, the design of the church they were completed by Mauro Codussi in early Renaissance style many years later.
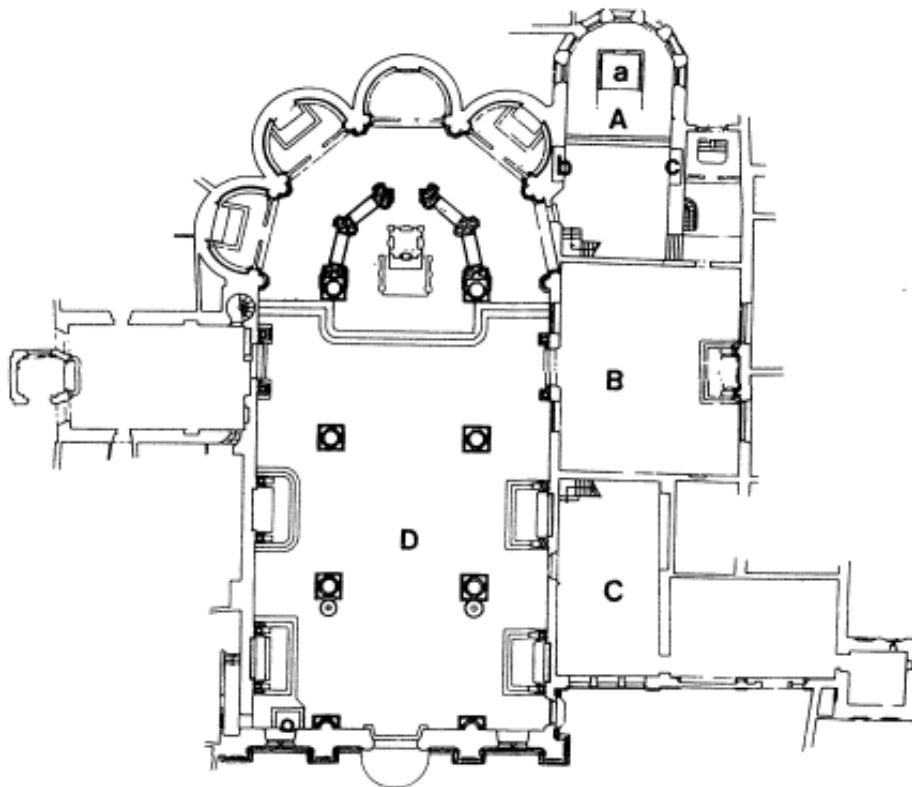

Fig. 1 Plan of the Church of San Zaccaria, Venice. (A=Chapel of San Tarasio [former chancel of nuns' church], B=Chapel of Sant'Atanasio [   ], C=end of original nave of nuns' church, D=present church of San Zaccaria. In A, a=High Altarpiece, b=Santa Sabina Altarpiece, c=Corpus Christi Altarpiece) (Radke, 2001).

2.1.2. Polyptych of the Virgin

In 1440, Elenà Foscari, abbess since 1437, began a new reconstruction campaign. The construction works were completed within a short time because already in 1442, Andfcafdél Castagno and Francesco da Faenza signed the frescoes in the vault and the archway. "The three magnificent altarpieces of the San Talasio church in the San Zakaria church in Venice date from 1443 to 1444. Antonio Vivarini worked closely with the engraver Ludovico da Forlì. This polytych is a spectacular combination of paintings and sculptures. must make this church's reputation become a sacred workshop." (Giandomenico Romanelli, Franca Lugato, Clara Gelao, Giovanni Valagussa, 2016) Polyptych of the Virgin is one of them.

At first, this Polyptych had silver antependium in the center. After Napoleon arrived in Venice in 1799, he brought a large number of artworks back to France, including this silver antependium. Therefore, a hole remained in the central part of the frame. Then in the 19 century, they found these Sant'Agnese's wooden paintings that were part of another polyptych, then transferred and inserted them here.

Now there are five paintings inlaid, two paintings on the outside of these three paintings are left St. Mark and right St. Elisabeth painted by Antonio Vivarini. In the center is "the Virgin to the throne and the child" on the left by St.Blaise and right by St.Martin, all three painted by Stefano di Sant'Agnese, in 1385. This polyptych has been placed in Chapel of San Tarasio in the church of San Zaccaria.

Fig. 2 View of apse and high altarpiece, Chapel of San Tarasio, San Zaccaria,Venice

All five paintings are wooden tempera and use rich gilding techniques. Radiography provides information about the current status of wooden supports, such as cracks, lack of wooden bases, etc. In the three works of Sant'Angese, the wooden support itself has at least two cavities.

St. Martin's preservation condition is the worst. By observing the wooden support, it can be found that it has undergone two restorations extensive interventions have been made. One of the restorations was completely cutting off the lower part of the painting and adding a new piece of wood. The other restoration was to remove the upper part of the plank from damage and remove it, then insert a new piece of wood, adding a total of eight pieces of wood. At the same time, three long planks are added on both sides and the middle to increase the strength of the wooden base. Saint Martin is not the only painting that leaves traces of restoration, these interventions may have also involved the surface of the painting, but there is no documentation to record these restorations.

IR image and XRF analysis can give us a clearer understanding of the history of these paintings.

Fig. 3 wood support restoration of St. Martin

2.2. Methodology

Infrared reflectography, namely the use of images electronically taken with infrared light, not perceived by human eye, is currently used in the field of cultural heritage mainly for paintings analysis in order to show the presence of underdrawings or alterations (Bloisi et al., 2010).

At the begging of the restoration process, ICR has also performed some non-destructive inspections on these paintings, such as UV images, radiographic, and Infrared reflectography (1100nm). However, in this case the IR1100nm image doesn't give a good result of underdrawings. To study the draft drawings is necessary to obtain IR 1700 images.

This thesis research will perform feather analysis in-situ based on existing inspection results and restoration work requirements.

On the other hand, in-situ XRF analysis will give us an idea about the chemical elements of the material used to make these paintings.

2.2.1. IR image

By InGaAs camera C10633 with 1cm ferrules and an infrared filter, which only allows 1500-1700nm infrared light to pass through. This camera has 320 × 256 pixels with EIA(60 Hz) or CCIR(50 Hz) and the standard USB 2.0 I/F for 14-bit Image acquisition with exposure control.

The camera attached to GigaPan EPIC 100 Robotic Camera Mount. The distance between the lens and the painting is one meter. Camera set by focal aperture: 8, focus distance:1.8

Since each picture needs to be divided into multiple parts for shooting, we decided to add a laser point next to the camera to optimize the positioning between each part. When taking photos, place a light on the left and right. Images have been acquired and managed with HCImage Live software.

Table 2.1 Working condition

Camera Type	D_CAM	Exposure	0.015000 s	Ferrules	1cm
Camera Size	320x256mm	Field of view	2 degrees	Focal aperture	8
Bit Depth	14-Bit	Resolution	96dpi	Focus distance	1.8

Fig. 4 IR photo shooting equipment   Fig. 5 IR photo shooting working in site

The image acquisition and processing consisted of the following steps:

(1) The lens will be displayed in the HCImage Live, using GigaPan EPIC 100 Robotic Camera Mount set up a new panorama. We only need to decide the upper right and lower left corners of the screen, GigaPan EPIC100 will automatically split this part of the picture into a grid of "n" rows and "n" columns and photographed sequentially from top to bottom and from left to right. Each shot covers an area of 320 × 256mm.

(2) Image acquisition by using HCImage Live. After the photo is saved, the GigaPan EPIC100 will automatically move to the next position, with 50% overlapping. High overlapping can help better postprocessing.

(3) Use the software ICE to check the completed photos on site. If the photos are missing, immediately make up the photos; after confirming that the photos are complete, adjust the height and position of the camera for the next part of the shooting.

(4) Postprocessing of images consisting, brightness, size, or other necessary adjustment application of Lightroom, photo stitching using Agisoft Metashape pro, Image analysis is performed in Photoshop.

2.2.2. XRF

EDXRF is a non-destructive technique that is well suited for the analysis of inorganic materials. Its ease of use and adaptability have made EDXRF the most widely used method of non-destructive elemental analysis.

The EDXRF analysis of paintings generally provides the following information:

(1) The identities of the elements and, therefore, the pigments used by the artist;

(2) The locations of restoration areas;

(3) Information indicating whether the work is a fake;

(4) Information about the effects of pollution on the surface of the painting(Ridolfi, 2017)

For this research, XRF analyses were performed in situ with Amptek Miniature X-Ray Source and the X-123SDD, connecting this equipment set to a set a +5 Volts DC input and a USB connection a computer, Ampteck DppMCA software was utilized for for acquisition and data processing. The X-ray source was emitting in the range from 10 keV to 50 keV.

The X-ray source was set to 37 kV and 15 μA to excite the characteristic X-rays of the ore sample between 0 and 37 keV.

The alloy samples used for stander contained 85% copper, 5% lead, 5% zinc,5% titanium.

Fig. 6 X-ray source and detector   Fig. 7 in-site XRF analysis equipment

2.3. Infrared panoramic photography and infrared photo processing

After taking IR panoramic photos on site, the photos still need to be edited and stitched together. There are two ways of stitch: manual and automatic.

Panorama stitching of infrared photos is a crucial issue because usually manual stitching is cumbersome and time-consuming, so finding an excellent automatic stitching method will save much time for research. If the correct operation method and software are found in an ideal situation, the on-site stitch of IR images will significantly improve work efficiency.

This chapter tested six commonly used software with panorama stitching functions. It used painting *St. Blaise* as samples. After taking IR photos, we will use different software to stitch and compare the results to find a better IR photo process.

When taking photos, place a light on the left and right, and the tripod is one meter away from the painting.

Distance between the lens and the painting surface is 100 cm, **"St. Blaise"** was divided into three parts, first part with 12 rows and 9 columns, 108 photos; second part 11 rows and 9 columns, 99 photos; last part 17 rows and 9 columns, 153 photos. 360 photos in total.

The ferrules used this time is 1 cm.

Fig. 8 St. Blaise

2.3.1. ICE (Image composite editor)

This software is designed for panoramic image stitching, only for the WINDOWS system.

The application takes overlapping photographs of a scene shot from a single camera location and creates a high-resolution panorama incorporating all the source images at full resolution. The stitched panorama can be saved in a wide variety of file formats.

After importing the photos into the software, we need to set the photos' order and the overlap ratio between the photos. Then stitching is performed by the software. When there are more photos, the larger the overlay area, the slower the stitching speed.

In the subsequent steps, we only need to follow the software's prompts to edit and modify the stitched images, such as adjusting the angle of the photo, cropping, and finally outputting the photo.
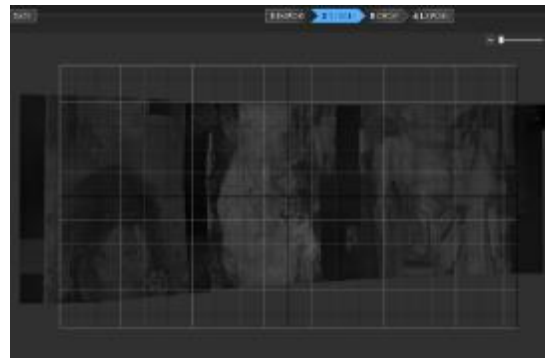

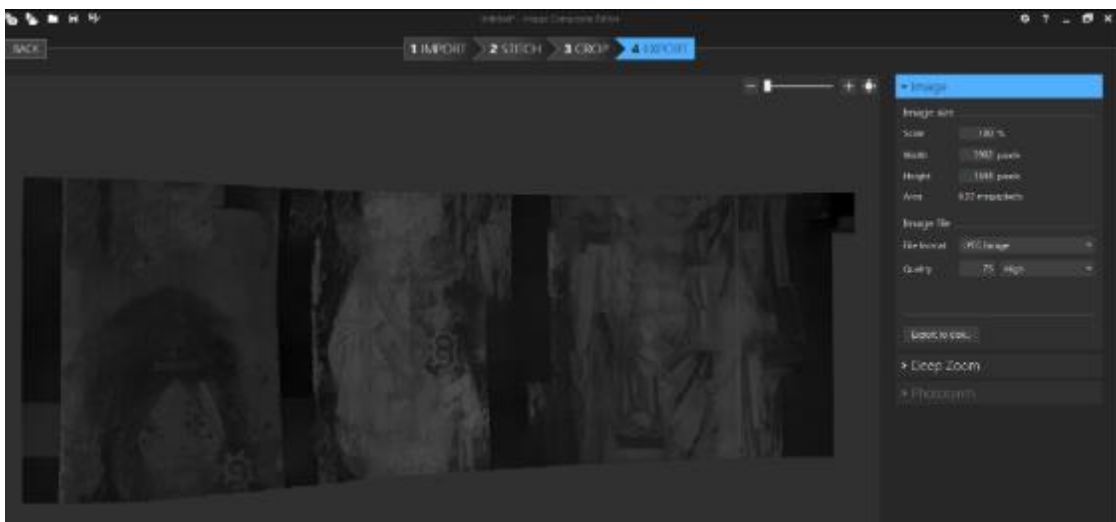Fig. 9 ICE operation interface

Fig. 10 St. Blaise stitching test

Fig. 11 "St. Blaise" stitching result, the image is recognized as three parts

Experimental operations and results show that this software is stitching all images through the manual data setting. It does not have actual image recognition capabilities.

Through Fig. 11, it can also be clearly understood that this software cannot effectively synthesize photos taken in batches into one picture. Therefore, ICE software is not suitable for the research of this thesis.

Although the splicing ability of this software is relatively weak, it occupies a small space and works fast, usually taking a few seconds to one min. This software is suitable for when we need to check whether there are missing images on site.

2.3.2. Photoshop

Photoshop is the most commonly used, full-featured photo editing software, supports multiple file formats.

The diversified functions of photoshop can cover all the needs of this project.

The IR photos taken on-site have low brightness, and each picture is automatically framed. These factors will affect the software's calculation of image stitching.

Before performing the picture stitching test:

First, use the "action record" for the pre-processing of a photo, for example.

1. Set single photo size to 11 cm wide and 8 cm high.
2. Adjust the brightness to 10.

The software records this operation. After that, the software can automatically run this step on all the photos that need to be stitched.

Use the photo merge function when stitching images, import the previously processed pictures, and the software will automatically perform calculations.
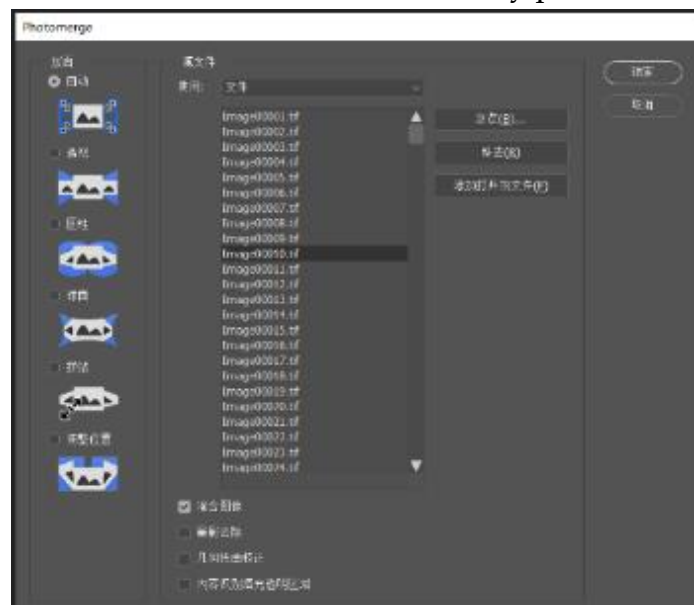

Fig. 12 Photoshop photomerge operation for "St. Blaise"

When we used PS to splice the IR photos of the "St. Blaise" automatically, we found that the PS will take up a lot of computer memory during calculations, so other

operations cannot be performed simultaneously. The operating system will freeze or even shut down automatically.

A personal laptop cannot support using PS to stitch all 360 photos at once. Not only that, the more images that are stitched at once, the more time it consumes will increase exponentially. So, 360 IR photos have been divided into two groups to perform the stitching process in PS. The stitching results of the first part are acceptable, the image is clear and accurate, there is no obvious distortion, and some images are not successfully spliced and are mainly concentrated on the edges. In this case, subsequent manual stitching is easy.

