Characterization of Early 20th Century Measurement Instruments: A Heritage Approach

Original
Characterization of Early 20th Century Measurement Instruments: A Heritage Approach / Angelini, E., Bongiovanni, M., Grassini, S., Es Sebar, L., Di Iorio, F.. - In: ACTA IMEKO. - ISSN 2221-870X. - ELETTRONICO. - (2025). (2025 IMEKO TC26 International Conference on Metrology for Archaeology and Cultural Heritage Bergamo, Italy October 15-17, 2025) [10.21014/tc26-2025.064].

Publisher:
ACTA IMEKO

Published
DOI:10.21014/tc26-2025.064

2025 IMEKO TC26 International Conference on
Metrology for Archaeology and Cultural Heritage
Bergamo, Italy, October 15-17, 2025

Characterization of Early 20th Century Measurement Instruments: A Heritage Approach

E. Angelini[1], M. Bongiovanni[2], S. Grassini[1], L. Es Sebar[1], F. Di Iorio[1,3]

[1] DISAT, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino (Italy)
emma.angelini@polito.it, sabrina.grassini@polito.it, leila.essebar@polito.it
[2] ARIA, Ufficio Gestione del Patrimonio Storico dell'Ateneo Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino (Italy), margherita.bongiovanni@polito.it
[3]Fondazione Centro per la Conservazione ed il restauro dei Beni Culturali (La Venaria Reale), Venaria (Italy), federico.diiorio@ccrvenaria.it

Abstract **A conservation campaign is currently underway, at Politecnico di Torino, to preserve a significant collection of measurement instruments and devices from the Department of Physics and the Advanced School of Electronics Laboratory, originally established by Galileo Ferraris in 1888. The collection comprises teaching and research apparatus used between the 1920s and 1960s, including voltmeters, ammeters, galvanometers, valve and battery testers, and other related equipment. The ongoing conservation effort utilizes non-invasive, in situ analytical techniques such as portable X-ray fluorescence (XRF), Raman spectroscopy, and multiband photogrammetry. These methods have enabled detailed examination of the materials and their degradation processes without compromising the integrity of the artifacts. Preliminary analyses have revealed a variety of corrosion morphologies, attributable to the use of different base metals, iron, copper, silver alloys and to variable environmental conditions over time. Galvanic corrosion is a frequent finding, particularly in areas where Cu-based and Fe-based alloys or gilded components, are in direct contact. Cross-polarized and Ultraviolet-Induced Luminescence Photogrammetry are being employed to generate detailed 3D models of the instruments, supporting both documentation and future conservation planning.**

I. INTRODUCTION

Measurement is a cornerstone of science, engineering, commerce, and everyday life. It represents a defining feature of scientific inquiry, offering a systematic and reproducible method for acquiring knowledge, particularly in contrast to qualitative observation. At its core, measurement involves interacting with physical systems to abstractly represent their properties through standardized methods and units. Among the many forms of scientific instrumentation, electrical and electrotechnical devices have played a pivotal role in the advancement of modern science and technology [1]. Developed from the 19th century onward, these instruments enabled the precise quantification of electrical phenomena, voltage, current, resistance, and more, supporting the rise of physics, telecommunications, and industrial development. Instruments such as galvanometers, voltmeters, ammeters, and resistance bridges not only facilitated technical progress but also reflected the craftsmanship and ingenuity of their makers. Often, the scientists who developed or used these devices were themselves skilled artisans or worked in close collaboration with instrument makers. These artefacts serve not only as functional tools but also as cultural witnesses, embodying the collaboration between scientific innovation and hands-on craftsmanship. As such, their preservation is essential not only to safeguard their material integrity but also to honour their historical, educational, and symbolic significance [2].

In this context, the preservation of scientific instruments is of great importance, as these artefacts can be considered tangible records of the evolution of scientific thought and experimentation. They offer a window into the creativity of past scientists and engineers. Scientific instruments are not merely historical objects, but embodiments of the practical application of scientific principles and technological progress over time.

II. THE CASE STUDY

At the Politecnico di Torino, a comprehensive conservation and research campaign is currently underway, focusing on a historically significant collection of electrical measurement instruments and devices. These artefacts originate from the Department of Physics and the Advanced School of Electronics Laboratory, an institution with deep roots in Italian scientific history.

