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Byzantine Sigillography and RTI: Insights from the DigiByzSeal Project in Cologne

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This contribution discusses the application of Reflectance Transformation Imaging (RTI) in Byzantine sigillography, focusing on the experience of the DigiByzSeal project in Cologne. The project addresses the challenge of analyzing damaged or corroded Byzantine seals by employing RTI, an imaging technique that involves multiple captures with varying light positions in order to reveal epigraphic and iconographic features that are otherwise invisible.

The paper also discusses the development of our RTI workflow, using an RTI Dome built at the Cologne Centre for eHumanities (CCeH), including capture preparation and determination of the optimal camera settings for each seal. Initially using *darktable* for tethered capturing, the project faced various issues and limitations, leading to the development of a custom capturing software. This software offers detailed control over camera configuration and streamlines the capture process, providing a user-friendly and efficient interface for capturing seals in a controlled environment. Further enhancements include the integration of Bluetooth connectivity to remotely control the RTI Dome, thereby fully automating the process. For the RTI processing part, *RelightLab* is presented as the software of choice, offering advantages over previously used tools in terms of user-friendliness and efficiency.

Finally, it is discussed how the RTI images obtained have proved crucial for the analysis and interpretation of seals from the Robert Feind Collection, showing the potential of RTI for studying damaged artefacts and contributing to research on Byzantine sigillography.

Cette contribution discute de l'application de la Reflectance Transformation Imaging (RTI) en sigillographie byzantine, en se concentrant sur l'expérience du projet DigiByzSeal à Cologne. Le projet aborde le défi de l'analyse des sceaux byzantins endommagés ou corrodés en utilisant le RTI, une technique d'imagerie qui implique plusieurs captures avec des positions de lumière variées afin de révéler des caractéristiques épigraphiques et iconographiques autrement invisibles.

L'article discute également du développement de notre flux de travail RTI, en utilisant un dôme RTI construit au Centre de eHumanities de Cologne (CCeH), y compris la préparation des captures et la détermination des réglages optimaux de l'appareil photo pour chaque sceau. Utilisant initialement darktable pour la capture en mode connecté (tethered), le projet a rencontré divers problèmes et limitations, ce qui a conduit au développement d'un logiciel de capture personnalisé. Ce logiciel offre un contrôle détaillé de la configuration de l'appareil photo et rationalise le processus de capture, offrant une interface conviviale et efficace pour capturer les sceaux dans un environnement contrôlé. Les améliorations supplémentaires incluent l'intégration de la connectivité Bluetooth pour contrôler à distance le dôme RTI, automatisant ainsi complètement le processus. Pour la partie traitement RTI, RelightLab est présenté comme le logiciel de choix, offrant des avantages en termes de convivialité et d'efficacité par rapport aux outils précédemment utilisés.

Enfin, il est discuté comment les images RTI obtenues se sont avérées cruciales pour l'analyse et l'interprétation des sceaux de la collection Robert Feind, montrant le potentiel du RTI pour l'étude des artefacts endommagés et contribuant à la recherche sur la sigillographie byzantine.

1 Introduction

§ 1 A major challenge in Byzantine sigillography is the vast number of specimens whose images and inscriptions, due to a high degree of damage or corrosion of the inscribed surface, cannot easily be recognized and read. Until now, these seals have often been excluded from scholarly publications or dedicated catalogues because the information they provide is usually too limited or unusable.

§ 2 Where direct inspection of the seal and the use of traditional photographic methods are not effective enough to read a damaged inscription or to understand the details of the iconography, other techniques, such as Reflectance Transformation Imaging (RTI), may be useful.

§ 3 RTI is an imaging technique in which objects are captured several times from a fixed camera position, varying the angle of the light source for each photo. Images are processed into a single, "relightable" RTI file, which can be viewed using dedicated software, for example the CHI *RTIViewer* (CHI 2024c), allowing the user to analyze the surface of the object by moving a virtual light source. In this way, epigraphic or iconographic features that cannot be detected with the naked eye or a high-resolution image can be made visible.

§ 4 For several years, RTI has been tested and used successfully on Byzantine lead seals at the Department of Byzantine and Modern Greek Studies of the University of Cologne in cooperation with the Cologne Center for eHumanities (CCeH) (Neuefeind et al. 2024; Catalano 2022; Catalano, Filosa, and Sode 2021, 298–304; Fischer and Makowski 2017). Presently, it is being used as part of the French-German project "DigiByzSeal – Unlocking the Hidden Value of Seals: New Methodologies for Historical Research in Byzantine Studies" (2022–2025). The aim of this project is to make approximately 2,000 seals from the private collection of Robert Feind digitally accessible, more than half of which show medium to severe damage or corrosion.

§ 5 The RTI workflow implemented in this project has been designed and continually adapted to meet the project's time and budget constraints without compromising the quality of imaging essential to facilitate research on the seals. It also ensures visual uniformity for subsequent display on the collection website. Given the necessity swiftly to train a team of assistants for competent and reliable execution of the process, emphasis was placed on the overall efficiency and user-friendliness of the workflow. At the time of writing, over 400 seals from the Robert Feind Collection have been captured and processed for RTI. The aim of this paper is to share insights into the RTI workflow, including challenges faced, solutions implemented, as well as observations that may be of interest to RTI practitioners and researchers interested in applying RTI to large collections of similar objects, and to those seeking to design or improve their own

RTI workflows. In what follows, we look in detail at the three main steps involved in producing a relightable RTI image from a seal: preparation of the seal, image capture, and image processing. A particular focus will be placed on the image capture phase, as it is the most time-consuming, the most problematic, and the one that has evolved the most over the course of our project. After a brief look at our data management strategy, the paper concludes with practical examples of how the RTI images produced have helped enable the reading of seals from the Robert Feind Collection.