The second part of the automatic stitching has a significant problem. The picture is deformed and missing very seriously, and the final picture cannot be used, which makes the test unable to continue.
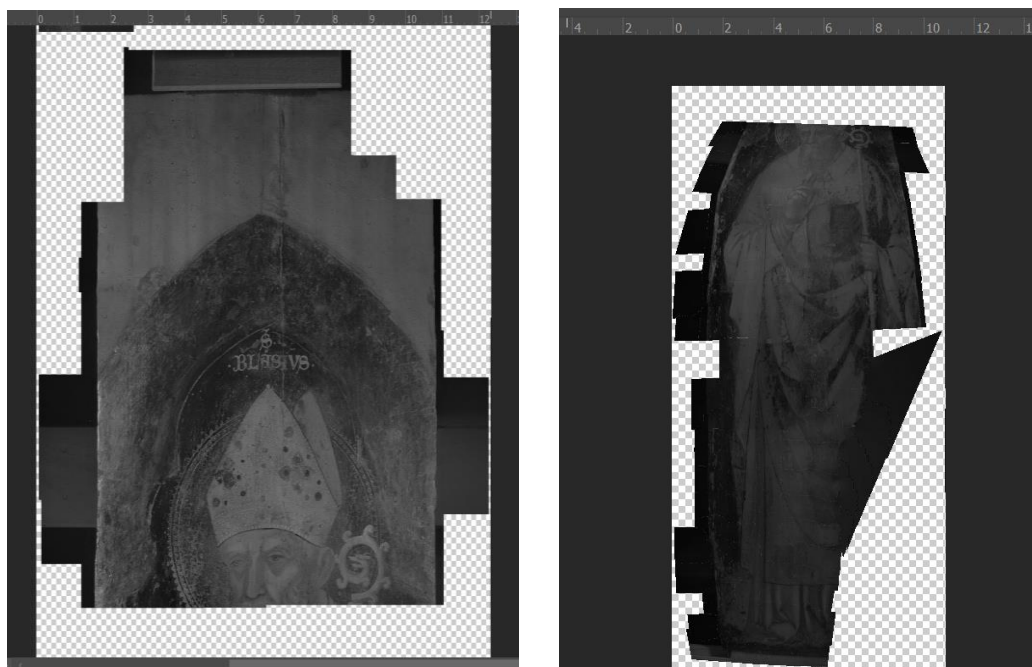
Fig. 13 Photoshop stitching "St. Blaise"

2.3.3.　Agisoft Metashape Pro

Agisoft Metashape is a software product that performs photogrammetric processing of digital images and generates 3D spatial data to be used in GIS applications, cultural heritage documentation, visual effects production, and indirect measurements of objects of various scales.(*Discover Intelligent Photogrammetry with Metashape*, 2021)

This software only can stitch imagine. The necessary pre-processing of the picture must be done with other software. For example, the framing frame automatically attached to the edge of the screen when taking pictures must be removed. On the other

hand, the picture's brightness will also affect the accuracy of software calculation and stitching, so it is necessary to adjust all pictures to similar brightness values as much as possible. We can use PS or lightroom to perform the above steps.

In view of the fact that the software not only recognizes the image, also recognizes the location of the photo from the three-dimensional level. The support body of this painting is curved, so the picture is divided into two parts and spliced to ensure the accuracy of splicing.

In Agisoft Metashape Pro, follow the workflow steps. First, add all 108 photos, which is a higher part of **"St. Blaise"** that need to be stitched in the seam "Chunk" and then start to Align photos. The software calculation shows that 107 photos are aligned.

Checking the unsuccessful image through the software, the edge of a picture is not recognized. The content of this image has been included in other images due to the high overlap rate of the photos when shooting, which does not affect the final result. The software once again shows the importance of increasing the overlap rate of photos when working on site.

In addition, in some cases, the first stitching can only successfully stitch a small part of the pictures. The software supports un the second time to align the photos. Choose "reference preselection" to help improve the accuracy and completeness of the second calculation. Two calculations can often greatly increase the success rate.

Fig. 14 Agisoft Metashape aliganed frist part St. Blaise

Fig. 15 Agisoft Metashape aliganed second part St. Blaise

Property	Value
Chunk 1	
Cameras	108
Aligned cameras	107
Coordinate system	Local Coordinates (m)
Rotation angles	Yaw, Pitch, Roll

Property	Value
Chunk 2	
Cameras	252
Aligned cameras	250
Coordinate system	Local Coordinates (m)
Rotation angles	Yaw, Pitch, Roll

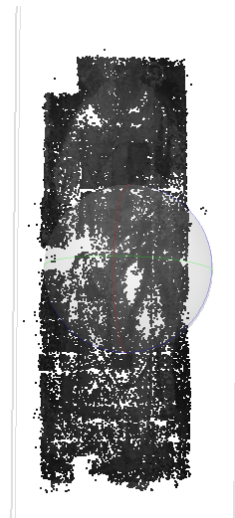Fig. 16 Agisoft Metashape aliganed frist part for "St. Blaise"

Fig. 17 Agisoft Metashape aliganed twice for "St. Blaise "

The next step is to "build dense cloud" , the higher the quality of the dense cloud will lead to the higher the accuracy of the later pictures, so try to choose the "ultra-high", then we will get a depth map and a dense cloud base on the all the aligned foto. Sometimes, the dense cloud will have some small missing parts, and it may be caused by lower image quality at the edges of some photos or errors in the software's spatial recognition.

Then follow the workflow use depth map as source data to "buil mesh" but as long as we know that photos are complete, these situations will not affect the final image.

There is a complete IR image in the software, and all the photo positions are recognized accurately, but the picture is blurred, and much detailed information is lost, "build texture" will fix this problem.

Add a new "Chunk," input another 252 IR photos of **"St. Blaise,"** and repeat the above operation.
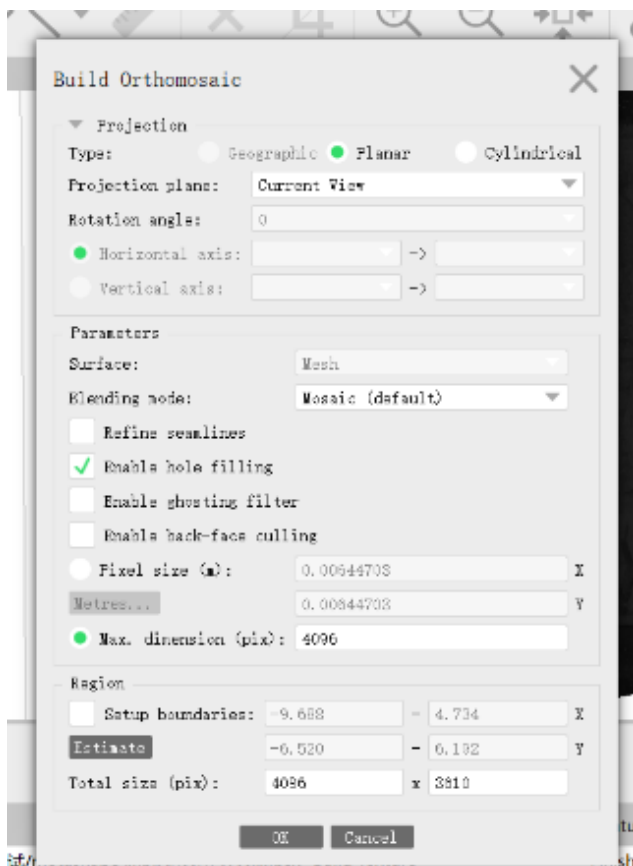

Fig. 18 Aisoft Metashape Pro orthomosaic and export orthomosaic (left)

Fig. 19 "St. Blaise" scendo part panorama by Aisoft Metashape Pro (right)

Before outputting the image, adjust the image to the position of the orthophoto and then run the "build Orthomosaic" function. After the software has completed this step,

the orthophoto map has been generated. Then, we only need to export the image from the software. The software supports the export of pictures in a variety of common formats. TIFF format will be used in this experiment and thesis project.

In this case, the last two images exported need to be put into Ps for manual stitching, but there is no doubt that this has greatly improved work efficiency.

2.3.4.   GigaPan stitch software

GigaPan stitch is GigaPan's image stitching technology that automatically combines the hundreds or thousands of images taken with a digital camera using the GigaPan EPIC series into a single image. The software is available for both Mac and Windows (*Gigapan*, 2018). The official GigaPan website provides a 15-day trial version of the software. The official version of the software can be exchanged with the GigaPan hardware serial number
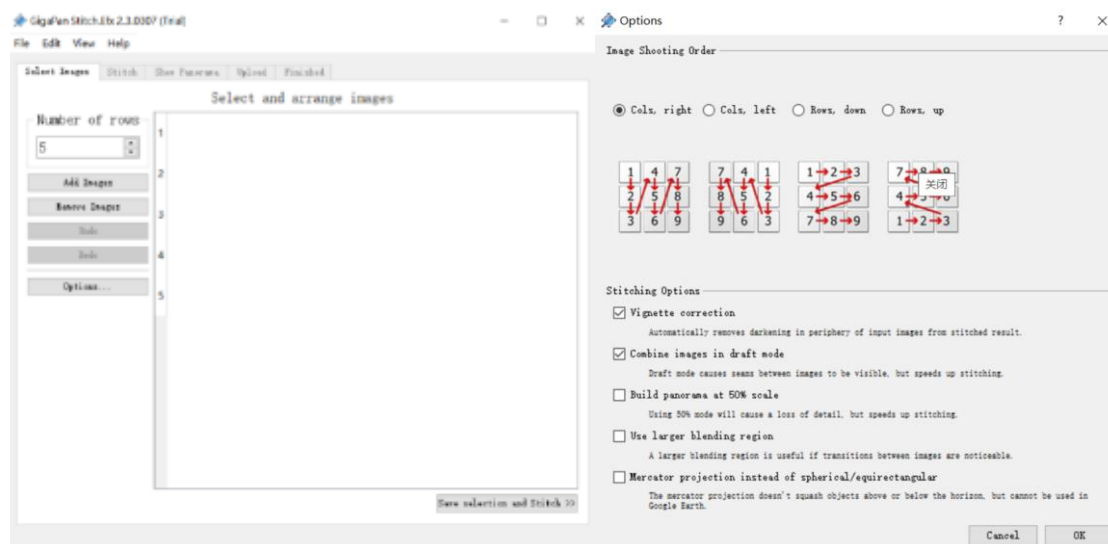
Fig. 20 GigaPan's Operation interface, picture recognition method

This software has stitch function only, so all photos need to be pre-processed with PS or altered Image editing software. For stitch, the GigaPan software operation method is straightforward. The basic principle is to import the photos taken simultaneously into the software and determine the shooting order. Then the software will quickly stitch the photos into a panorama. The calculation speed is fast.

Because the software and hardware are matched, the angle and deformation of the photo itself are perfect. If the photos to be stitched are taken simultaneously, this software may meet the basic stitching requirements.

Fig. 21 GigaPan's stitching progress
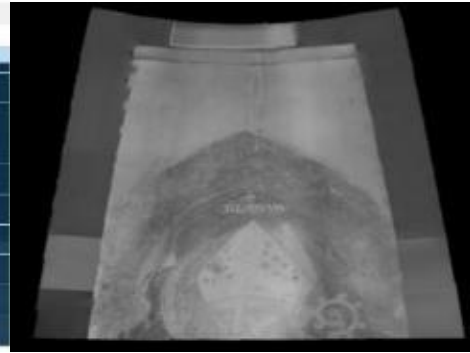
Fig. 22 stitching result of first part St.Blaise
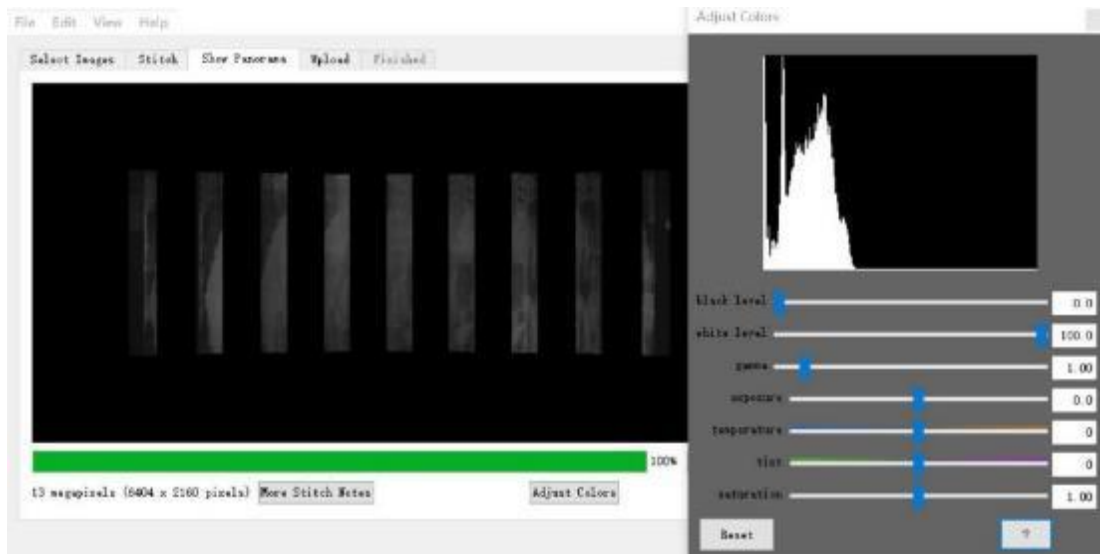
Fig. 23 GigaPan stitching result of second prat St.Blaise

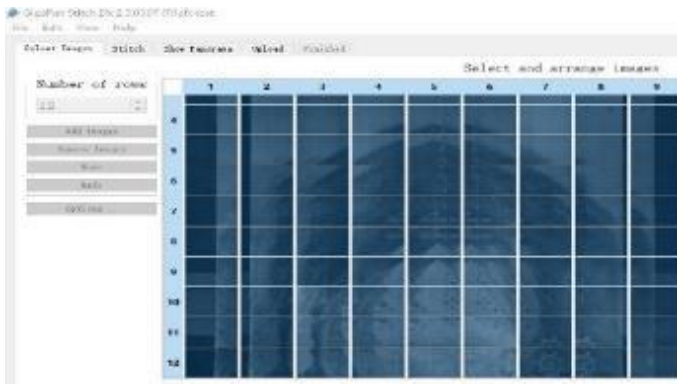By testing the stitching results, we found that when all the photos in the panorama are taken at the same time, the GigaPan software can complete the stitching, But in many cases, when the photo overlap is high, the software cannot complete the stitching well (see Fig. 23). Nevertheless, this software does not have the ability to calculate and recognize images autonomously. So, the photos are taken in multiple groups, e.g., **"St. Blaise."** Must import three parts of the image separately to get three partial panoramas and finally stitch them manually through PS. When the size of the painting itself is larger, it will reduce our work efficiency.