The laboratory was founded in 1888 by Galileo Ferraris, one of the most eminent Italian physicists and electrical engineers of the 19th century. Galileo Ferraris is best known for his fundamental contributions to the theory of alternating current (AC), including the invention of the rotating magnetic field, which laid the foundation for the development of the induction motor, independently and contemporaneously with Nikola Tesla [3]. His 1885 experiments demonstrated the possibility of generating continuous rotation using two-phase AC, a revolutionary idea that profoundly influenced the future of electrical engineering, Fig. 1.

Fig. 1. Reconstruction of Galileo Ferraris' rotating magnetic field motor. Developed in the 1880s, Ferraris' design laid the foundation for the induction motor by demonstrating the generation of continuous rotary motion using two-phase alternating current (Istituto Elettrotecnico Nazionale Galileo Ferraris, Collezione antichi strumenti).

In addition to his scientific achievements, Ferraris was a committed educator and science communicator, deeply engaged in promoting technical and scientific knowledge in Italy. He was a professor at the *Scuola di applicazione per gli Ingegneri* di Torino, that in 1906 became Politecnico di Torino, and an early advocate for the application of physics to engineering practice. His pedagogical philosophy emphasized hands-on experimentation and precise measurement, and he believed that a strong grounding in physical sciences was essential for future engineers. His commitment to education and innovation helped establish Turin as a key centre for electrotechnical research and teaching in Europe.

The instruments collection reflects Ferraris's legacy, representing both the pedagogical tools used to train generations of engineers and physicists, as well as the research apparatus that contributed to the advancement of electrical science during a crucial period of technological development in the 20th century. In 1934, the collection was transferred to the newly established *Istituto Elettrotecnico Nazionale "Galileo Ferraris"* (National Electrotechnical Institute), named in his honour. The institute played a major role in Italy's scientific and industrial modernization, especially during the interwar and post war periods, and became a national hub for the development of standards, measurements, and electronic instrumentation.

The instruments in the collection span the period from 1920 to 1960, a time of rapid innovation in electrical theory and measurement technology. They include galvanometers for detecting electric charge and potential differences with high sensitivity, voltmeters and ammeters for routine electrical measurements, galvanometers for tracing small currents, as well as valve testers, battery testers, power supplies, and converters used in both teaching and research. The presence of both Italian and international makers reflects a vibrant exchange of scientific and industrial expertise across borders.

Technically, these devices embody the transition from purely analog to early electronic instrumentation, incorporating technologies such as vacuum tubes, precision resistors, magneto-mechanical systems, and, in later models, the first semiconductor components. They also reflect changes in industrial design and materials, from handcrafted wood and brass components to synthetic materials such as Bakelite, ebonite, and early plastics, many of which now pose complex preservation challenges due to aging, corrosion, and material instability [4].

Beyond their technological significance, these instruments are tangible expressions of Italy's engagement with international scientific currents and serve as material witnesses to the way measurement shaped the pedagogy and practice of electrical engineering in the 20th century. Their preservation is essential not only for safeguarding a unique aspect of material culture, but also for understanding how science and technology were taught, disseminated, and practiced in institutional and national frameworks. In honouring Ferraris's vision, this conservation campaign underscores the enduring value of historical instruments as both scientific heritage and educational legacy.

III. PHYSICO-CHEMICAL AND OPTICAL CHARACTERIZATIONS

Portable X-ray fluorescence spectroscopy (XRF) was employed to analyze the surface composition of a representative selection of early 20th-century electrical measurement instruments, with particular attention to metallic alloys, gilded components, and areas affected by corrosion. Measurements were conducted using a Bruker Tracer 5i portable spectrometer, equipped with a 20 mm² CCD detector and a rhodium (Rh) anode. The instrument was operated at 40 kV and 30 µA, with a 3 mm collimator and a composite filter (Cu 75 µm / Ti 25 µm / Al 200 µm) to optimize detection sensitivity across a broad energy range. Spectral data were acquired and processed using Artax Spectra 8.0.0.476 software. Due to the absence of standard reference materials and calibration models, the results are interpreted in a semi-quantitative framework. Nonetheless, this approach enables reliable identification of principal elements in the alloys (e.g., Fe, Cu, Zn, Sn, Pb, Ag), offering insight into manufacturing practices and material degradation. In particular, XRF analysis has been instrumental in correlating corrosion typologies with the base metal composition of various components, especially in cases where different alloys were combined (e.g., copper-based versus ferrous elements), which often led to galvanic corrosion phenomena.