2 The CCeH RTI Dome

§ 6 To capture the images, the Cologne team uses a custom RTI Dome built at the CCeH by a group led by Marcello Perathoner (Perathoner 2018). Whereas the more widely used Highlight RTI method consists of taking a series of images by manually rotating the light source (often a hand-held flash) around the object, the Dome method is characterized by fixed light arrays embedded in the Dome structure. The capture process can be fully automated, allowing for high image acquisition speeds as well as uniform and standardized images, making the Dome method particularly suitable for capturing an entire collection of a large number of very similar objects, such as seals.

§ 7 The CCeH Dome (**Figure 1**; **Figure 2**) consists of a hemispherical light-proof shell with a diameter of 50 cm with 60 LEDs mounted on the inside. The camera, a Nikon D800 with a Nikon AF-S Micro Nikkor 105mm f/2.8G ED lens for macro photography, is positioned on the top of the Dome, with its lens pointing down directly towards the seal inside the shell. The camera and LEDs are operated by an Arduino-based controller (**Figure 3**) that drives the LEDs and is able to control the camera. The controller has two modes of operation: a *pilot light* mode where it turns on all LEDs simultaneously for taking test exposures used to determine the optimum capture settings for a specific seal, and the *RTI run* mode for capturing a series of photos for processing into relightable RTI images.

Figure 1: The CCeH RTI Dome with the Nikon D800 camera mounted on top.

Figure 2: The LEDs mounted inside the Dome.

Figure 3: The controller box.

3 Capture preparation

§ 8 The seal is placed on an 18% Kodak grey card to allow for accurate and consistent exposure and colour balance calibration. A photographic scale is fixed to one side of the card to provide a reference for the size of the seal. The scale is as thin as possible to avoid casting shadows onto the adjacent seal. For each series of captures, the seal is placed closer or farther away from the scale depending on its size (roughly divided into three categories: small, medium, and large). This is done to ensure a degree of uniformity when the images are later cropped to create the RTI files, not only with respect to the obverse and the reverse of the same seal, but within the entire collection.

§ 9 After the seal is prepared, suitable camera settings have to be determined to ensure that the photos taken are sharp, have high detail resolution, and are correctly exposed. This involves finding a suitable combination of *aperture* (*f-number)*, *shutter speed*, and *ISO sensitivity.* The *aperture* controls the size of the lens opening. A smaller f-number corresponds to a larger lens opening, allowing more light onto the sensor. It affects not only the brightness, or *exposure*, of the image, but also the *depth of field*, meaning how much of the image appears sharply focused. *Shutter speed* determines how long the camera's sensor is exposed to light. In macro photography with stationary targets, this mainly affects the brightness of the image, but also how much it is susceptible to vibrations: a longer shutter speed increases the risk of blurring due to vibrations that could be caused by the camera's mechanics or external factors. The *ISO number* determines the sensor's sensitivity to light. A higher number allows for better exposure in low light conditions but can introduce noise or graininess to the image.

§ 10 Factors determining the optimal combination of these settings are the lighting conditions, subject or camera movement, the desired depth of field, the type of camera and lens use, and the physical characteristics of the target object such as colour and specularity. In RTI Dome photography, the controlled and consistent lighting and the immobility of the target allow for consistent camera settings throughout and in between shots and for some flexibility in the shutter speed. As high detail resolution is crucial for RTI, a smaller aperture (i.e., higher *f-number*) is desirable to ensure that the whole object is in sharp focus. However, higher *f-numbers* risk diffraction, which can reduce sharpness and introduce graininess and colour artefacts. In practice, seals have shown a specific sensitivity to lower *f-numbers*. Especially for larger seals and those with dents, bumps, or generally pronounced features (letters and iconography), numbers below *f18* have consistently led to blurry areas (as illustrated in **Figure 4**). To prevent under-exposure or images that are too dark, a higher *f-number* requires a longer exposure time, which in turn increases susceptibility to vibration-induced blurring. Therefore, the ideal setting is the least narrow *aperture* (i.e. the lowest *f-number*) where the whole seal remains in focus, paired with the shortest possible shutter speed that still allows enough light for correct exposure. A slight increase in *ISO sensitivity* can be a helpful adjustment, allowing for a faster shutter speed while keeping the image sufficiently bright.

§ 11 To determine the optimal capture settings, we conducted a series of tests with seals varying in colour, size, and surface characteristics (e.g., yellow-white patina, brown patina, grey patina). While for other set-ups the optimal values will differ, we found that apertures ranging from *f16* to *f20*, combined with shutter speeds between *1/5* and *1/6* of a second, generally yielded the best results, as we could raise ISO sensitivity to *200* (up from the default of *100*) without introducing perceivable noise.

§ 12 To save time during the shooting setup, the team compiled a reference list with images of various typical, representative seals, each paired with capture settings that have consistently produced optimal results. This serves as a practical guide to the assistants, providing them with a starting point that reduces the need for extensive experimentation.

Figure 4: Comparative shots of the reverse of seal SB-357 (Robert Feind Collection) at different apertures, the brightness held constant by adjusting shutter speed: *Aperture f13*, *shutter 1/15s*, *ISO 200* (left) and *Aperture f18*, *shutter 1/4s*, *ISO 200* (right). Notice the blurred parts of the image with wider aperture (i.e. lower f-number) on the left, especially at the surface of the letters and increasingly towards the outer area of the seal.

3.1 Deciding on RAW vs. JPEG capture

§ 13 Professional cameras have the ability to produce RAW image files instead of compressed JPEGs, thus containing the raw and uncompressed data from the image sensor. RAW files have the advantage that many more parameters of the image that influence quality and accuracy can be adjusted after capturing. RAW files need to be converted to JPEG before processing them into RTI images. RTI guides, for instance those by Cultural Heritage Imaging (CHI 2011) and Historic England (Historic England 2018), often recommend shooting in RAW format, followed by manual editing and conversion to JPEG for RTI processing input. However, our trials have shown that manually editing and converting RAW files to JPEGs, while aiming to match the camera's quality, is both time-consuming and prone to errors in our context, where we benefit from controlled and reproducible lighting conditions provided by the Dome setup. The consistent lighting environment lessens the need for extensive post-processing. As such, it was concluded that this process does not yield significantly better quality RTI images compared to using the camera's direct JPEG output. Recognizing that the camera is adept at producing high-quality JPEGs, the decision was made to use the

JPEGs generated by the camera for RTI, while still archiving the RAW images. This approach ensures that if there is a need to rethink this decision later in the project, or if any issues with the JPEGs emerge at advanced stages, new JPEGs can be created from the archived RAW files and processed into new RTI images.