In addition, the quality of the final output image is lower than other software. The resolution is only 2208x1596 pixels. As a non-professional image software, the stability of this software cannot be guaranteed. Errors or automatic shutdowns occurred many times during the test.
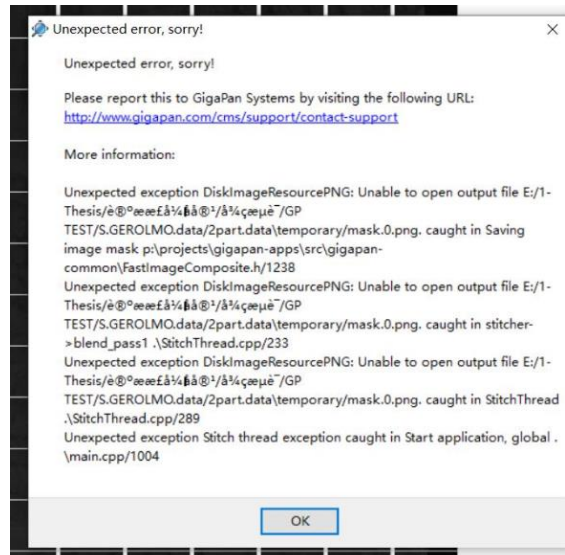
Fig. 24 GigaPan software reports an error

2.3.5.   PTGui Pro

PTGui is a panorama photo stitching program for Windows and macOS developed by New House Internet Services BV. PTGui was created as a GUI frontend to Helmut Dersch's Panorama Tools. It features its own stitching and blending engine along with compatibility to Panorama Tools (*Panorama Stitching Software*, 2000).
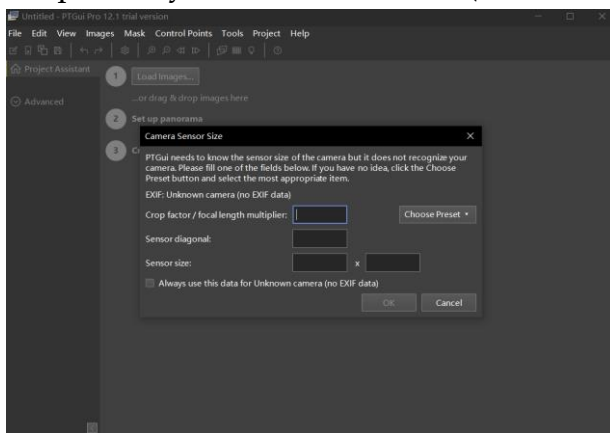
Fig. 25 PTGui pro camera sensor prameter setting
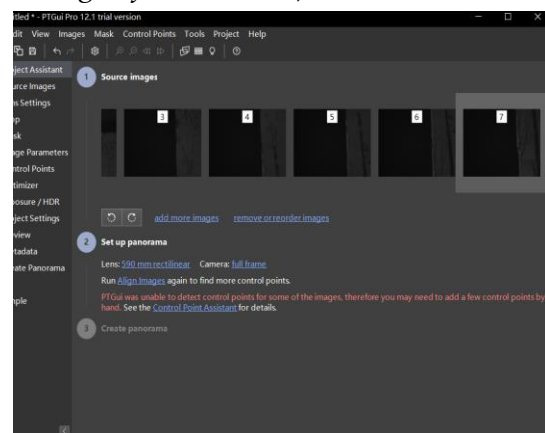
Fig. 26 PTGui pro's stitching progress

The common camera sensor size is built-in Ptgui. Choosing the parameters that match the camera can help the software correct photo distortion and optimize the panorama. However, the IR camera we use is not included, this will not affect the subsequent stitching steps.

This software has basic photo processing functions, which we can complete the pre-processing and stitching of photos by using only one software. For example, after using PTGUI, we successfully stitched "St. Blaise"
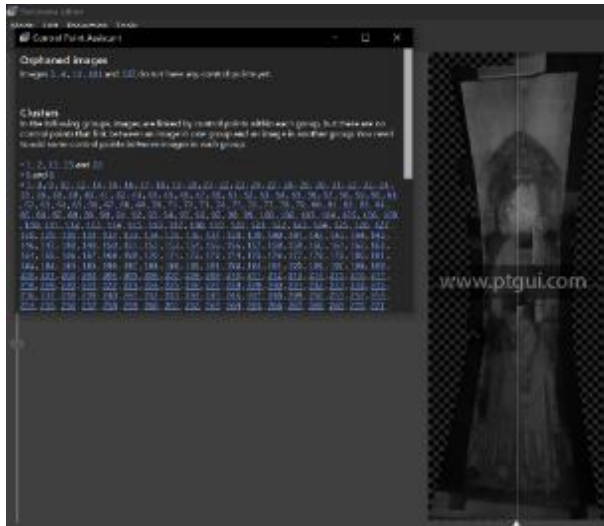
Fig. 27 PTGUI Auto-Panorama report   Fig. 28 PTGUI Panorama post adjustment function
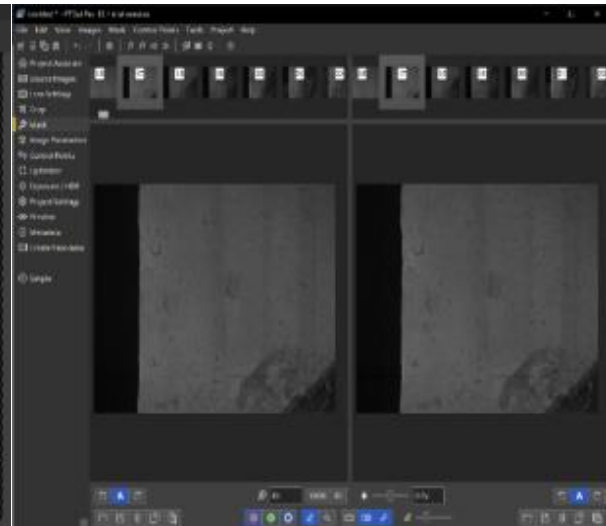
After the panorama is generated, the software also supports artificial adjustment of the panorama. If some pictures are not successfully spliced, we can manually add control points so that the software can recognize these missing images; or adjust the picture's color to improve export the image's visual effect. The software also allows editing of masks and control points for each picture in the panorama. In our experiment, all photos are successfully stitched, and this step is not required.

In addition, PTGUI supports adjusting the perspective of the picture to a certain extent. It can attach the photo to a three-dimensional space, such as a cylinder or a sphere. In our case, the 2D perspective is the most suitable.

Nevertheless, because the software could not recognize the lens we used, there was a problem with the distortion of the panorama, which needed to be corrected with PS. At the same time, because in this test, we are using the trial version of the software, so the final exported image will be automatically attached with a watermark.

This software has complete functions, but it is difficult for people who are just starting to use it.

Fig. 29 PTGUI trial version eport panorama of "St. Blaise"

2.3.6.   **Lightroom**

Adobe Lightroom is a creative image organization and image manipulation software developed by Adobe Inc. Its primary uses include importing/saving, viewing, organizing, tagging, editing, and sharing large numbers of digital images.(Murphy, 2012)

Lightroom has a complete photo editing function. We can directly change the dimension, exposure, contrast, tone curve, and sharpening of the photo in modifying photo. We only need to edit one photo and then automatically synchronize this operation to all the photos in the folder. The operation is fast and straightforward.

Fig. 30 Lightroom photo edit interface

When testing the painting "St. Blaise", first adjusted the exposure to +1.00 and the sharpness to +10, synchronized this parameter to 360 photos.

After the photo stitching is completed, the projection method can be selected according to the actual situation of the image, and the boundary deformation can be corrected. In this case, the cylindrical projection method was selected, and the boundary deformation value was set to 70 to achieve the best picture effect. Confirm the merged image after all operations are completed. This operation will take a few minutes.

Fig. 31 Lighitroom stitching process

Fig. 32 Post-editing of Lighitroom

Fig. 33 lightroom stitching first part of St.Blaise

Fig. 34 lightroom stitching second part of St.Blaise

Fig. 35 lightroom stitching third part of St.Blaise

Lightroom is not a professional software for image stitching, nor can it recognize the distortion caused by the lens. At the same time, it does not provide 2D plane images when stitching. Must choose the image to be projected on a cylinder, a sphere, or a particular perspective. Therefore, the final generated photos still need to be processed in ps. Relying on the actual size of the painting and the visible light photo, adjust the perspective, deformation, and size of the IR panorama.

The speed of editing and stitching pictures using lightroom is relatively fast. It does not require high computer configuration. It can process a large number of pictures at one time, but its stability can't always be guaranteed. During the test, there has been a problem of picture synthesis failure, and if it is in the stitching process when some photos can't be successfully spliced, the software does not support manual operation.

Through the test results of the above six software, we decided to use Agisoft Metashape Pro for the stitching of IR images for this thesis project, and at the same time use Lightroom and PS to assist.

Table 2.2 Summary of photo stitching software test

Photo Stitching Software Test				
Software	**Version**	**Abstract**	**Advantage**	**Disadvantage**
Image Composite Editor	2.0.3	Software dedicated to panoramic image stitching. The application takes a set of overlapping photographs of a scene shot from a single camera location and creates a high-resolution panorama incorporating all the source images at full resolution. The	1. Fast image recognition 2. Simple to use 3. Free for all WIN user	1. Poor picture calculation ability, only relying on picture sorting for stitching 2. Manual modification is not allowed 3. Not avilable for Mic user
Photoshop	2021	The most commonly used ,full-featured photo editing software, supports multiple file formats.	1.Easy to obtain software and relatively simple operation 2.When the photo coincidence degree reaches the requirement (about 50%-70%), the software has strong automatic recognition ability and can stitching image automatically. 3.Can automatically calculate the picture, but also allows manual post-editing of the picture 4.Supports multiple output file formats to meet various 5.When the photo overlap is too low, can manually stitch.	1.When stitching photos, the calculation time is relatively long compared with other software. 2.The computer configuration requirements are high, and a normal ues laptop can only compute about 100 pictures at a time. Therefore, when the number of photos is large, it is necessary to perform calculations in batches first, and finally perform manual stitching. 3.For automatically stitching, software requires high level photo overlap.
Agisoft Metashape pro	1.7.1	A software product that performs photogrammetric processing of digital images and generates 3D spatial data to be used in GIS applications, cultural heritage documentation, and visual effects production as well as for indirect measurements of objects of various scales.	1.Automatically recognize the similarity of photos and calculate them, without telling the order of photos. 2.When the photo coincidence degree reaches the requirement (about 50%-70%), the software has strong automatic recognition ability and can stitching image automatically. 3.Fast calculation speed,and high accuracy, stable. (＊Can stitch about 400 photos at once,the upper limit is unknown）	1.Does not support manual stitching and editing. Needs to be used with photo editing software for subsequent processing. 2.Because this software performs 3D calculations, sometimes the calculated pictures are not in the same spatial plane. 3.Requires high level of photo overlap
Gigapan Stitch software	2.1	It's proprietary and only for use with GigaPan hardware. This software is basic, has abilities in stitching together panoramas with multiple rows of images.	1. The software designed to match the hardware has high compatibility with the hardware. 2.Fast stitching, good calculation ability 3.Able to adjust color manually after the stitching 4.Can ensure the consistency of the final size of the batch stitched pictures	1.Only hardware owner can get licence of this software, for others allow to use the trial version for 14 days 2.Does not support manual stitching, needs to be used with photo editing softwarefor subsequent processing. 3.It is required to set the shooting order when imput photos, so it is not possible to stitch together photos taken in batches at one 4.Non-professional software, so the stability is poor, and the automatic shutdown occurs many times during the test 5.Requires high level of photo overlap 6.Low resolution of exported pictures
PTGui Pro	12.1	professional level photo stitching software, include things like generate control points, work with HDR source images and create HDR panoramas, viewpoint correction, and masking.	1. Professional picture editing and stitching software, which can meet a variety of requirements 2.Fast stitching. Also allows manual post-editing of the picture. （＊Able to stitch about 400 photos at once,the upper limit is unknown） 3.Automatically recognize the similarity of photos and calculate them, without telling the order of photos.	1. For novices, the operation is more complicated, especially in photo editing 2.Software licenses are expensive (110 Eruo for PTGui pro). The trial version has no expiration date, but the output pictures have obvious watermarks. 3. Requires high degree of photo overlap
Lightroom	1.0.3	Adobe Lightroom is a creative image organization and image manipulation software developed by Adobe Inc. Its primary uses include importing/saving, viewing, organizing, tagging, editing, and sharing large numbers of digital images.	1.Easy to obtain software and relatively simple operation 2.Pre-processing or stitching of photos, the operation is simple and quick 3.Image output in various formats 4.Have certain picture calculation ability	1.When running on a laptop, the large amount of pictures will cause stitching failure or a substantial increase in stitching time 2.Non-professional software for image stitching, nor can it recognize the distortion caused by the lens 3. Not support manual operation.

3. Image Analysis Results and Discussion

The traces in each IR image will be divided into preparatory drawing, painting repentances, restoration/repainting works, three layers for discussion.

3.1. St.Mark (by Antonio Vivarini)

Under IR 1700nm, transparent pigments are red, ocher and orange; absorbent pigments are green, brown, black.

Fig. 36 IR 1700nm and visible light image of St. Mark

Preparatory drawing

Preparatory drawing was performed with mixed technique:

Engravings with the aid of technical drawing tools (ex. compass, ruler / square) was applied in aureole, right edge of the table and the book.

A very rich punching technique is used at the aureola.
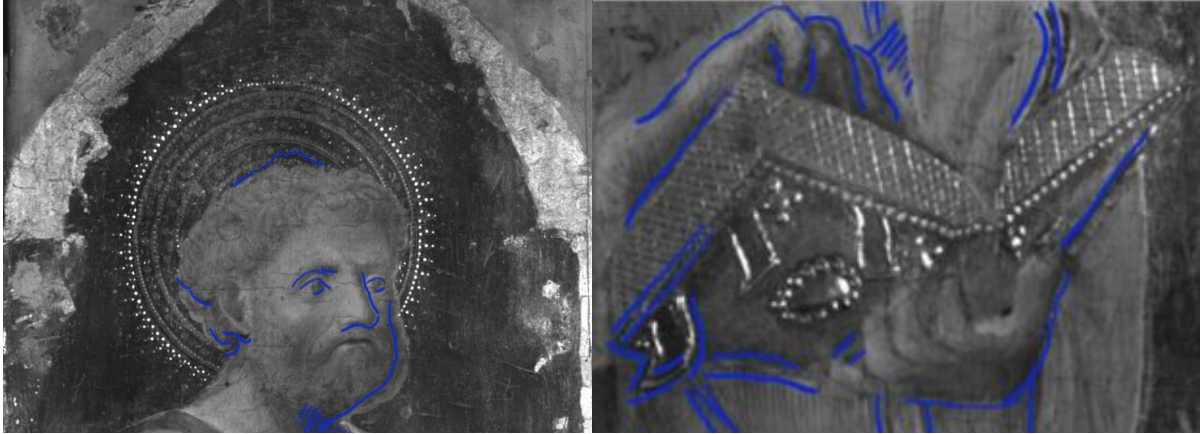
Fig. 37 Sketch traces of the portrait of St. Mark Fig. 38 Sketch traces of book and hand

(The blue line in the picture is the trace of the draft shown in the IR1700nm image; the yellow line corresponds to the changes made by the artist while painting, and the red corresponds to the repaired area.)

An actual preparatory drawing made with a dry point, maybe charcoal is visible only on the base with the name of the Saint. We do not know if it is present in all paintings because it is covered by absorbing/reflecting infrared radiation pigments, so there invisible.

Fig. 39 "San Marco" embodies the use of charcoal

Along the main lines that internally define the Figure of San Marco there are some drawing strokes made with a thin brush and an absorbent pigment (dark in IR), which are sometimes left exposed (e.g., top of the hair, auricle, nasal septum, drapery of the robe and mantle, sleeves and hands, cover and pages of the book, feet ...)

The shadows are sketched with a brush, with parallel lines between them, having a diagonal or vertical course, sometimes crossed.

Painting repentances layer

In the painting repentances layer, multiple modifications have been found.

There are several traces in St.mark's left auricle.

Fig. 40 multiple traces of the auricle in IR image camper visible light image

When comparing the visible light photo and the IR image, in IR image the eyebrows were initially more extended in the original sketch.

The left hand in the painting (viewer's perspective) was originally designed to be higher, and the cuff design is also very simple, which is entirely different from the complex cuff folds in the visible light photos. The back of the right hand was one designed more tilt, and there are evident traces of two little thumbs in the IR image.

Fig. 41 Modified traces of hands, sleeves, pleats in IR image camper visible light image

In the IR image, the left foot was stockier, the right one less shortened, but there are multiple revision marks on the right foot, so the original trace appears unclear.
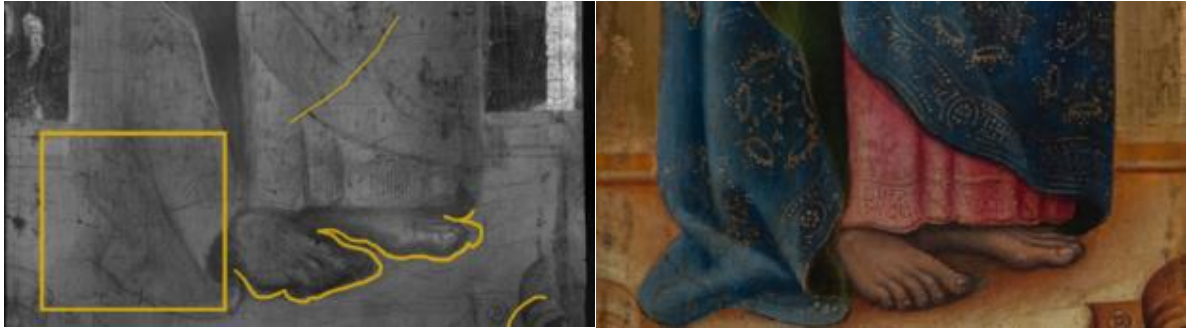
Fig. 42 Modified traces of feet, and pleats in IR image camper visible light image

The pleats in the draft are much simpler than the final effect, and this phenomenon is reflected in many places. For example, the cuff on the left, the robes on the ground next to the left foot, and the red robes on the right. At the same time, we also found a sketch trace on the blue robe on the right that was opposite to the existing pleats.