Raman spectroscopy, a non-invasive technique for identifying corrosion compounds and surface residues, was used to characterize degradation layers and residual materials on selected instruments [5]. The analyses were performed in situ using three portable Raman systems with excitation lasers at 532 nm, 785 nm, 1064 nm. The 532 nm measurements were carried out with a BWTEK iRaman Plus (range: 65-4200 cm^{-1}; resolution: 7.3 cm^{-1}), while the 785 nm and 1064 nm analyses used BWTEK modular systems with BTC675N and BTC284N spectrometers, respectively (range: 65-3350 cm^{-1} and 100-2500 cm^{-1}; resolution: 6-10.56 cm^{-1}).

All instruments were paired with a BAC151® portable microscope, equipped with lenses allowing spot sizes from 300 µm to 20 µm, and a camera for documenting analysed areas. This multimodal setup enabled the detection of iron oxides, basic copper salts, sulphates, and organic residues, offering valuable insights into corrosion processes and past conservation treatments.

In parallel, photogrammetry was employed to generate high-resolution, metrically accurate 3D models of the instruments under study. These digital reconstructions serve as a non-invasive tool for the visual documentation and monitoring of historical artefacts, providing a permanent digital record that complements traditional cataloguing methods. The photogrammetric workflow involved the use of calibrated camera system, a rotating platform and a controlled lighting conditions to ensure consistency and repeatability in image capture. These models support multi-scale analysis, allowing researchers to zoom in on minute details such as surface wear, corrosion pits, or inscriptions, while preserving the broader structural context of the object. Beyond their value in conservation and technical analysis, these 3D models also play a crucial role in scientific communication, museum outreach, and virtual access, especially in cases where physical handling of the artefacts is limited due to fragility or institutional constraints. The models were further enriched by integrating data from UV-induced luminescence and visible light imaging, combining surface geometry with diagnostic imaging data to reveal hidden features, residues of organic materials, or areas of previous intervention [6]. To enhance the reliability of the reconstructions, particularly for components with shiny, reflective, or metallic surfaces, which typically present challenges in photogrammetric processing, polarized filters were applied to both light sources and camera lens during image acquisition. This approach helped to minimize specular reflections and reduce algorithmic reconstruction errors, thereby improving reconstruction and texture fidelity, as well as the visual realism of the final model. The resulting outputs offer a comprehensive digital replica that supports both scholarly research and long-term heritage management.

IV. MEASUREMENT INSTRUMENTS

A. Instrument 1

Among the historical scientific instruments examined within the scope of this study is a finely engineered Torsion Balance with circular dial, produced by the well-known German manufacturer Hartmann & Braun of Frankfurt am Main, Fig. 2. Dating from the 1930s, this instrument is a compelling example of early 20th century precision metrology, embodying both mechanical ingenuity and materials typical of pre-WWII German scientific craftsmanship. Its operation is based on a rotary lever mechanism which serves to compensate the torque exerted by the suspended load. The user finely adjusts the lever to bring the needle to the zero line, marked at the 3 o'clock position on the dial. This mechanical zeroing technique reflects the meticulous engineering standards of the era and allows for highly accurate readings. Once equilibrium is achieved, the weight can be read from one of the two circular mirrored scales, a design feature intended to reduce parallax error during measurement. This type of balance would have been used in a laboratory setting for scientific or industrial applications requiring extreme precision, and today it offers important insights into the evolution of micro-mass measurement.

Fig.2. Torsion Balance, Hartmann & Braun manufacturer, analysed by XRF and Raman.

To better understand the material composition and manufacturing techniques of the instrument, X-ray fluorescence spectroscopy was employed.

Spectral analysis was conducted on three distinct structural components, providing a detailed breakdown of the constituent materials. The main structural framework of the balance is composed of an alloy consistent with steel, suggesting resistance to corrosion and long-term durability, important attributes for instruments subjected to regular handling and environmental exposure. As shown in Fig. 3(1), the identified elements were primarily Fe, Ni and Mn together with trace amounts of Cr, As, and Rh. The significant presence of manganese is consistent with ferrous alloys commonly used during the period of the torsion balance, where Mn was added to improve strength and hardness. The presence of trace elements such as arsenic may be residues from manufacturing processes or surface treatments of the period.