4 Notes on the development of the capture workflow

§ 14 The Dome and the controller's hard- and firmware design draws inspiration from earlier designs, such as those by Kinsman (Kinsman 2016) and Pawlowicz (Pawlowicz 2017). In these, the controller automates the image capture process in the following way: it activates an LED, prompts the camera to take a photo, and then pauses for a predetermined duration to ensure the image is fully captured before moving on to the next LED. This cycle repeats itself until all LEDs have been used. The exact duration of each photograph can vary due to factors such as camera settings, image size, and the camera's internal buffer state. Since the controller cannot precisely detect when an image capture is complete, it must wait sufficiently long after each shot to ensure the LEDs are not turned off too early, in order to avoid collecting unusable images. Consequently, the actual time spent capturing most images during a session is often longer than the camera's exposure time.

§ 15 The CCeH controller takes a different approach by delegating the task of synchronizing flash and shutter to the camera (Perathoner 2018). This is achieved by utilizing the *continuous high-speed* or *burst* capture mode commonly found in professional cameras. In this mode, the camera takes a series of shots as fast as it can while the shutter button is activated. The controller acts just like an external flash gun that is activated by the camera for each shot, turning the external flash on only as long as required. When the RTI capture run is initiated on the controller, the controller triggers the shutter, and the camera starts taking photos. With each signal from the camera, the controller illuminates a different LED on the Dome. This process continues until each LED has been used for a single shot. Once all LEDs have been used, the shutter is turned off, marking the completion of the capture run.

§ 16 The Nikon D800 available for our project is a digital single-lens reflex (DSLR) camera, which uses a mirror to direct light from the lens to the viewfinder. During a photo capture, this mirror flips up to allow light to reach the digital sensor, and then flips back down post-exposure. This mechanism offers precise framing and focusing through the viewfinder. However, the mirror's movement for each photo can cause vibrations, potentially leading to slight blurriness in images under certain conditions. In practice, these vibrations have proved to notably reduce the sharpness of the RTI images if any photo in a series is affected by this issue.

§ 17 Flipping the mirror up and down in a DSLR not only causes potential vibrations, but also adds to the overall time taken for the capture process. To address these issues, some cameras offer a mode where the mirror is kept up continuously. While this disables the viewfinder, the camera's internal display (or a connected computer) can still show the live feed from the sensor. The minor loss in framing accuracy is not a concern in contexts such as Dome RTI photography, because the positioning of the camera and the target object is predetermined.

§ 18 The Nikon D800 does not have a specific mode to hold the mirror up, but, as with most professional cameras, offers an exposure delay mode that delays the shutter release for a set interval of time after the mirror flips to allow any vibrations to dissipate. However, the minimum delay possible on the D800 is one second. For an RTI capture run of 60 images, this adds a minute to the capture process.

§ 19 It has been found that the *live view* feature for the D800 serves as an effective workaround. In this mode, the live feed from the sensor is displayed on the camera's internal screen, bypassing the need for the mirror and viewfinder. When combined with the *continuous high-speed* mode, as used in our Dome setup, the mirror remains up throughout the entire capture series. This approach not only significantly reduces the time required for image capture, but also minimizes vibrations, leading to clearer and more consistent images. When buying a camera specifically to be used in RTI Dome photography, professional mirrorless cameras, such as from the Canon EOS R or the Nikon Z series, can be a viable alternative.

§ 20 The Dome's original design catered to a workflow commonly found in other projects, where series of images of one or several objects are captured and saved on a memory card such as an SD or CompactFlash card. These images are later transferred to a computer for processing into relightable RTI images. However, transferring images from the memory card to the computer is time-consuming. Additionally, this method makes it difficult to inspect the images right after capture for issues like blurriness. To overcome this, the use of tethered capture has been suggested for RTI captures (Wagensonner 2015). This method involves directly connecting the camera to a computer with a cable, allowing for immediate transfer of images. This approach saves time by enabling direct processing of the images into RTI files directly after capture, allowing for the immediate inspection of the resulting relightable images for issues like blurriness, which may not be apparent in the individual images.

4.1 Tethered capturing workflow with **darktable**

§ 21 Tethered capturing is supported in most professional cameras utilizing the *Picture Transfer Protocol (PTP)*. Regardless of its name, it not only transfers pictures from the camera to the computer, but also allows the remote control of certain camera functions. This can include changing capture settings such as exposure or aperture, or triggering the shutter to take a photo. It also allows the retrieval of a live preview of what the camera's sensor is seeing on the computer's screen, similar to using *live view* on the camera's rear display. To use tethered shooting, specific software that can communicate using this protocol is required. Available options include commercial software such as *Adobe LightRoom*, *CaptureOne*, and *SmartShooter*, closed-source freeware such as *SofortBild* for Mac, *qDslrDashboard* or *Nikon NX Capture*, and free and open-source software (FOSS) like *digiCamControl* for Windows, *Entangle* for Linux, as well as cross-platform FOSS options such as *darktable.* The project team assessed the above-mentioned freeware and FOSS software and found that all of them suffered from at least one of the following issues:

- Quirky, non-intuitive interfaces, which pose challenges for shooting assistants without a background in photography.
- Constraints in setting file names and directory patterns for image series, often requiring complex steps or being inflexible.
- Lack of cross-platform support, a crucial feature since our team uses Mac, Windows, and Linux.
- Problems with remote *live view* mode. Activating or deactivating live view randomly makes the software or the camera get stuck.
- Lack of stability; random crashes.
- Being closed-source, which limits adaptability and flexibility, features which are especially important for applications in research contexts.