An incomplete sketch of the base is presented in the IR image. The base in the sketch is lower than the existing position, slightly smaller in size, and the curve is opposite. Comparing the base part of the IR image with the radiographic image, we find that the base in the radiographic is slightly smaller, and the bottom of the base is a rectangular step instead of a curved shape.

Fig. 43 the base of St.mark in visible light
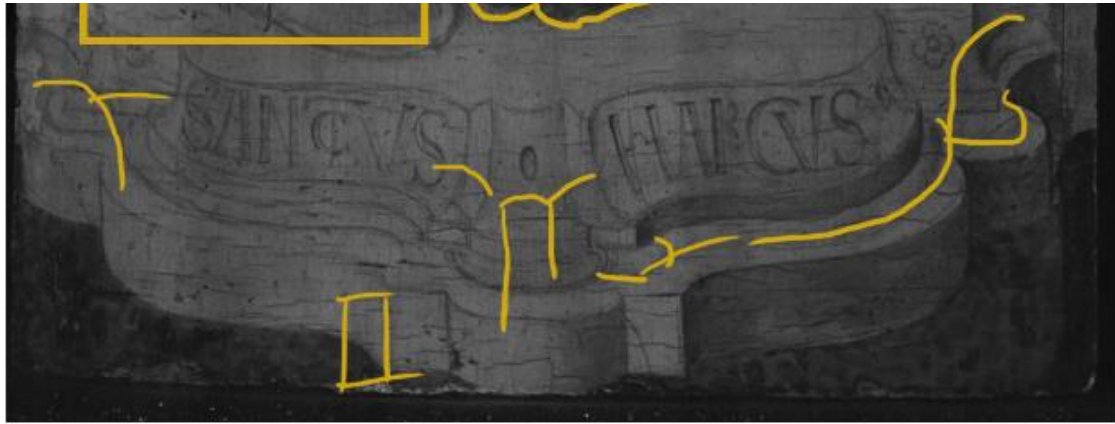
Fig. 44 the base of St.mark in IR
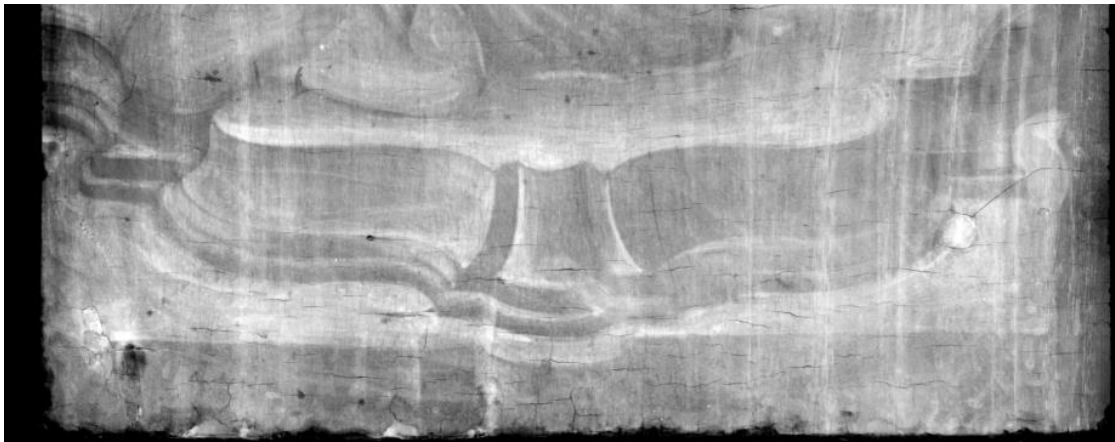
Fig. 45 the base of St.mark in radiographic

Restoration/repainting works

In the IR image, the gilded part shows two completely different colors. The gold layer of the outer ring is very light, while the gold layer of the intermediary is almost black. There is a clear boundary between the two. At the same time, the restorer found a varnish mixed with yellow pigment on the outer gold layer. Combined with historical records, it can be inferred that the light-colored gold layer under visible light was done during historical restoration or repainting.

The same phenomenon also appears on the robe. Some golden decorative patterns in visible light are not visible in the IR image, such as the lower edge of the blue robe on the right and the blue robe on the forearm on the left, and these two existing images are all different from the original sketch design, they have been modified into a richer expression of folds. So it is inferred that these two places have been restored or repainting.

As far as preservation is concerned, the condition of this painting is the best among the five paintings.

Fig. 46 the restoration trace of St. mark in IR image and visible light image

Fig. 47 Restoration traces of decorative patterns on San Marco's robe

3.2.   St. Elisabeth (by Antonio Vivarini)

Under IR 1700nm, transparent pigments are red, blue, ocher; absorbent pigments are green, black.

Fig. 48 IR 1700nm and visible light image of St. Elisabeth

Preparatory drawing

In this painting, the artist used various painting techniques, engravings with technical drawing tools, such as rulers and compasses. Mainly shown on parts of the book, aureole, and parallel lines along the left side of the table, they have a very regular shape. The engravings are also present along with the book's pages, St. Elizabeth's outline, some drapery, and decorations of the Saint. They were not showing a trace of drawing tools. The shapes of these lines are more fluid and changeable. They probably draw by freehand or with the help of cartoons.

The punching technique is used at the aureole and robe decorations, and it is richer and more diverse than the one used in St. Mark's.
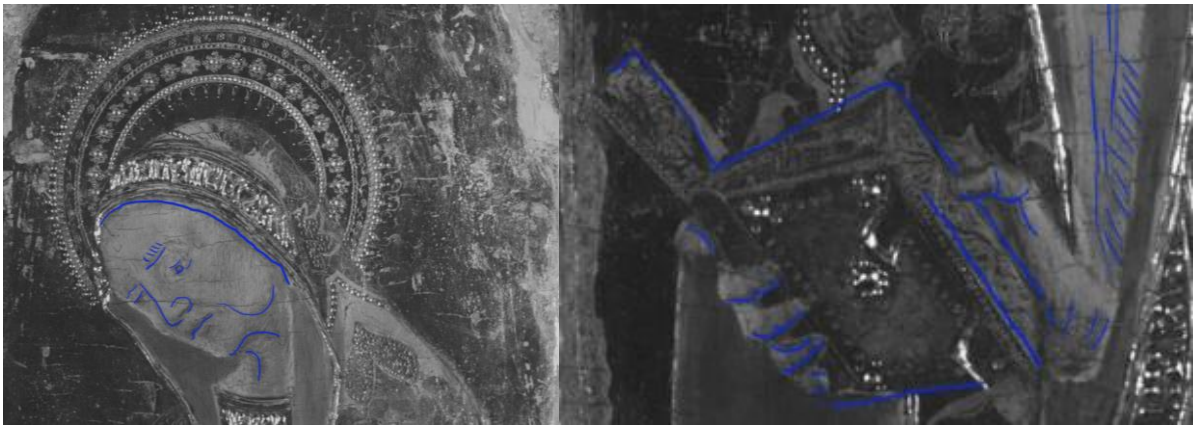
Fig. 49 Sketch traces of the portrait of St. Elisabeth   Fig. 50 Sketch traces of book and hand

Through the preparatory drawing trace of face, hands, clothes, and shadows, they show brush marks, instead the base with the name of the Saint was instead made with a dry point, like charcoal.

Fig. 51 "St. Elisabeth " embodies the use of charcoal

The image clearly draws the shadows, both on the clothes and on the face. It is similar to San Marco in this respect.
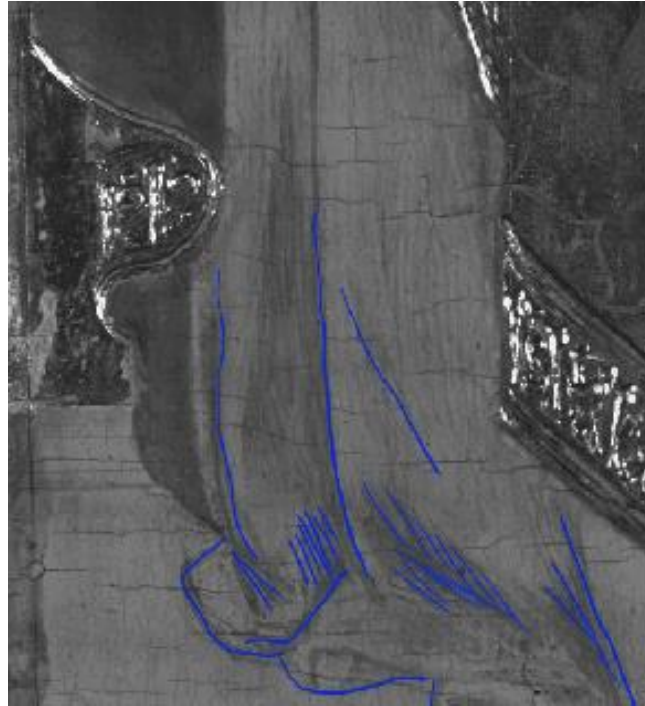
Fig. 52 St Elizabeth's pleated sketch

Painting repentances layer

Comparing the visible light image with the IR image can clearly find the position of the mouth has been changed. In the first draft, it appeared a little more foreshortened.

Fig. 53 Modification of lips and neck in IR image camper visible light image

The little finger of the right hand in the sketch is short, and the position of the right palm and cuffs have changed, which means that perhaps the position of the right palm in the original design is slightly higher than the current image.

Fig. 54 Modification of hand, book and pleat in IR image camper visible light image

The folds of the drapery in the lower band of the red robe are more articulated than in the simpler original design
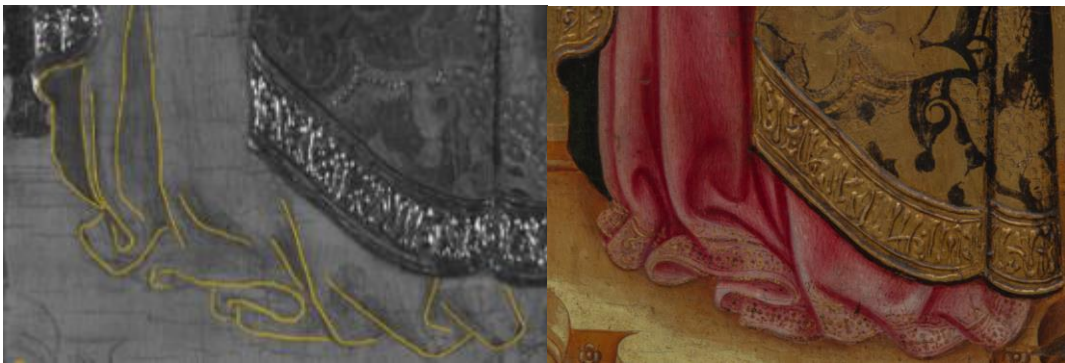
Fig. 55 Modification of robe folds in IR image and visible light image

By comparing visible light images, IR images, and radiografic bases, a situation similar to that of St. Mark appears: we can see that a base is painted lower than the current base, smaller in size, and has a shadow on the right side.

Fig. 56 Modified the traces of St. Elizabeth's pedestal in IR

Fig. 57 St. Elizabeth's pedestal in radiographic

Fig. 58 St. Elizabeth's pedestal in visible light

In this painting, the artist used complicated gilding decoration techniques on the mantle and painted black on the part of the decoration. From the visible light photos, the black painted on the gold layer has obviously fallen off. However, in the IR image, the black decorations on the mantle are transparent, even if they are very abraded, while the golden areas appear dark. It is thus possible to read in a sort of negative the decoration of the mantle,

Restoration/repainting works

In the gilded part of the screen, two colors with different shades still appear in the IR image, and the dividing line is obvious. The light-colored parts are mainly distributed at the edge of the screen, and the area on the left side is wider than the right side. These light-colored gold layers should be caused by the use of gold different from the original gold-plated material in the later restoration or redrawing intervention.

Fig. 59 the restoration area of St. Elisabeth in IR image and visible light image

On the left contour edge of the face and both sides of the neck, there are small areas of light color that are completely different from the original color. After comparing the UV image at this position with the IR image, it is found that these areas with different colors are in the UV. The image presents a black absorption phenomenon that does not blend with the surrounding colors at all, so it is inferred that it was part of a restored intervention. The colors around the base of the screen are also judged to be restored.

Fig. 60 restoration area in St. Elisabeth portrait

Comparing the IR image and the visible light photo, the coat folds near the right wrist have been changed, and the green at this position seems to have been repainted.

3.3.   St. Blaise (by Stefano di Sant'Agnese)

Under IR 1700nm, transparent pigments are red, blue; absorbent pigment is black.

The transparent rectangles on the clothing at the bottom right and middle bottom of the screen are where the restorer does the cleaning test, which has nothing to do with the information of the painting itself.

Fig. 61 IR 1700nm and visible light image of St.Blaise

Preparatory drawing

From the traces of aureole and trilobate termination in the painting, we can see that engravings probably used drawing tools such as compasses. The circle of aureole exceeds the edge of the collar on the left to form a cross.

Punching technique is used at the aureole.

Fig. 62 Sketch traces of the portrait of St.Blaise

Judging from the painting traces on the IR image, part of the preparation drawing is made by dry points, such as a charcoal. (e.g. eyes, eyebrows, nasal septum, some tufts of beard, long shaft of the pastoral); on the other hand often the outlines are brushed with a wet black tip, like right collar, sleeves, dress, these area probably was made by brush.

In the lower left band of the white dress we found some diagonal lines parallel to each other, perhaps to indicate the shadows.
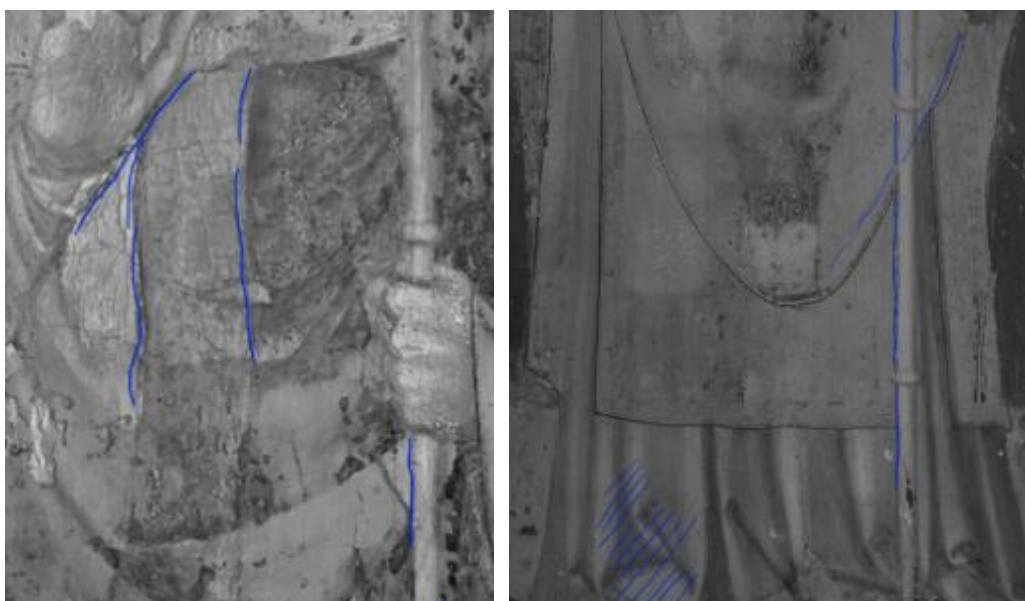
Fig. 63 Sketches of pleats and pastoral

Painting repentances layer

There is a rectangular painting trace on the collar below the left and similar traces on the right collar at the same position. Based on this, perhaps the artist originally designed the collar to be lower than it is now.

Comparing the visible light photos and IR images, the saint's left hand in the painting is thinner in the original sketch, while the right hand can only see the knuckles of the back of the hand, but not the fingers. These have been modified in the final scene.

In the white pleats at the bottom of the drawing, the original pleats sketch was finally rendered with new folds added.