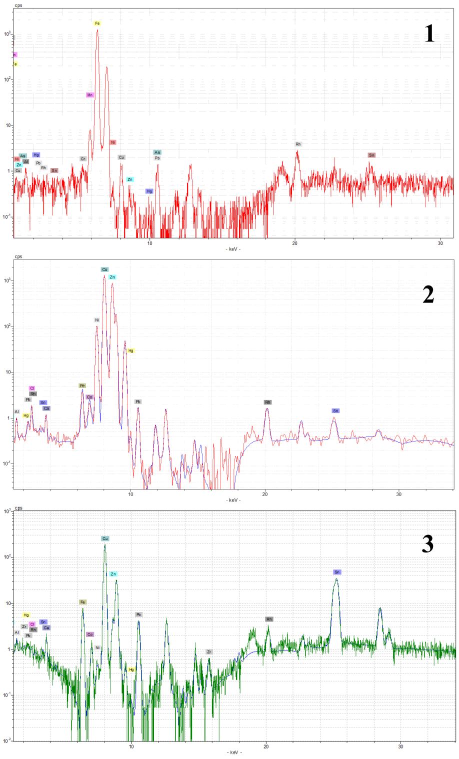

Fig. 3. Torsion Balance. XRF spectra recorded in different areas: (1) the back of the main body, (2) the adjusting rod on the front, (3) the load support.

X-ray fluorescence (XRF) analysis was used to identify the composition of the adjusting rod, which plays a crucial role in balancing the lever mechanism, Fig. 3(2). The results indicate that it is made of a Cu-Zn-Ni alloy, consistent with historical nickel silver, also known as German silver, rather than traditional brass. The deliberate inclusion of nickel alongside copper and zinc suggests intentional alloying to improve mechanical strength, corrosion resistance, and aesthetic qualities, nickel silver being particularly valued for its resemblance to polished silver. In addition to the main elements, the XRF spectra revealed the presence of Hg, and minor amounts of Fe, Sn, Co, Rh, which may reflect residuals from historical manufacturing processes or alloying impurities. The detection of chlorine (Cl) may be related to contamination from storage conditions.

Based on XRF analysis, Fig. 3(3), which revealed the presence of Cu, Zn), and Pb, it is reasonable to conclude that the load support is composed of a leaded brass alloy, a copper-zinc matrix with added lead, commonly used in precision mechanical components of the period for its strength, corrosion resistance, and excellent machinability.

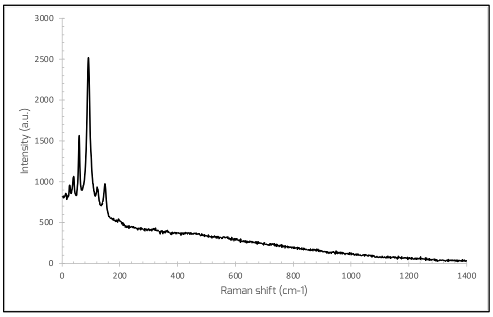

Fig. 4. Torsion Balance: Raman spectrum identifying goethite, α-FeO(OH), in the corrosion products on the base of the instrument.

Further insights into the degradation of the torsion balance were obtained through Raman spectroscopy, which targeted corrosion products on specific areas, particularly those showing reddish-brown discoloration indicative of oxidation. The analysis confirmed the presence of goethite, α-FeO(OH), a common iron oxyhydroxide formed under atmospheric conditions. Its identification was based on characteristic Raman bands around 300 cm^{-1}, 390 cm^{-1}, and 480 cm^{-1}, corresponding to the vibrational modes of its crystal structure.

These results strongly indicate that iron-rich components of the instrument have undergone gradual oxidative alteration, likely due to prolonged exposure to humid or oxygen-rich environments. The predominance of goethite, rather than more aggressive phases such as lepidocrocite or hematite, suggests a relatively stable and uniform corrosion process, likely occurring under low-chloride, low-sulphate conditions. This interpretation is further supported by the minimal detection of such anions in the XRF data. Overall, the findings are consistent with the instrument's age and storage history and underscore the slow yet persistent nature of corrosion in historical metallic artefacts, even when stored under generally stable environmental conditions.