As it was found that *darktable* posed the fewest challenges for accommodating the RTI workflow, it was decided to use this software for capturing the first seals in the collection. *darktable* is an image management, photography workflow, and photo-editing application geared towards (semi-)professional photographers. While being feature-rich, flexible, and customizable, its user interface is rather unique, quite complex, and has a steep learning curve. Still, a step-by-step guide produced by the project team, combined with hands-on training, enabled the assistants to quickly become acquainted with the software and produce good and consistent capture results.

§ 22 The *darktable*-based tethered workflow has been used for capturing the first seals. With this workflow, the Dome controller is connected to the camera using two cables: one for controlling the shutter, and one for receiving flash signals. The camera is connected to the computer using a USB3 cable for receiving captured photos and sending new settings and triggering shots. Any memory card in the camera should be removed, as it has been found that a card can sometimes interfere with the tethered capture process.

§ 23 The *darktable* user interface consists of several views, of which the “lighttable view” for managing images and image folders, the “darkroom view” for reviewing (and potentially editing) photos, and the “tethering view” (**Figure 5**) for controlling the camera and setting image metadata were those used in our process. The software enables users to establish a customizable naming pattern for filenames and for directories where images from a capture session are saved. This session is set up prior to beginning the capture, identified by a user-defined jobcode. *darktable* was configured to automatically save photos in a folder named after the jobcode, which we decided would always be the number of the seal being photographed. This approach ensures a uniform directory structure and eliminates the need for manual creation and naming of directories.

Figure 5: The *darktable* tethering view.

§ 24 The actual capture process in *darktable* then involves these steps:

1. Enable (“mount”) the camera in *darktable*’s UI and then switch to *tethering view.*
2. Set camera-specific capture settings that could have been reverted by the camera when turned off or might have been changed if the camera has been used for purposes other than RTI capturing. For the Nikon D800, it was found that setting *capture target* to “Internal RAM” and *recording media* to “SDRAM” was necessary to ensure a reliable tethered capture process. *Image quality* should be set to “NEF+Fine,” which makes the camera produce both a RAW and a high-quality JPEG file for each capture.
3. Create a new session using the jobcode “test,” which directs test capture images to a separate “test” folder. This segregation avoids confusion with the actual RTI image series, simplifying later processing.

4. Set seal-capture settings that depend on the physical characteristics of the seal, such as *aperture* (*f-number*), *shutter speed* and *ISO sensitivity*.
5. Capture a test photo using *darktable*'s interface, then switch to the *darkroom view* to examine its brightness, contrast, sharpness, and other qualities. If needed, adjust the capture settings, retake the photo, and repeat this process until the photo reaches the desired standard of quality.
6. Change to the *tethering view* again.
7. Start a new session using the seal number as the jobcode, ensuring images are stored in the appropriate folder for the RTI series.
8. Begin the RTI capture sequence via the Dome controller and wait for *darktable* to receive all image files.
9. Switch to the *lighttable view* to inspect the captured images.

4.2 Drawbacks of the darktable*-based workflow*

§ 25 While the *darktable*-based tethered capturing workflow for the most part worked well, a number of drawbacks were encountered:

- **Stability issues**: While *darktable* is generally stable and mature software, our specific setup and workflow requirements often led it to crash or to become unresponsive, particularly in the middle of a capture run. This could also leave the camera in a non-functioning state. Resolving these issues typically required multiple attempts to restart *darktable*, power cycling the camera, and reconnecting it to the computer. These disruptions necessitated frequent intervention by technical staff to restore functionality.
- **Limited support for *continuous high speed/burst* mode**: While taking a single photo is possible by clicking a button in *darktable*'s UI, it does not support operating the camera's *continuous high speed/burst mode*, which we use to capture the RTI series as quickly as possible. Thus, RTI series capture had to be initiated via the Dome controller.
- **Remote live view limitations:** The live preview feature in *darktable*, intended for remote image viewing from the camera, has consistently been unstable and thus deemed unreliable. Consequently, it was excluded from our workflow, and as a result, the camera's viewfinder had to be used for adjusting the position and focus of the seal.
- **Constraints in mirror-up operation**: Neither *darktable* nor any other evaluated tethered capture software supports the use of *continuous high-speed/burst* mode while keeping the camera's mirror up for reducing image blurriness due

to vibrations. The workaround of using *live view* mode to keep the mirror up, effective when capturing to a memory card, is not available in tethered mode as the camera disables the internal live view when connected to a computer. We thus resorted to using *exposure delay* mode, which, despite adding time to the process, proved faster than shooting to a memory card with the *live view* workaround and subsequently transferring files for processing.

4.3 Developing a custom capturing software

§ 26 In an effort to overcome these limitations, preliminary tests were conducted using *libgphoto2* (Meissner et al. 2024), a library utilized by *darktable* and other open-source tethering software for camera communication via the PTP protocol. Using available bindings for the *Python* programming language for this library enabled direct, low-level interaction with the camera, bypassing *darktable*'s constraints. This approach provided detailed control over the camera's configuration and the capture process, executed step-by-step through a Python script. This led to several discoveries:

- The camera being left in a non-functioning state when the capture process is interrupted for any reason was traced back to the need for the camera to clear its internal buffer memory. This buffer, used for temporary file storage before transferral to the computer, requires time to empty due to its faster processing speed compared to USB transfer rates. Interruptions in the receiving software can interfere with the camera's shooting ability.
- It was found that *continuous high-speed/burst* mode can be activated by sending a specific series of settings and commands to the camera. Additionally, a command to flip and hold the mirror up before initiating burst capture was identified. These features were inaccessible in tethering software, likely due to their niche application in our specific process requirements and the particular camera model used.

These insights showed the viability of implementing a highly optimized, completely automated tethered capture process that combines mirror-up operation with continuous high-speed capturing. It was consequently decided to create a custom capturing software with a user interface specifically tailored to the RTI workflow intended to replace *darktable* for the capturing segment of our process.