Fig. 64 Modification of hands in IR image camper visible light image

Fig. 65 robe folds in visible light image

Fig. 66 Modification of robe folds in IR image

Restoration/repainting works

The preservation of this painting is not very good. The wooden support has apparent signs of restoration, so it is speculated that the painting has also been restored or repainted. This speculation was confirmed in the following IR images, UV images, and the cleaning work of the restorer.

First, the non-original decorations on the miter are transparent, including some white spots on clothing and some gems.
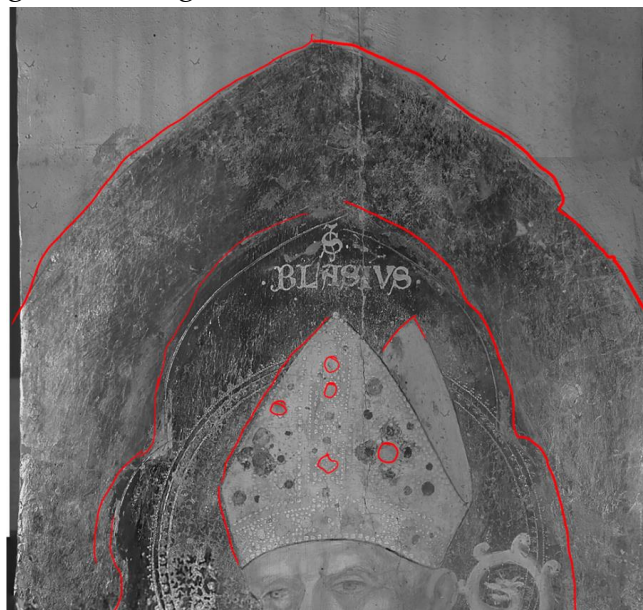
Fig. 67 restoration area of St.Blaise

In the gold-plated part, the IR image shows three different colors. The original gold layer presents a dark color similar to black; the outermost gold layer presents a very light gray, and the third type of gold layer is distributed on the clothes and the small place where the original gold layer meets is a darker gray. This kind of color difference is not obvious in the 1100nm IR image. But because the color of the

three types of gold under visible light is not the same, so in the historical restoration process, in order to make it appear the color agreement, repair the pigment mixed varnish is used on the gold layer for toning, which allows us to see the corresponding relationship between the three different gold layer area distributions after comparing the IR 1700nm image with the UV image.
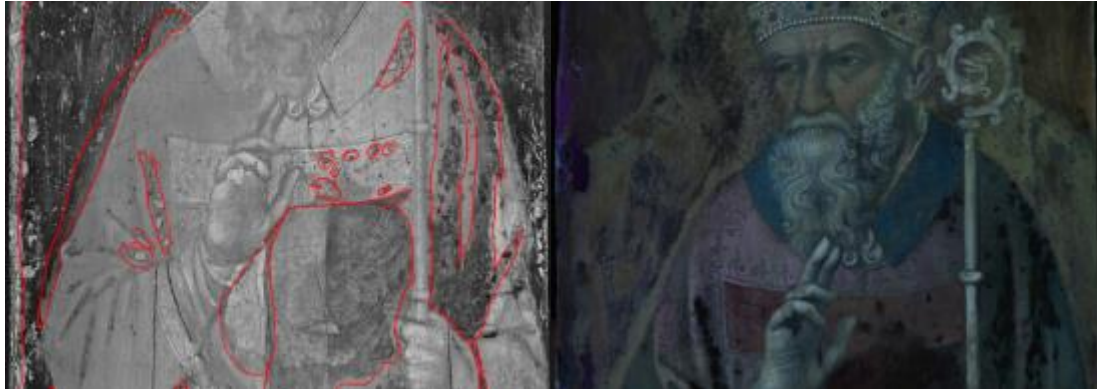
Fig. 68 restoration area of St. blaise in IR image conform with UV image

Secondly, under visible light, decorative patterns are drawn on the saint's clothes in the painting, but these parts of the patterns disappear in the IR image, and these disappeared patterns should be drawn during redrawing or restoration.

The green band of the bottom in the IR image appears transparent, and no brush strokes are seen, which implies that this area layer has been redrawn.

The strange signs at the bottom right of the robe appear to be two parallel engravings with pictorial retouching along the edges. Later it was confirmed by the restorer that it was the traces of the previous repair filling.

Fig. 69 restoration area in bottom of St. Blaise in IR image and visible light image

Cracking invisible under visible light

As mentioned earlier, this painting is in poor condition, so there are many cracks in the picture. Some small cracks are difficult to observe under visible light, but they are visible in the IR image. This type of information is very important to

restorers, allowing them to understand the preservation of the painting before the restoration work begins.

Fig. 70 The black line reflects the cracking in the IR image compare with visible light image

3.4.   St. Martin (by Stefano di Sant'Agnese)

Under IR 1700nm, transparent pigments are red, blue; absorbent pigment are black and brown.

Fig. 71 IR 1700nm and visible light image of St. Martin

Preparatory drawing

The boundary of the image of the saint in the IR image indicates that it may be engraved with the help of cardboard. From the traces of aureole and trilobate termination in the painting, we can see that engravings probably used drawing tools such as compasses.

There are parallel diagonal lines in the lower right corner of the IR image and the hem of the clothing, which means that the artist once drew a sketch, but because the painting repentances layer later covered it with a black line, we now through the IR image can't clearly identify the preparatory drawing.

The punching technique is used at the aureole.

Fig. 72 Sketch traces of St. Martino

Painting repentances layer

Comparing the IR image and the visible light image, the sketch of the saint's eyes is not wrinkled, the eyebrow on the left is slightly raised, and the arc of the mouth is relatively flat, unlike the current one.

There are two parallel lines on the thickness of the book's pages, which could correspond to the original position drawn of the book clip.

When we took the IR image of St. Martin, the restore had already completed the cleaning work on it, so many traces are no longer detectable, but by comparing the visible light photos before cleaning, that still infer the position of the two cuffs of the saint.
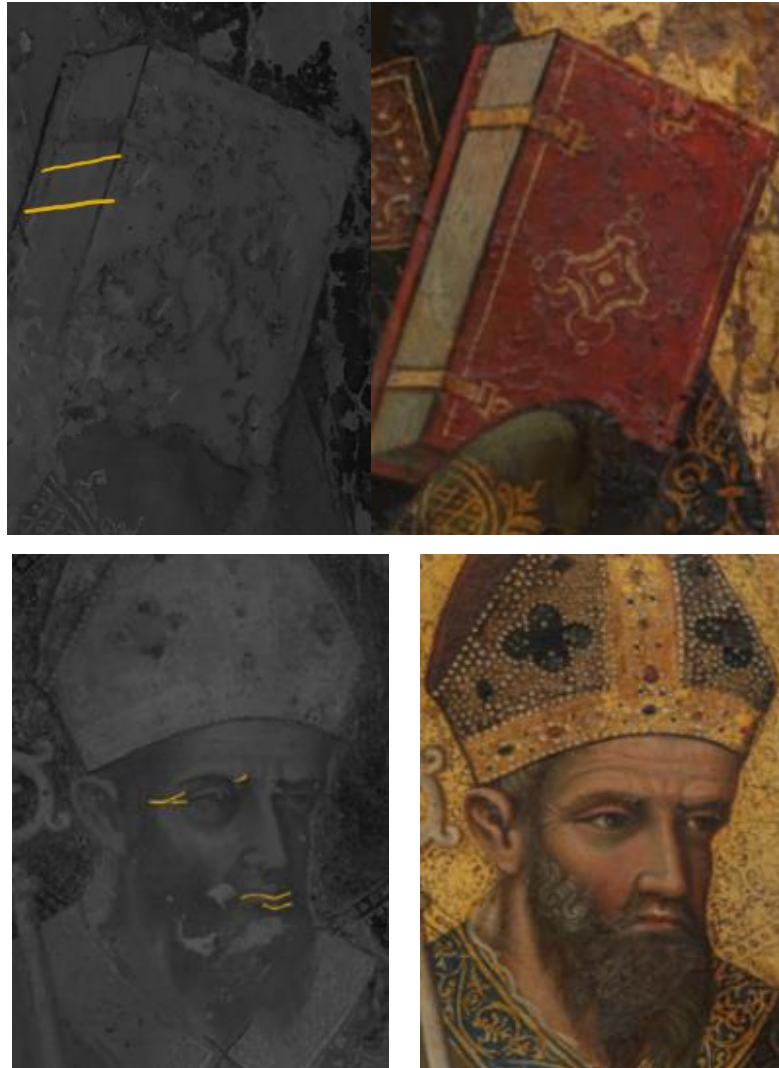
Fig. 73 Traces of modification in Saint Martin

Restoration/repainting works

The preservation of this painting is the worst among the five paintings.

As mentioned above, the cleaning work of the restoration has been basically completed. Therefore many restoration or repainting areas have been removed. Thus, there is little information that can be observed through IR images. Compare the existing IR photo with the visible light photo, in the lower band of the white robe, the folds of the drapery are evident incoherent with each other: when the lower band of the panel was rebuilt, the whole white robe was repainted: now the cleaning has brought to light the original color and the folds do not match more to the repainted ones.

The decorative details on the top of the scepter, the right set of St. Martin in the IR image are slightly different from those in the visible light photos. In the UV image, the surrounding area of this position shows traces of later redrawing. Therefore, it is speculated that these decorative details are also involved in the scope of redrawing.

Fig. 74 restoration area of St.Martin in IR image and visible light image

Fig. 75 restoration area in UV image

From the visible light photos, we can already find that the gilding position of this painting has many obvious damages. In the IR image, only the lower right and the right collar are located. The positions where these clothes are connected to the gilding have a small area of gilding repair. The gold appears in a lighter gray than the original gold layer, so we speculate that these are two different gold-plated materials. But in this painting, there is no such large area as in the previous paintings. The color is in sharply contrasting with the original gold layer and the second gilding with a designed shape.

It should be emphasized that although this painting has undergone extensive restoration in history, the IR image can provide less information because the cleaning work has been completed. Just like the gold-plated part shows two different colors in the UV image. The reaction does not exist in the IR image because the varnish has been completely removed.

After superimposing the radiographic image and the IR image, it is shown that the current main restoration areas are caused by the damage of the wooden support.

Fig. 76 IR image overlay with radiographic image

3.5.   The Virgin to the throne and the child (by Stefano di Sant'Agnese)

Under IR 1700nm, transparent pigments are blue, red, orange, violet; absorbent pigments are black and green. The green pigment of the lower part of the background becomes transparent in IR1700 (as opposed to the green of the upper background, which is absorbent): the author's signature can be read much better.

Fig. 77 IR 1700nm and visible light image of the Virgin to the throne and the child

Preparatory drawing

Like the other four paintings, we can still find signs of artists using drawing tools, mainly used in aureole, trilobate termination, and throne. Punching and relief decorations in plaster techniques were applied in aureoles.

The preparatory drawing seems to have been made with a thin, dry point e.g., charcoal which in IR appears very clear, but is not fully readable in the whole picture.(Fig.78) In the visible areas, the strokes are multiple and uncertain, in correspondence with the shading and drapery of the Madonna and Child dresses, the lines become denser to suggest the final chiaroscuro effects.

In the visible light image, the contour lines are clean and defined with a dark brush, which in some areas appears black in IR while in others it is more transparent.

Fig. 78 Sketch traces of the Virgin to the throne and the child

Painting repentances layer

The baby's palm was originally facing slightly to the right (from the viewer's direction). Now it is facing the viewer.

The contours of the faces of the Virgin and Child were originally a little more rounded and fuller; in the visible light image, the shading on the cheeks of Mother and Son is more thinned and defined than in IR1700.

The folds of the clothes of the Child and the Madonna have been modified.
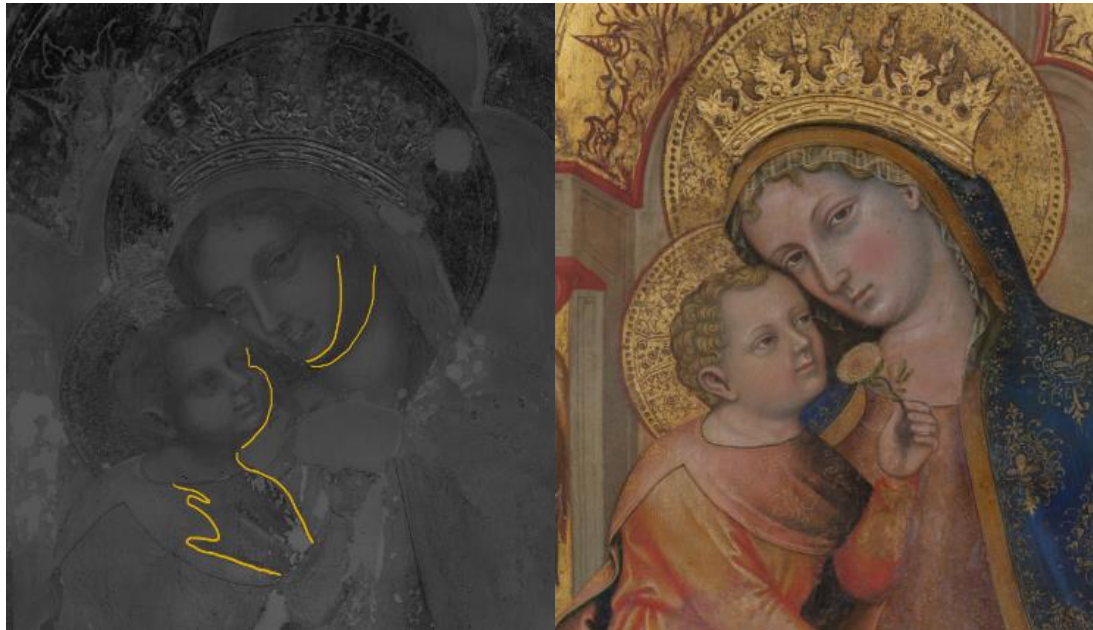
Fig. 79 Traces of modification of the Virgin and child in IR and visible light image

The position of child's left foot and right hem were originally designed to be lower, but they were later raised.

Fig. 80 Traces of modification of the Child's foot, hem in IR image and visible light image

In the angel on the left side of the painting, the position of the arms has been raised and the folds on the dress and the neckline have also been changed.

The angel on the right side has an added crease at the elbow, and the creases at the bottom of the clothes are simpler at first; immediately below the area where the angels cross their arms, there was originally no fold.

Fig. 81 Traces of modification of the angle in IR image and visible light image (left)

Fig. 82 Traces of modification of the angle in IR image and visible light image (right)

At the bottom right of the painting, you can see that the folds on the robe of the Virgin did not appear in the sketch. There was a sharp corner shape in the lower right corner, which was later hidden in the painting.

Fig. 83 Traces of modification of the robe folds in IR image and visible light image

Restoration/repainting works

Currently, the painting has been cleaned up, and many repaint and restorations have been removed. There is little information observable through IR images.

By comparing visible light photos, UV images, and IR images, it is considered that the green on both sides of the top are repainted.

Judging from the different reactions of the gold layer under infrared light, the extra circle of the golden background of the Virgin is restored. At the same time, the intersection of the aureoles of the Virgin and the Child, and the aureole of the Child, also shows signs of restoration.
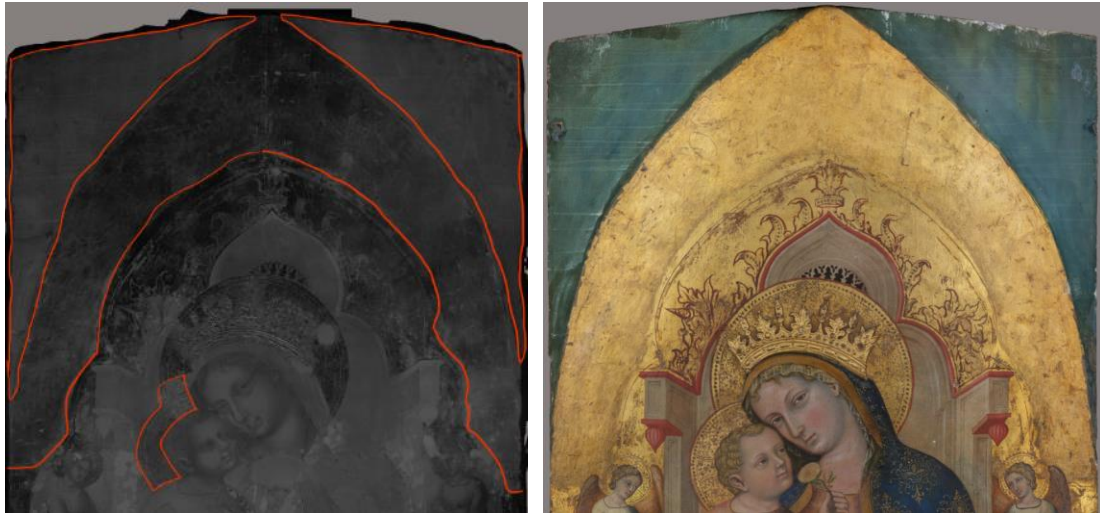
Fig. 84 restoration area of up part of the Virgin to the throne and the child in IR and visible light image

Fig. 85 restoration area of both sided of the seat in IR and visible light image

The gold layer on both seat sides of the Virgin also shows signs of restoration.