B, Instrument 2

As part of an interdisciplinary initiative to document and analyse historical scientific instruments, an experimental photogrammetric workflow was applied to a finely crafted moving-coil galvanometer with mirror (first half of the 20th century) from the same collection, Fig. 5. This methodology addresses the well-known challenges of digitizing highly reflective metallic surfaces, typical of early 20th century scientific instruments, while enhancing surface characterization through multiband imaging.

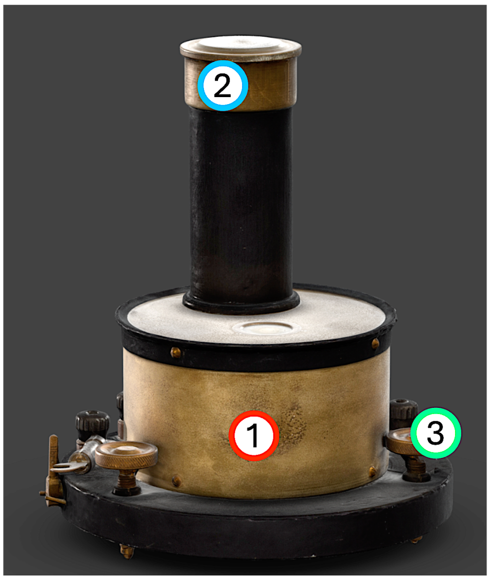

Fig. 5. Moving-coil galvanometer with mirror: High-resolution 3D reconstruction, with indication of XRF analysis areas.

The technique combines visible light (VIS) and ultraviolet-induced luminescence (UVL) imaging within a single high-resolution 3D model. To suppress specular reflections, which typically compromise accuracy when photographing polished or metallic surfaces, cross-polarizing filters were applied to both the light source and the camera. This setup enabled the creation of a high-fidelity mesh, capturing even subtle details such as tool marks, inscriptions, and corrosion features, with minimal optical distortion.

Two distinct texture maps were generated for the same geometry: (i) VIS texture, which provides a realistic rendering of the object's surface under standard illumination, revealing material finishes and morphological features (Fig. 5); (ii) UVL texture, which highlights areas with organic residues, varnishes, coatings, or corrosion products that fluoresce under UV excitation, revealing features invisible under visible light (Fig. 6).

This approach proved particularly effective for the galvanometer, whose metallic casing and internal elements present significant challenges due to their reflectivity and surface complexity. Conventional photogrammetry often struggles with such materials, producing highlight blowouts or distorted geometry. However, the cross-polarized setup mitigated these issues, resulting in a cleaner mesh and more faithful textures.

The UVL texture revealed luminescent responses on insulating components and terminal zones, which may correspond to aged organic coatings or contaminants introduced during handling or prolonged storage. These features, undetectable under VIS, offer valuable diagnostic information for material characterization and conservation assessment.

Fig. 6. UVL texture applied to the same 3D model of Fig. 5. Areas of luminescence reveal possible coatings or degradation residues.

By integrating the VIS and UVL textures onto a single digital replica, users can toggle between imaging modes to examine structural design, material decay, or evidence of past interventions. This layered visualization is especially valuable for researchers and conservators seeking to study the ageing behaviour of complex historical artefacts without compromising their physical integrity.

In parallel, to expand the analytical depth of the model, X-ray fluorescence (XRF) data were overlaid onto the 3D geometry of Fig. 6. Spectra acquired from several locations on the galvanometer revealed a predominance of brass across components, with subtle variations in elemental composition, Fig. 7. These minor differences, likely tied to specific functions or surface treatments align with standardized industrial practices of the early 20th century while offering insight into manufacturing techniques or repair history.

The integration of compositional, morphological, and spatial data into a single interactive platform greatly enhances the model's interpretative potential.

Researchers can navigate the artefacts virtually, accessing point-specific spectral data and correlating material composition with areas of wear, treatment, or degradation.

In summary, the photogrammetric pipeline developed in this study, featuring cross-polarisation, multiband texture mapping, and spectral data integration, represents a significant advancement in the digital documentation of reflective scientific heritage. Beyond supporting non-invasive diagnostics and comparative material studies, it offers new opportunities for virtual exhibition, educational use, and long-term conservation planning.