§ 27 The open-source software (Schaeben 2023) is developed in *Python* and uses the *python-gphoto2* bindings (Easterbrook 2023) for the *libgphoto2* camera communication library, which is written in *C*. For its user interface, it uses the *PyQT6* bindings to the cross-platform *Qt* framework written in *C++*. Using *Python* and *Qt* ensures cross-platform compatibility with Mac, Windows, and Linux. In addition to the implementation of the optimized capture process, it was designed with the following key requirements in mind:

- **Robustness and fail-safe mechanisms:** The software was designed to be resilient, capable of handling such disruptions as lost camera connections or process interruptions. Communication with the camera happens in a separate thread, ensuring that the user interface is always responsive. If problems arise or anything gets stuck, the software employs several strategies to re-establish a functioning state without user intervention. For instance, it ensures the camera buffer is consistently cleared to prevent lockups.
- **Automated camera configuration:** As outlined in the *darktable* workflow, critical settings such as *capture target*, *recording media*, and *image quality* need to be correctly set in preparation for tethered shooting. As these remain consistent across all captured objects, they are automatically set before each capture is initiated. This eliminates the need for users to remember and possibly correct these settings.
- **Automated file management:** On initiating a capture session, the software automatically creates a corresponding directory structure on the disk. Test captures are segregated from the image files from the RTI series, avoiding the need to manually change directories to prevent later mix-ups at the processing stage. Additionally, it copies a light position (LP) file for the Dome (which contains the exact positions and angles of each LED on the Dome needed for RTI processing) alongside the captured images, so it can be automatically picked up by the RTI processing software. In case of a need to interrupt or restart the capture process, it offers an option to clear previous files, avoiding any mix-ups before processing.
- **Reliable live-view integration:** The software includes a stable and dependable live-view feature assisting in positioning and focusing the seals that was designed for seamless integration with the overall workflow.
- **User-friendly and workflow-oriented interface:** The user interface was designed to be simple and self-evident, providing all functionality required for the RTI capture workflow, and nothing more. It only exposes those camera settings to the user that need to be altered for each captured object.

4.3.1 First trials and further improvements

§ 28 After the initial version of the software was developed and introduced to the shooting assistants, the first captures of seals demonstrated a notable reduction in processing time. The assistants reported ease of use and increased comfort, along with a decrease in potential errors, thus lessening both mental strain and the likelihood of needing to discard and redo captures. Additionally, the need for involving CCeH staff for troubleshooting problems was significantly reduced. But still more room for improvement was identified.

§ 29 The CCeH Dome and controller were designed with portable, non-tethered operation in mind, shooting to a memory card without the need for a computer. It is only connected to the camera to trigger shots and receive flash signals, and to the Dome itself to turn LEDs on and off as required. While this design is simple, flexible, and self-contained, it does present some obstacles to a smooth tethered shooting process. Operating the controller in order to, for instance, turn on and off the *pilot lights* for positioning and focusing the seal, requires physical movement to and from the controller and careful attention to ensure the correct sequence of buttons is pressed. This manual operation becomes particularly problematic if an RTI run encounters difficulties or has to be aborted before completion. In such cases, the LED counter on the controller must be reset by pressing the reset button, otherwise the next run may not start correctly, potentially beginning with the wrong LED.

§ 30 To address this, a Bluetooth module has been added to the controller and its firmware has been updated to allow for remote control by the image acquisition software developed for this project. With the integration of Bluetooth connectivity, the controller can now be operated remotely to turn the pilot lights on and off and to reset the LED counter when necessary. This has fully automated the process, seamlessly integrating these controls into the overall capture procedure. As a result, manual interventions are no longer needed, further streamlining the workflow and reducing the time and effort needed for a capturing run.

4.3.2 Final tethered capturing workflow using CCeH’s capturing software

§ 31 The user interface of the capturing software (**Figure 6**) reflects the two stages of capturing: testing and adjusting the capture settings by taking one or more test images, and then capturing the RTI image series.

§ 32 Before starting the capture process for a seal, a session is created, named after the number of the seal that will be captured. After entering the seal number and clicking the *create session* button, a corresponding directory structure is created on the disk, and the shooting controls are enabled.

§ 33 The capture session starts in *preview* mode. Here, users will first activate the remote *live view*, which retrieves a low-resolution, real-time preview of what the camera’s sensor is seeing. A click on the *live view* button will enable the *pilot lights* on the controller and begin to grab preview images from the camera. This is used to check and

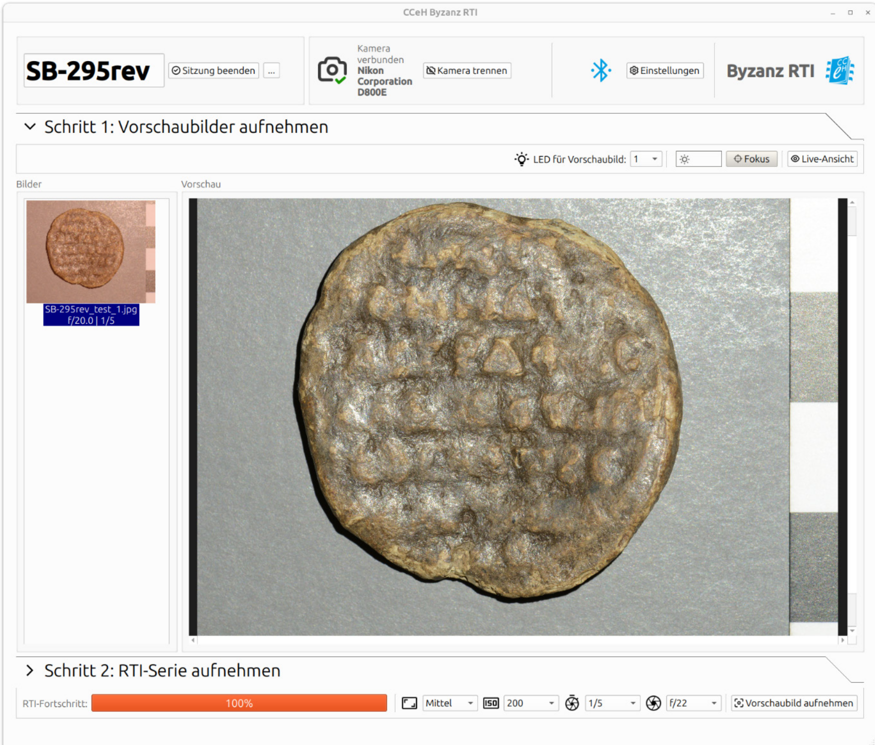

Figure 6: *Preview* mode of the CCeH capture software.

adjust the positioning of the seal. Focus can either be adjusted manually using the focusing ring of the lens or through the camera's autofocus, activated via the focus button in the capturing software. From experience, the autofocus on the Nikon D800 works extremely well for our purposes. While careful manual focusing does not significantly improve results, it does require more time. Therefore, we prefer autofocus in our workflow.