The lower band of the work appears globally repainted, but the overlapping of the pictorial layers does not allow a clear view of the original layers. Comparing the IR images of 1700nm and 1100nm, it can be found that the shape of the base of the painting is not the same. This may be modified during restoration, but it is not certain. The radiographic image shows that the wooden support at the bottom of the screen is seriously damaged, which may also lead to the loss of some original sketches..
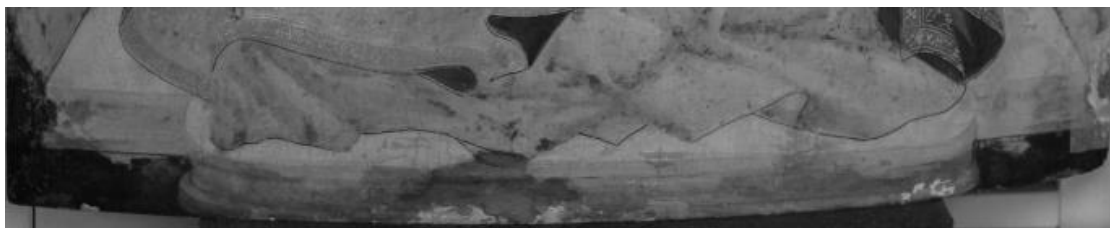
Fig. 86 Base part of the Virgin to the throne and the child in IR1100nm

Fig. 87 Base part of the Virgin to the throne and the child in IR1700nm
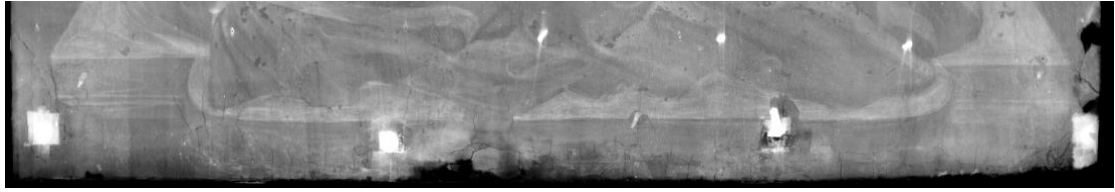
Fig. 88 Base part of the Virgin to the throne and the child in radiographic

4. XRF Analysis Results and Discussion

The primarily purpose of XRF is to testify chemical element of painting material and pigments. According to different needs, a total of 38 points were tested on the 5 paintings.

4.1. St. Mark (by Antonio Vivarini)

Eight different test point was taken on this painting.

Table 4.1 XRF result of St. Mark

|	Sn	Ca	Ti	Sr	Fe	Cu	As	Ba	Pb	Zn
1-Azure		1133	99	54	999	69001	111	111		
2-Azure		1860	62	149	1367	82874				
3-Blue		4328	103	50	618	45477				
4-Blue		364		67	508	11725			14525	
5-Green		586		91	811	113075			2852	15117
6-Yellow	200	58		60	940				19645	
7-Light gre		1024		94	1249	77078			6094	10442
8-Red		271		76		77			11678	

1.Azure

Three tests made in azure background (Fig. 92 XRF test points in St.Mark) first spot covered by varnish layer, other two spot discovered by varnish. These three XRF spectrums all showed two peaks from Ca and Sr. These two element presences indicate the classic gypsum mix rabbit-skin glue preparation, which appears in the spectra of all test points, no further explanation will be given if there are no special circumstances. One intense Cu peak can be related to the copper present in azurite ($Cu_3(CO_3)_2(OH)_2$). The other There are traces of Ba and As in these spectra. Ba may come from barite, this kind of material normally used in the 19th century. This is a clue that these blue backgrounds may not be original. Arsenic is sometimes used for anti-woodworm or hypothesis of the use of Scheele's green. The XRF spectroscopy chemical elements at these three points are almost the same, with only slight differences in content. Therefore, the material used in the varnish layer cannot be reflected.
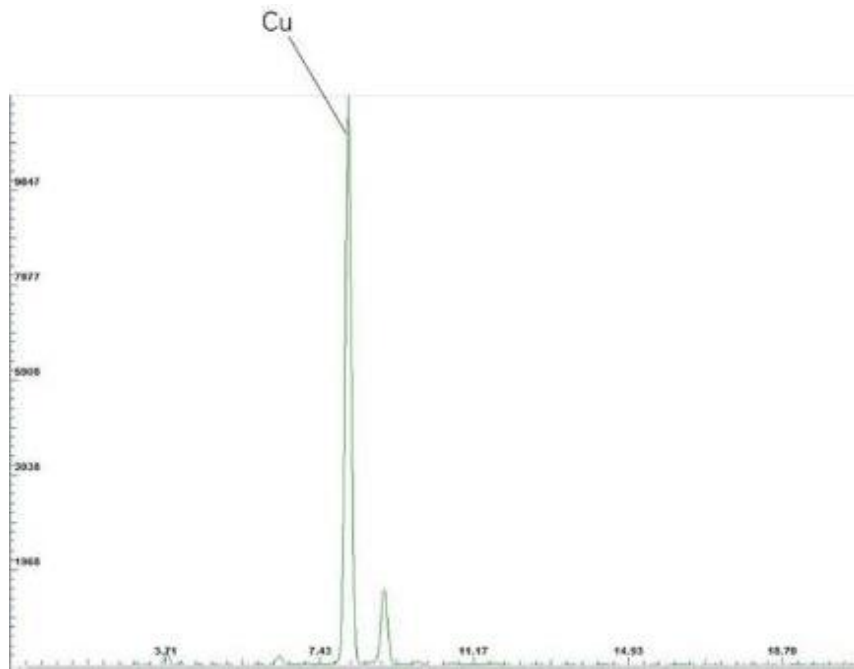
Fig. 89 XRF spectrum of 1-Azure in St. Mark

2.Blue

One test for 4-light blue dress at the height of the sleeve. In addition to the strong Cu peak from azurite in this XRF spectrum, there is also a strong Pb peak, which reflects the presence of lead white ($Pb_3(OH)_4CO_3$), Fe peak is relatively weak, it may come from ocher (Fe_2O_3).
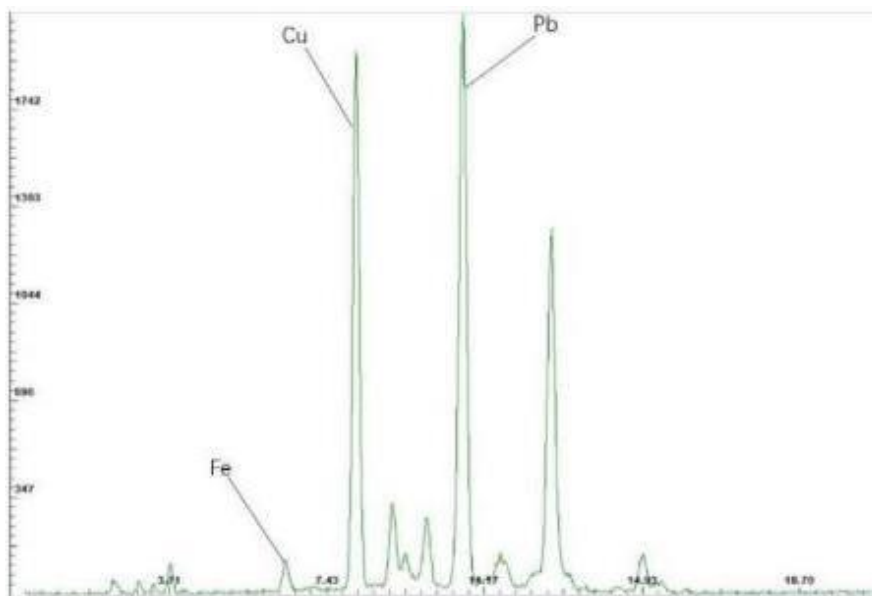
Fig. 90 XRF spectrum of 4-Green in St. Mark

3.Green

Two test points have been taken for the green pigments, one in the dark green of the robe, another in the light green lawn. The XRF spectroscopy chemical elements at these two points are almost the same. Spectrums showed an intense Cu peak which can

be related to malachite ($Cu_2(OH)_2CO_3$). There are also two short peaks belonging to Zn and Pb, which may be impurities present in the copper of malachite.

4.Yellow

One test was made in light yellow of the base. There is one intense peak of Pb in the XRF spectrum, and there is also a small Sn peak, indicating the pigment could be lead-tin yellow ($Pb2SnO4$) as known as "giallino"
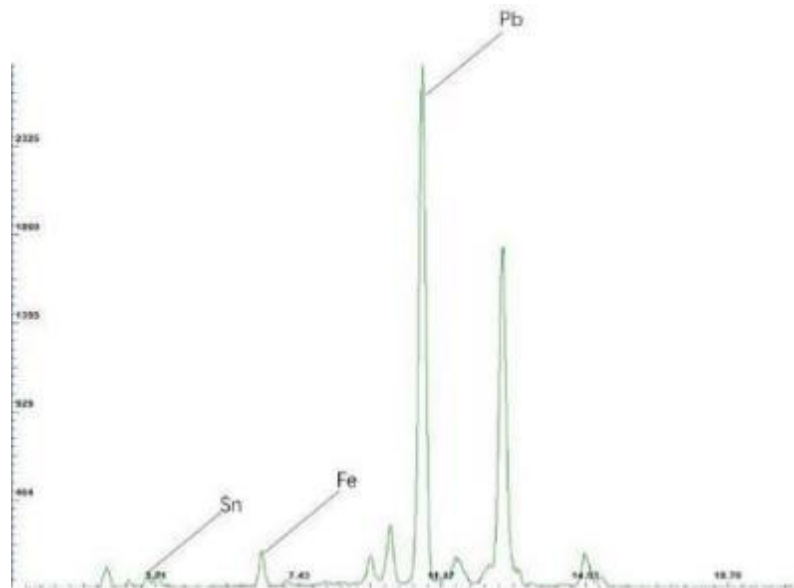
Fig. 91 XRF spectrum of 6-Yellow in St. Mark

5.Red

One test for medium dark red of the robe, in this XRF spectrum, no indicator elements related to the red pigment were detected, so it is speculated that the artist used an organic pigment, which may be lacquer.

Fig. 92 XRF test points in St.Mark

4.2. St. Elisabeth (by Antonio Vivarini)

Six different test point was taken on this painting.

Table 4.2 XRF result of St. Elisabeth

	Cl	K	Ca	Sr	Fe	Cu	As	Cd	Au	Pb	Zn	Hg
1-Azure			2059	134	1374	81745	154					
2-green		172	894	63	1057	138792		93		4243	20604	
3-red			204	84		94				11395		
4-golden			3864	198	3117	111			4933			
5-black	59	207	1938	122	1279	304			4600	8312		
6-complexi			786	80	93	285				13300		1504

1.Azure

This test was made in the azure background. This XRF spectrums showed an intense Cu peak, which can be related to the copper present in azurite ($Cu3(CO3)2(OH)2$).

2.Green

One test for dark green of the robe. In addition to the strong Cu peak which can be related to malachite ($Cu_2(OH)_2CO_3$), There are also two short peaks belonging to Zn and Pb, which may be impurities present in the copper of malachite, A weak Fe peak may be present in terra.

3.Red

One test for medium-dark red of the robe, this XRF spectrum contains a very faint Cu peak while the other peaks point to elements that don't match the common red inorganic pigment composition, so it is suspected that lacquer was used for this red color.

4.Golden

A test was performed on the gold part, whose main chemical element is Au, and another intense Fe peak in this XRF spectrum, originating from a clay below the gold layer, this clayey mixture with variable quantities of iron oxides, greasy to the touch and reddish, used as an adhesive layer under the gold leaf in the gilding of non-metallic objects. A very tiny copper peak is present, which is perhaps some tiny impurity in the gold leaf.
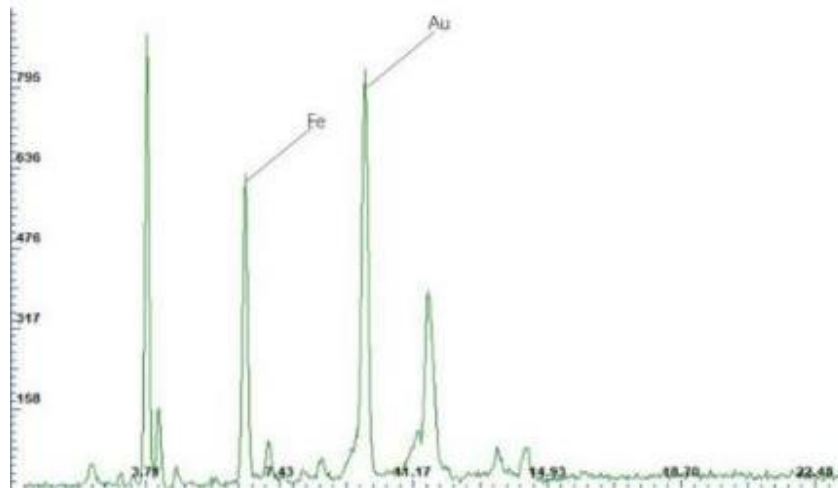
Fig. 93 XRF spectrum of 4-golden in St. Elisabeth

5.Black

This test point was performed on the black color used for the decoration above the gold layer. In this XRF spectrum, in addition to the element's appearance in the spectrum of the gold layer. However, the spectrum did not reveal any significant element related to black pigment.

There is a K peak in the XRF spectrum, and ICR's laboratory, previously sampled and analyzed by FTIR was considered lapis lazuli. So, through these two tests, it can be judged that this pigment is lapis lazuli.

6.Complexion

The complexion test point on the forehead of St. Elizabeth. In XRF spectrum showed an intense Pb peak prove the existence of lead white. The other, shorter peak comes from Hg, which may indicate cinnabar (HgS). Weak Cu peak and Fe peak can be related to copper green and ocher.

Fig. 94 XRF spectrum of 6- complexion in St. Elisabeth

Fig. 95 XRF test points in St.Elisabeth

4.3.   St. Blaise (by Stefano di Sant'Agnese)

Eight different test point was taken on this painting.

Table 4.3 XRF result of St. Blaise

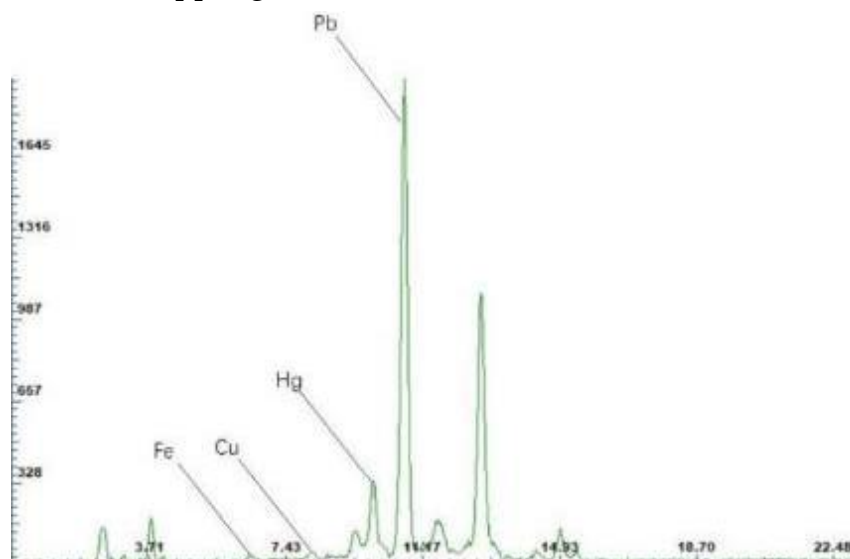|	Sr	Ca	Fe	Cu	Pb	K	As	Hg	Mn
1-green	117	4800	334	15281					
2-red complexion	173	603	621		12674			165	
3-blue	366	972	417	54	12603	301			
4-red	113	843	96		598			19656	
5-light purple	70		531	179	14203				
6-dark purple	214	494		15629	12437				
7-green	170	5587	1120	68			3156		53
8-black	189	869	601	20671	2043				51

1. Green

Two points were tested in the green part of this painting. The test point 1-green is located at the green background at the top of the painting, and the other point 7- green is located at the green background at the bottom of the painting.