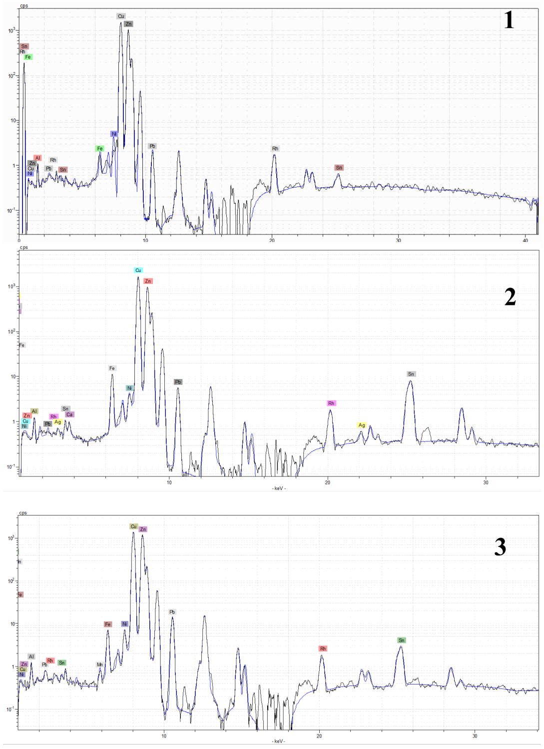

Fig. 7. Moving-coil galvanometer with mirror: XRF spectra recorded on the three areas indicated in Fig.5, reveal the presence of brass.

The more information embedded within the digital model, whether visual, analytical, or structural, the more comprehensive and valuable the documentation becomes, reinforcing the role of digital heritage tools in preserving and interpreting scientific instruments of historical and cultural significance.

V CONCLUDING REMARKS

This study demonstrates the value of integrating physico-chemical analysis with advanced imaging and digital documentation in the conservation of scientific heritage. The early to mid-20th century electrical instruments examined are not only milestones in the history of science and technology but also tangible artefacts of educational and industrial development in Italy and beyond.

The use of non-invasive techniques, such as portable XRF, Raman spectroscopy, and cross-polarized multiband photogrammetry, has enabled detailed analysis of materials, manufacturing methods, and corrosion processes without damaging the artefacts. These methods have clarified both original technological choices and long-term degradation mechanisms, including galvanic corrosion between dissimilar metals.

In parallel, the creation of high-resolution 3D digital models, enhanced with spectral and luminescence data, represents a major step forward in digital heritage. These models are powerful tools for documentation, monitoring, and conservation, and they support remote study, public engagement, and virtual exhibitions, especially when physical access is restricted.

The instruments studied also carry important historical and pedagogical value, many being linked to Galileo Ferraris, a pioneer in alternating current and engineering education. They reflect the evolution from mechanical to electronic instrumentation and Italy's active role in the international scientific community of the time.

The interdisciplinary methodology developed here can serve as a model for similar conservation projects, enabling long-term monitoring and comparative research across collections. Integrating compositional, structural, and visual data within unified digital frameworks opens new opportunities for collaboration and interpretation.

This work reinforces that scientific instruments are not merely obsolete tools, but cultural artefacts, witnesses to the intersection of science, technology, craftsmanship, and education.

ACKNOWLEDGEMENT

This publication is part of the project PNRR-NGEU which has received funding from the MUR – DM352/2022.

REFERENCES

[1] J.Bennett, "Science and Instruments, 1600–1900", Oxford University Museum of the History of Science, 1989

[2] N.R. Giere, "Scientific Perspectivism", University of Chicago Press, 2006.

[3] G.Ferraris "Rotazioni elettrodinamiche prodotte per mezzo di correnti alternate", Atti della Reale Accademia delle Scienze di Torino, 1888.

[4] S.MacDonald, "Preserving the Material Past: Materials, Artefacts and Conservation Science", UCL Press, 2011.

[5] T.de Caro, E.Angelini, L.Es Sebar, "Application of μ-Raman spectroscopy to the study of the corrosion products of archaeological coins", Acta Imeko, Vol.10, No.1, 2021, pp. 234-240.

[6] F.Di Iorio, G.Fiocco, R.Angeloni, L.Es Sebar, S.Croci, F.Cacciatori, M.Malagodi, F.Pozzi, S.Grassini, "Violins unveiled: a photogrammetric framework integrating multiband and spectroscopic data for in-depth examination of two musical instruments", Sensors, Vol.25, 2025