Figure 7: Capture settings.

§ 34 In the next step, the relevant capture settings are adjusted (**Figure 7**). These are, from left to right: *capture format*, *ISO sensitivity*, *shutter speed*, and *aperture*. The *capture format* setting has been added because the Nikon D800 offers an option to use only a portion of the photo sensor, effectively cropping the image to predetermined dimensions before saving or transferring it. This feature, originally intended for compatibility with lenses designed for smaller sensors, benefits our workflow by reducing file sizes. Since we preserve both RAW and JPEG files, and RAW files are sizable, this adjustment is crucial for speeding up file transfer. During capture, the camera simultaneously writes files to its internal buffer and begins transferring them to the computer. However, the transfer rate lags behind the camera's photo capture and buffering speed. Once the buffer is full, capturing is paused until enough files are transferred to the computer to free up buffer space. Most seals comfortably fit within the medium or small cropped image sizes, so selecting a smaller size when feasible significantly cuts down the total time for a capture run.

§ 35 Once the settings have been adjusted, a click on *capture preview image* triggers the camera to take a photo using the specified settings. By default, the software directs the Dome controller to activate the first LED for the preview shot, located on the Dome's upper LED ring. This light illuminates the seal from a high angle, ensuring consistent lighting and comparability across shots. The resulting image can be reviewed in the capture software's interface, allowing for further adjustments and additional preview shots to be taken if needed. All preview images for a session are displayed in the left sidebar along with their respective capture settings, so they can be reviewed and compared to help determine the optimal settings.

§ 36 When ready, the interface can be transitioned into *RTI series capture* mode. Here, a click on *start capture* will initiate the capture sequence. The incoming images appear on the left sidebar and can be inspected as they come in. The capture run can be cancelled at any time if necessary and re-started.

4.4 RTI processing with **RelightLab**

§ 37 Until recently, *RTIBuilder,* developed by the Cultural Heritage Institute (CHI 2024b), was the go-to software for processing RTI image series. It serves as a graphical interface for the *PTMFitter* tool, a command-line utility released by HP Labs in 2001 (HP Labs 2001). *PTMFitter* is the core component that processes individual images into a relightable image. However, it must be downloaded separately and has become difficult to find nowadays. Despite its widespread mention in nearly all current RTI guides, *RTIBuilder* has significant drawbacks. It has not seen updates since around 2013, and *PTMFitter* has been discontinued by its creators. Running the software on recent Windows or Mac systems is challenging, and there is no official Linux support. Its user interface, requiring several steps, some redundant for Dome-based RTI, assumes a highly specific and nested directory structure for input files. Users must manually select the light position (LP) file and the software struggles with directory names containing spaces or image files with uppercase JPEG extensions—a common default naming pattern in many cameras. This requires meticulous manual preparation and can lead to time-consuming troubleshooting when problems occur; discussions of these problems and their workarounds can be found on the CHI Forums (CHI 2024a).

§ 38 A new RTI processing software, *RelightLab*, has been in active development by Federico Ponchio and his team at the *Visual Computing Lab* of the *Istituto di Scienza e Tecnologie dell'Informazione* (CNR-ISTI) (Ponchio 2024). Written in *C++*, it is a cross-platform suite that includes image processing routines for creating RTI files with various algorithms, a command-line interface, and a graphical user interface suitable for both Dome and Highlight RTI workflows. At the outset of the ANR/DFG project in 2022, we assessed *RelightLab* as a potential alternative to *RTIBuilder/PTMFitter*. We found it not only functional but, even in its developmental stage, also more user-friendly and efficient. Comparisons of RTI images processed from the same input files with *RelightLab* and those produced using *RTIBuilder/PTMFitter* revealed minor differences in colour accuracy, but overall, the image quality was similar. For these reasons, coupled with its active development and the developer's responsiveness to queries and issues, we decided to use *RelightLab* as the RTI processing software in our project. In March 2023, CHI officially recognized *RelightLab* as the successor to the now outdated *RTIBuilder* (Schroer 2023).

4.4.1 Importing and cropping the images

§ 39 Importing the image series of an object into *RelightLab* for processing is as easy as opening the folder that contains the image. The light position (LP) file for the Dome, copied alongside the images by the capturing software, is loaded automatically if found. Just as with *RTIBuilder*, *RelightLab* allows the JPEG images to be cropped prior to processing, which is important to ensure a uniform display for the whole collection (**Figure 8**). To maintain consistency, the cropping process includes several key steps, amongst others: choosing the same aspect ratio for the frame for all seals (we use the postcard format for our project); ensuring the central placement of the seal in the frame chosen when cropping; and keeping the same size and, as far as possible, the same position of the cropping frame for the reverse and the obverse of one seal.