The first XRF spectrum showed a strong Cu peak which may be related to malachite $(Cu_2(OH)_2CO_3)$,

The second XRF spectrum showed an intense As peak, which may come from orpiment (As2S3) pigment. Fe and Mn peaks can be linked to terre ombra. This kind of pigment is often used to adjust color brightness. There are no elements that point to green and blue in this spectrum, therefore speculated that organic pigments, such as indigo, may have been used. When indigo is mixed with orpiment, it gets green.
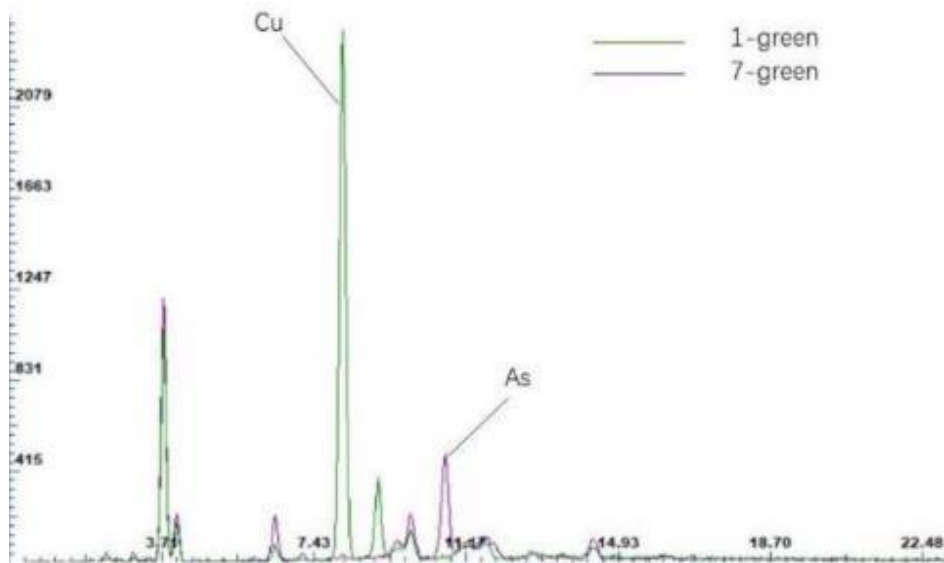
Fig. 96　XRF spectrums of two green test points in St. Blaise

2.Red complexion

The test point takes in the dark part of the cheek. The highest peak belongs to Pb, which is indicated to be lead white, the lower peak is Fe is ocher, and the Hg peak suggests that cinnabar was used.

3.Blue

The 3-blue test point in the lower part of blue robe. This XRF spectrum has a significate K peak, and no other elements that can be related to blue pigments appear, which suggest this blue color could be lapis lazuli. In order to confirm this result, we need other test results for comparison.

4.Red

The 4-red test point is located on the lining of the red robe. An intense Hg peak was appeared, which most likely related to cinnabar.

5.Purple

Tested separately on 5-light purple and 6-dark purple on the robe. Strong Pb peaks appeared in the two XRF spectrums, indicating the presence of lead white ($Pb_3(OH)_4CO_3$). But there are more Cu in dark purple than light purple. It could be related to azurite ($Cu_3(CO_3)_2(OH)_2$). There no element that could be linked to the red pigment, so it is very likely that a red lacquer was applied.
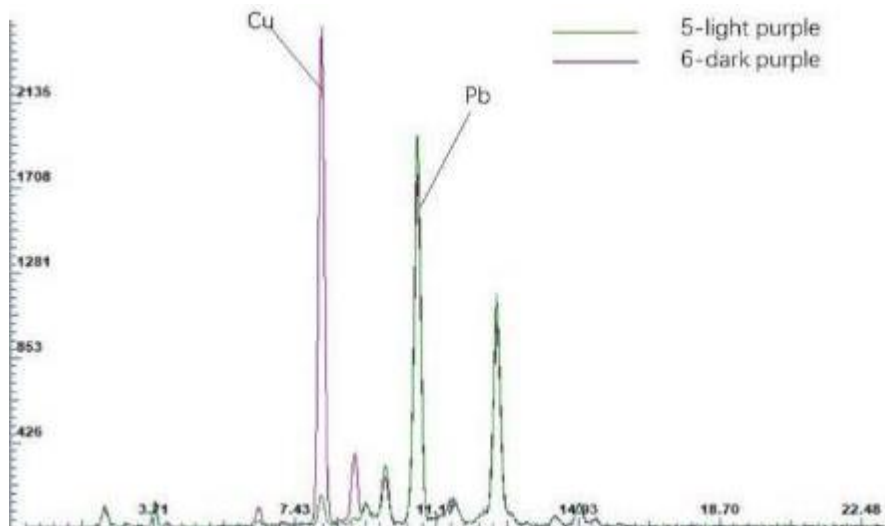
Fig. 97 XRF spectrums of two purple test points in St. Blaise

6.Black

The restorer discovered this black area during the cleaning work and is considered to be the remaining part of the original painting layer, so it is essential to understand its pigment composition.

This XRF spectrum showed an intense peak of Cu, which can be related to azurite ($Cu_3(CO_3)_2(OH)_2$), and it also contains Fe peak and Mn peak, suggesting terra ombra was used here, therefore this black color maybe actually is dark blue.

Fig. 98 XRF spectrums of 6-black test points in St. Blaise, partial zoom (right)

Fig. 99 XRF test points in St. Blaise

4.4.   St. Martin (by Stefano di Sant'Agnese)

Seven different test points was taken on this painting.

Table 4.4 XRF result of St. Martin

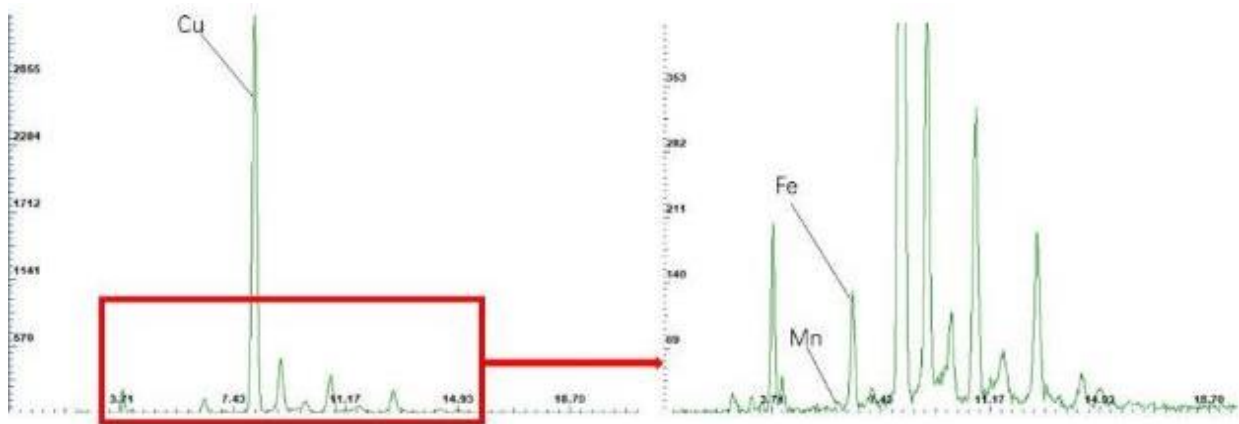|	S	Sr	Ca	Cr	Au	Fe	Cu	Pb	As
1-light green		129	746			2240	54750	12585	
2-preparation	361	1049	9107					374	399
3-dark green		317	1836			1513	54504	1203	
4-red		403	2150		4356	1943	46050	3995	
5-red		264	1317			102	504	15286	
6-white		52	81					15302	
7-white		116	943	176		857		17473	

1. Light green

The test point 1 is light green in the lower part of the robe. The most intense peak identified to Cu, which can be related to the malachite ($Cu_2(OH)_2CO_3$), in the main time the pigment contains Pb, which should be lead white ($Pb3(OH)4CO3$), used to increase color brightness. A small amount of Fe was shown in this spectrum, related to ocher.

2. Preparation

Select a peeling area to test the composition of the preparation layer. The most present element is Ca with a small amount of S, which clearly shows the presence of gypsum ($CaSO_4 \cdot 2H_2O$). The second highest peak is Sr belong to rabbit-skin glue. A small amount of As usually present for repelling insects on wooden supports.
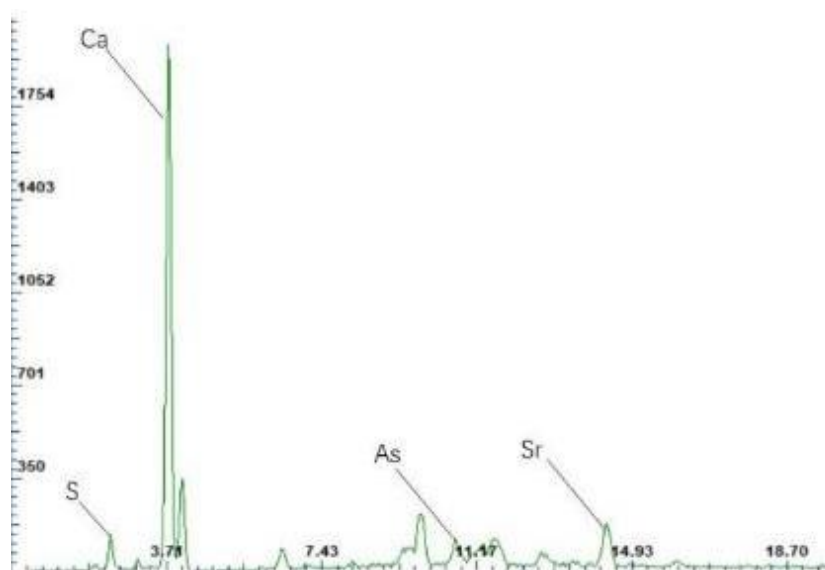

Fig. 100 XRF spectrums of 2- preparation test points in St. Martin

3. Dark green

This test point 3 was taken in the dark part of the green robe. The element contained in the XRF result is the same as that of test point 1, which proves that the same kind of pigment is used. (See above)

4. Red

One test point 4 is red in the upper layer of gold, and test point 5 is red in the center of the clothing.

The 4-red XRF spectrum contain a high amount of Cu and Au, which could become from the golden decoration layer. A Fe peak the obvious presence of Fe peak, indicates that the red pigment is ocher.

The 5-red test point, the result showed a very intense peak of Pb. Therefore, there is a high probability that lead white is mixed in the pigment. But the XRF spectrum has no Hg signal, low amount of Fe, so there is no cinnabar or ocher. From the above, it is speculated that an organic lacquer was used.
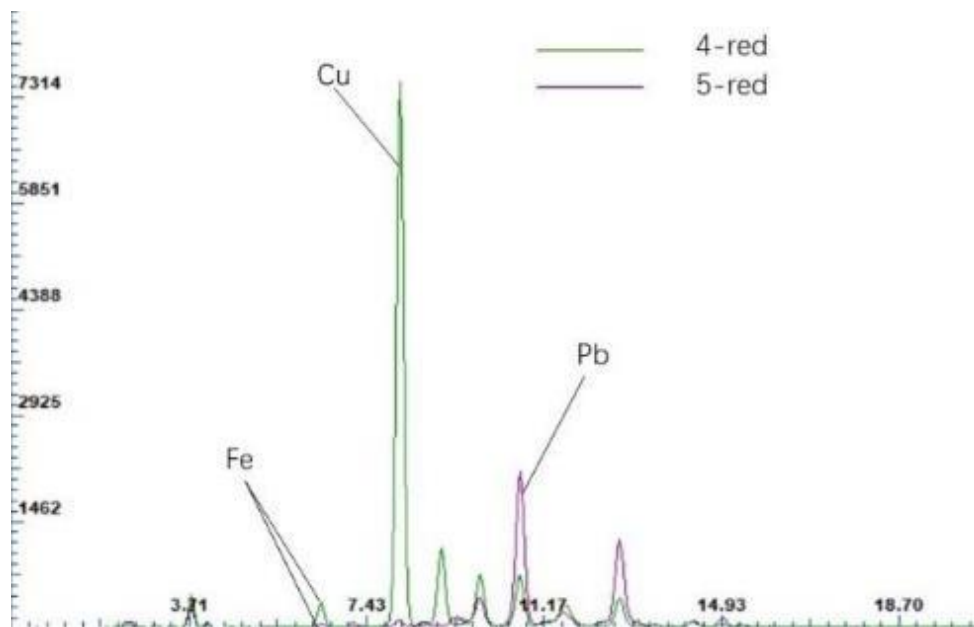
Fig. 101 XRF spectrums of two red test points in St. Martin

5. White

There are two different test points on white color, one in the cleaned area and the other in the uncleaned restoration area.

The 6-white XRF spectrum revealed a substantial amount of Pb, which can be related to the lead white. The 7-white has the same Pb element. In addition, it also contains Fe and Cr, which can be related to the chrome green (Cr_2O_3).

Fig. 102 XRF spectrums of two white test points in St. Martin

Fig. 103 XRF test points in St. Martin

4.5.　The Virgin to the throne and the child (by Stefano di Sant'Agnese)

Eight tests points was taken on this painting.

Table 4.5 XRF result of The Virgin to the throne and the child

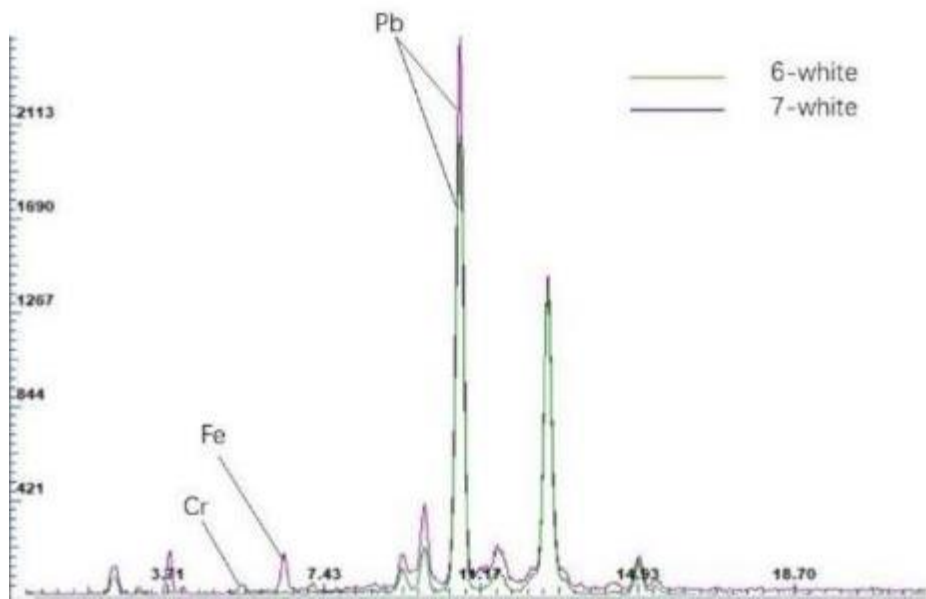|	Ca	Sr	Fe	Cu	Au	Pb	Hg	K	Mn
1-red complexion	229	115				28027	1119		
2-white	4175	146	1926			7539			
3-complexion	1617	127	475			11551	101		
4-dark orange	2344	93	5995			5638	2586		
5-blu	806	206	335			17458		503	
6-dark purple	901	96		550		13086	1492		
7-black	8980	519	2258			5273		100	61
8-golden	2346	249	12043	109	8386				

1.Complexion

Two tests were made for complexion, point 1-red complexion take in the virgin's cheek. The XRF spectrum showed two significant peaks Pb and Hg, that can be related to lead white ($Pb_3(OH)_4CO_3$) and cinnabar (HgS). In another test point, 3-complexion, located in the right-side angle's face, had a test for the complexion, the XRF spectrum except for Pb and Hg also contains Fe, which could be ocher.
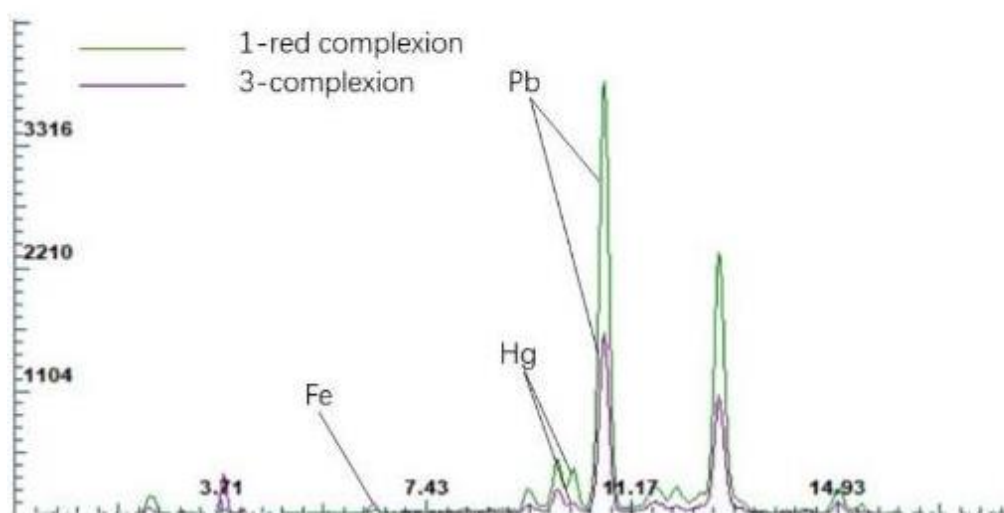
Fig. 104 XRF spectrums of two complexion test points in the Virgin to the throne and the child

2.White

Test point 2-white is decorative white dots on the top of the virgin's head. The XRF spectrum contains an intense Pb peak, proving that the white pigment is lead white.