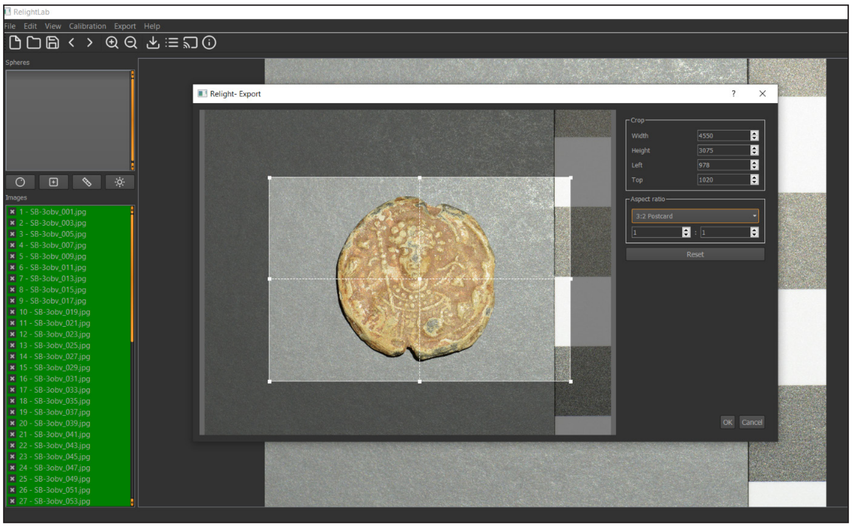

Figure 8: *RelightLab*, cropping settings.

4.4.2 Choosing an output format

§ 40 After cropping, an output format for the resulting RTI file has to be chosen. *RelightLab* supports several of these. Polynomial Texture Maps (PTM) is widely used and was the first format developed for encoding RTI images (Malzbender, Gelb, and Wolters 2001). A more recent and also widely used alternative, based on different mathematical principles, is the Hemispherical Harmonics-based HSH format developed by CHI (Wang et al. 2009) and also supported by *RTIBuilder*, which promises better detail and higher accuracy, especially for highly reflective surfaces (Historic England 2018, 27; see also CHI director Carol Schroer's comment on whether to choose PTM or HSH on the CHI forums at Schroer 2012). Currently, we use the PTM format for our output to use in research. The reason is twofold: first, the rendering software *RTIViewer* (Palma 2024) implements more rendering modes for PTM than for HSH, and secondly, it has shown that while HSH usually produces more granular images that highlight the texture of the surface, this has not generally been useful for improving the readings of the seals (see also the examples in **Figure 9**). Besides PTM and HSH, *RelightLab* supports additional formats, such as RBF and YCC, and also offers different encoding parameters for each of these formats (Ponchio, Corsini, and Scopigno 2019; for an interactive web-based comparison of all supported formats, see Ponchio 2019). It also supports exporting these formats suitable for distribution on the web and for viewing in a browser using the *OpenLIME* (CRS4 and CNR–ISTI Visual Computing Lab 2022) viewer. Each of these formats comes with a set of advantages and trade-offs, and an in-depth comparison and analysis of which format and what parameters to use in which cases would be beneficial. When our project starts publishing the RTI images on the collection website, a decision for a suitable web format will have to be made.

§ 41 However, as we keep the original JPEG and light position files, the decision for an output format is not set in stone. If deemed of interest in the future, different RTI formats such as HSH can always be generated from the input at a later time.

4.5 Data management

§ 42 The captured images in JPEG and RAW formats as well as the processed RTI files are primarily stored on external hard disks. As a first data protection measure, all files are synchronized to Nextcloud, a self-hosted, open-source cloud storage and collaboration software instance provided by the CCeH as soon as they are produced. This has the additional advantage that the RTI images can be instantly used in teaching and research. As a second data protection measure, an archiving workflow has been established in collaboration with the Data Center for the Humanities (DCH) at the University of Cologne. The DCH periodically acquires batches of our data, augments them with crucial metadata for optimal long-term retention, and transfers them to the university's computing centre for tape-based archival storage. While the JPEG files are always kept available, the RAW files are deleted after each archiving run to save space on the hard disks. If the need arises, they can be retrieved from the archive at any time.

4.6 Results of RTI applied to research on seals

§ 43 The resulting RTI images can be displayed and analyzed with suitable software such as the *CHI RTIViewer* or *OpenLIME*. Unclear characters and iconographic features can be zoomed in and focused by finding a suitable lighting angle, while further details can be enhanced using various display modes. In particular, the Specular Enhancement, Normals Visualization, and Diffuse Gain modes, implemented by the RTIViewer for RTI files, have proved beneficial for seal analysis (**Figure 9**).

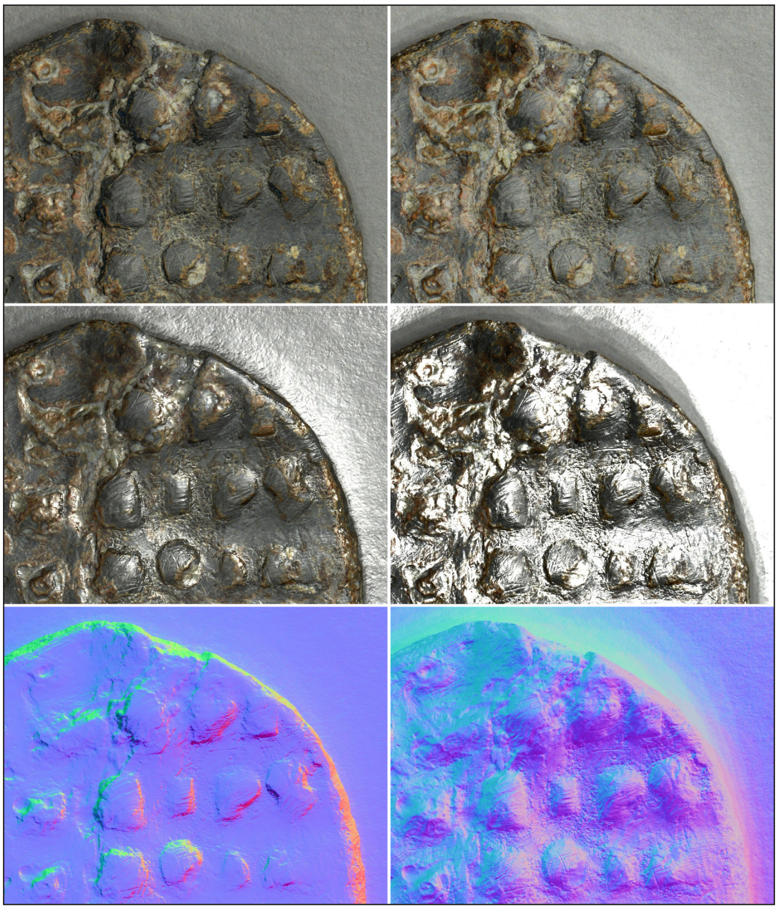

Figure 9: Reverse of seal SB-258 (Robert Feind Collection) captured with different rendering modes. Top left: Diffuse Gain PTM; top right: Default HSH RTI. Middle left: Specular Enhancement PTM; middle right: Specular Enhancement HSH RTI. Bottom left: Normals Visualisations PTM; bottom right: Normals Visualisations HSH RTI.