3.Orange

Test point 4-dark orange was taken in child's clothes. There are three main elements, Fe, Pb, and Hg. Fe led to the ocher pigment, Pb indicated to lead white, and Hg is more likely to come from cinnabar (HgS).
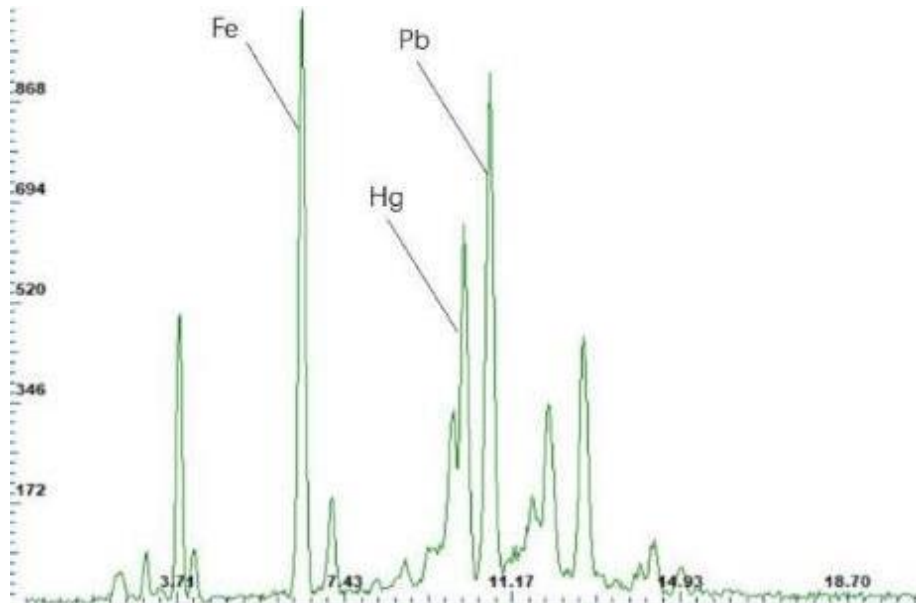
Fig. 105 XRF spectrums of 3-orange test points in the Virgin to the throne and the child

4.Blue

This test point is located in the blue robe. The XRF spectrum 5-blu contains one significant K peak, which suggests that this pigment may be lapis lazuli.
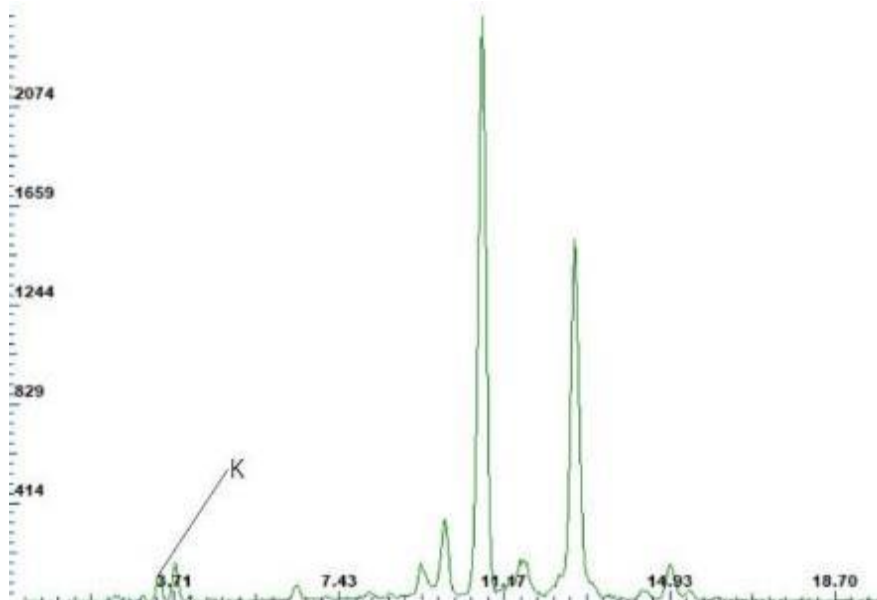
Fig. 106 XRF spectrums of 4- blue points in the Virgin to the throne and the child

5. Dark purple

Test point 6-dark purple taken in the virgin's red robe. The highest peak belongs to Pb, which could be related to lead white ($Pb_3(OH)_4CO_3$); Hg peak most likely prove the

presence of cinnabar; there also some amount of Cu suggests that maybe some green pigments were used, such as malachite ($Cu_2(OH)_2CO_3$).

6. Black

One test made in Artist's black signature. The XRF spectrum showed Fe peak and Mn peak, these two elements which can be related to umber.

7.Golden

This test point is located in the 8-golden background. As expected, the XRF spectrum showed very strong Au and Fe peaks, coming from the gold layer and the preparation layer below it.

Fig. 107 XRF test points in the Virgin to the throne and the child

5. Restoration and Scientific analysis cooperation

In order to make better use of the scientific analysis results, it is essential to understand the restoration work and determine the focus of the analysis by communicating with the restorers. This chapter is about the mutual support between restoration work and scientific analysis in this research. The doubts in the restoration work will be answered by scientific analysis, and the findings in the restoration will make up for the aspects that are not covered by the scientific analysis. Maximize the use of information from both parties and avoid blindly providing analysis data and results and neglecting their use.

In this study, we mainly learned about the cleaning process in restoration work. During the cleaning process, the restorers will constantly discover the information reflected in the painting, and at the same time, they will continue to produce new problems. For example, they were identifying the restoration and original areas, the artist's painting techniques, understanding the production process, et cetera.

The solvent used in the subsequent cleaning is determined by multiple cleaning tests with different proportions of the solution.

The principle of the cleaning test is to start with the solution with the lowest evaporation rate and then increase the evaporation rate. On the other hand, the chemical properties of the solvent used should be similar to the substance being cleaned. Restorers mainly used TACO7[1]and solvent gel to clean the "polyptych of the Virgin."

According to the restorer's investigation of the church's preservation environment, the preservation environment has a humidity of 90%, which poses a considerable challenge for preservation. To not cause considerable changes in the material humidity, these paintings will be stored in a small room with an ambient humidity of 70%.
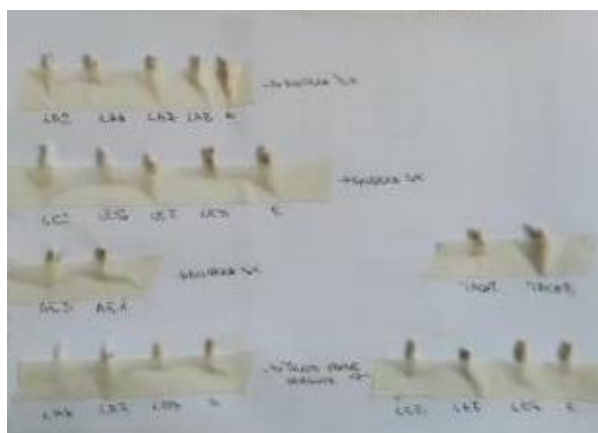

Fig. 108 Restoration cleaning test result record

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[1] A cleaning solution containing ethyl alcohol 45%, acetone 21%, petroleum ether 34%.

5.1. Cleaning discovery and image analysis

Through the observation and discussion of these paintings, it was speculated that this Virgin's polyptych should have two times restoration, but the specific dates are unknown.

The gold surrounding the Figures in these five paintings has been gilded at least twice, especially in the three works of Sant'Angese. The scope of the second gilding is huge. Because these works were obtained from other places, some restoration was carried out to feet in the frame. In addition to supplementing and expanding the scope of the gold layer, they also used varnishes with colors to make the added gold layer the same color as the original gold layer. This is the same result of the different infrared light reactions of the golden part in the IR image.

Through radiography provides information about the current status of wooden supports, such as cracks, lack of wooden bases. In the three works of Sant'Angese, the wooden support itself has at least two cavities.

The restorers found that the upper part of the Child's right hand was resorted entirely, including the preparation layer, and decided to remove it during the cleaning process. This situation is almost not shown in the UV image. In the IR1700nm image obtained later, it is observed that the original sketch (although incomplete) of the hand is different from the one under visible light.

Fig. 109 restoration area in visible light (left)

Fig. 110 restoration area in UV (middle)

Fig. 111 restoration area in IR (right)

In the restoration position on the Child's clothes, the restoration engineers found a small square canvas after removing the paint and preparation layers. After removing the canvas, they found a green interlining cloth underneath. It is speculated that the green interlining of the stratum is to make up for the defects of the board itself and create a relatively flat surface. The square canvas on the upper level is compelling proof of past restoration history. Coincidentally, the same kind of green interlining appeared

at the bottom of the" Virgin to the throne and the Child". Although some information has been obtained in the image analysis, such a complete hierarchical relationship can only be known when the restorer performs the cleaning process.

Fig. 112 The canvas added in the past restoration is removed

When the restorers were cleaning the paintings, they found that in the other four paintings except for Saint Elizabeth, the decorative patterns on the clothes of the characters were all painted in two different periods. This finding is consistent with the results obtained in the subsequent IR image analysis.

Present the results of the image analysis to restorers.

Fig. 113 The first time IR image result presentation   Fig. 114 The second time IR image result presentation

5.2.   The pertinence of XRF analysis

In this in-site XRF analysis, restorers were invited to participate. The selection of test points was mainly focused on the positions where the restorers had doubts about painting pigments during the cleaning process. Briefly discussion on test results, the scientific analysis methods were used to answer them as much as possible.

Fig. 115 in-site XRF analysis with restorers participate (left)

Fig. 116 prof. Ridolfi discuss the detection location and results with the restorer (right)

In the initial stage of the cleansing of "the Virgin to the throne and the child" Judging from the state of varnish cleaning, perhaps a small amount of color has been added to the varnish in the past. The same situation appears in the green background of Saint Elizabeth and Saint Mark. There are two layers of colors drawn in the green area above the Figure. Through observation, it is found that the lower layer is blue with higher saturation, and the upper layer is green.

St. Elisabeth's close decoration Because there is a black on the gold layer, it is easily removed during the cleaning process, but it is unclear what kind of black material is used here. After FTIR analysis of this pigment by ICR's laboratory, it was considered to be lapis lazuli. Later, when we performed XRF analysis, we tested this pigment and confirmed that the pigment is lapis lazuli. See above for details in 4.2.

The green repainting layer on top of St. Elizabeth and St. Mark was removed, revealing the original blue pigment. During the cleaning, the restorer deliberately reserved a small area for subsequent XRF testing, aiming to explore the difference between the two different paint layers' original material.

St. Martin, Due to the restoration of the wooden support, a large area of the painting layer is repainted. Since this work has a complicated restoration history, it is necessary to explore the original materials. For example, the restorer found a completely different red below the repaint layer during the cleaning process. To ensure that the subsequent restoration work will not affect it, XRF analysis of these original materials is required. After testing, it is confirmed that this red color is cinnabar.

6. Conclusion

The multi-analysis approach applied in this study is proved helpful information for restoration work and improved documentation of Polyptych of the Virgin in Church of San Zaccaria. All the questions asked in chapter 1 have been answered.

This research also solves the difficulties in stitching a large number of IR images, provides a new working method for the same type of work, and improves efficiency.

6.1.   Research result

Through the IR images, we have learned the drafts of the five paintings to the greatest extent. Obviously, the sketches of Antonio Vivarini are very detailed and accurate. The corresponding Stefano di Sant'Agnese's sketches are relatively rough and often used later to supplement the details.

For clothing details, the artist has changed to varying degrees when drawing, adding clothes folds and decorative patterns.

We determine the range of all past restoration areas by comparing IR, UV, and radiographic images. The most obvious is the golden backgrounds of the five paintings have been greatly enlarged, and the bottoms have also been restored. The three paintings by Sant'Agnese had significant problems with wooden support. Most of the restoration areas in the paintings correspond to the damaged position of the wooden support.

Using in-situ XRF analysis, the researchers successfully identified most of the pigments and materials used in painting, and other testing methods are needed for the qualitative determination of organic materials.

Table 6.1 Summary of pigments and materials used in painting

	Pigment/Material	Indicative element
Blue	Azurite	Cu
	Lapis lazuli	K
	Indigo	-
Red	Ocher	Fe
	Cinnabar	Hg
	Lacquer	-
Green	Malachite	Cu

	Chrome green	Cr
Yellow	Giallino	Pb, Sn
	Orpiment	As
White	Lead white	Pb
Golden	Gold	Au
Preparation	Gypsum	Ca, S
	Rabbit-skin glue	Sr

6.2.   Innovation in IR image processing

At the beginning of the research, producing high-quality IR images in a reasonable time was a complex problem. Previous studies of the same type used manual stitching. Reducing time-consuming means reducing the number of pictures. Even so, they still have to face long and complicated picture adjustments. However, the total area of the research object this time is large, and the fineness of the pictures is required. Therefore, instead of traditional manual stitching, we were the first to test this by software and revealed comparable results for the different test methods.

In the end, 2546 IR photos were obtained in this research, and five complete IR images of the wooden tempera paintings were produced. This result laid a good foundation for the smooth follow-up of this research, and the results of software testing have important practical implications in the same type of research.

6.3.   Close co-operation

In order to explore the cooperative way of restoration and scientific detection, we have a more comprehensive and intuitive understanding of the object under study. I attended a five-month restoration course. During the period, three presentations of IR image analysis were presented to the restoration technicians, including four paintings in this research.

In addition to understanding how the restorers work, I also learned their new findings on these five paintings being studied for the first time. Of course, these findings often bring new problems, which have become the focus of our subsequent scientific analysis. Through this attempt, we believe that this form of close cooperation can better achieve the purpose of scientific restoration. Of course, this advantage will be more prominent in on-site analysis and testing.

Through more optimized cooperation methods, some limitations in this research can be improved, such as adjusting the shooting order of IR images and acquiring IR images before some redrawing traces are completely cleaned. Perhaps more information can be obtained. The material analysis results in this study should be cross-confirmed by other analysis methods to improve their accuracy. However, this study was in a particular period of the Cov-19 epidemic, so the time allowed to enter the ICR laboratory was limited. Under the constraints of many realistic conditions, it was not possible to use more analytical methods.

In conclusion, we believe this study can provide sound scientific support of Polyptych of the Virgin and follow-up related restoration work. Attempts in software splicing and field analysis can also provide new ideas for the same type of research. Results of image analysis in this study can also contribute to a better understanding of the characteristics of the two great artists.

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