§ 44 The analysis and interpretation of seals from the Robert Feind Collection is the topic of regular research meetings within the DigiByzSeal project. As the RTI files are stored in the cloud, all participants can access them from anywhere at any time. This allows them to prepare and review the material as required before and after each session. Using RTI files has reduced the need to examine the original objects, while at the same time improving the likelihood of a successful interpretation of their inscription or iconography. For instance, almost the entire inscription on the reverse of SB-42 (**Figure 10**), an eleventh-century seal from the Robert Feind Collection that has suffered significant damage and corrosion, was restored following the RTI process.

Figure 10: Left: reverse of SB-42 (Robert Feind Collection) captured with a Canon EOS 300D. Foto: Robert Feind; right: RTI of reverse of SB-42 (Robert Feind Collection) displayed with the rendering mode Diffuse Gain.

The inscription of the seal SB-42 can now be read as follows:

.ΙΚΟΛ,|.Π̣ ΙΣΚΟ|..ΡΑΛΛ̣ |.ΩΝ

Νικολ(άῳ) [ἐ]πισκό[π(ῳ) Τ]ράλλ[ε]ων

The issuer is safely identified as Nikolaos, bishop of Tralleis (*PBW* Nikolaos 20191; PBW 2016). However, the improvements in legibility are insufficient for a complete reconstruction of the genitive plural of the town of Tralleis. The forms Τράλλων and Τράλλεων are both attested without distinction (Nesbitt and Oikonomides 1996, 52), and both may be possible here. At the beginning of the last line, there is space for an *epsilon* that may have been erased and is now undetectable even in RTI images. In this instance, the correct interpretation can be inferred by comparing the seal with similar ones (not parallel specimens) of Nikolaos (IFEB 275, published in Laurent 1963, no. 268; another seal is published in Schlumberger 1884, 260; two seals belonging to the Dumbarton Oaks Collection: BZS.1955.1.4668 and BZS.1958.106.135 [Nesbitt and Oikonomides

1996, no. 38.4a and 38.4b] are also published in *DO Online* [Dumbarton Oaks 2020a; Dumbarton Oaks 2020b]), and by the arrangement of the letters on the surface of the object, both of which point to Τράλλεων.

§ 45 The effectiveness of the RTI technique relies on the condition of the object. Our experience from the research meetings suggests that a complete inscription may often be retrieved by identifying a small number of letters, particularly if a similar or parallel seal is found in a database by using the collected data. Currently, around 80 damaged seals from the Robert Feind Collection have been analyzed solely based on RTI images. Of these, roughly 70% were successfully interpreted, evidencing the potential of RTI technology to study collection artefacts that have not undergone comprehensive examination due to their poor condition (Catalano 2022, 156–157).

5 Conclusion

§ 46 By learning from experience and consistently refining our processes, we have arrived at an efficient workflow for Dome RTI tailored specifically to the documentation of seals. Streamlining the capture preparation phase by, for instance, creating and providing reference material for the camera settings, as well as using *RelightLab* instead of *RTIBuilder* in the RTI processing phase, has resulted in significant efficiency boosts. With the current version of our workflow, it takes on average approximately 10 minutes to fully prepare, capture, and process a set of images into an RTI file for one side of a seal.

§ 47 While a streamlined tethered capture workflow is attainable with freely available software such as *darktable* (which might work more reliably for other camera models and Dome configurations) or commercial alternatives, the efficiency of the capture phase was increased by developing a custom tethering software, emphasizing the advantages of collaborative efforts between domain experts and DH centres.

§ 48 With the current version of our workflow, it takes on average 10 minutes to fully prepare, capture, and process a set of images into an RTI file for one side of a seal, which is a significant reduction from the 20–30 minutes per side per seal required in earlier versions. Importantly, the improvements not only reduce time, but also ensure process reliability and user-friendliness, allowing new assistants to be trained quickly to produce consistent, high-quality results without much supervision.

§ 49 While it would be desirable to know how our process compares to other commercial or publicly funded RTI systems (such as broncolor [broncolor 2024] and Truvis [Truvis 2024] with the Truvis Authentica RTI processing software or the domes built by RTI Dome [RTI Dome 2023]), we do not have access to such systems at the current stage of the project.

§ 50 Though our software is tailored to our specific requirements, it can accommodate other workflows and is currently being prepared for adoption by the French team of the ANR/DFG project, which will use different Dome and camera models.

§ 51 From a sigillographic perspective, this article has illustrated the benefits of using the RTI technology applied to seals as demonstrated by the case study from the Robert Feind Collection.

§ 52 The practical benefits of this technology, particularly for seals that have undergone significant wear or damage, are also demonstrated by the high success rate in interpreting specimens in poor condition achieved in the DigiByzSig project, on the basis of RTI images alone. For the first time, previously inaccessible specimens can now be thoroughly examined and integrated into scholarly research.

§ 53 RTI has proven to be a valuable technique for addressing challenges associated with the preservation of historical artefacts, combined with the need to make them accessible to a wide range of researchers. By integrating data management practices such as cloud synchronization, we have enabled the direct use of RTI images in ongoing research, narrowing the gap between image acquisition and scholarly analysis while also ensuring the longevity of the images and associated metadata. Accessibility of collection objects is improved, opening them up to scholars for more nuanced examination than traditional photographs allow, regardless of their location. Finally, the adoption of RTI images reduces the need for autopsy of the seal, thereby reducing the need to handle the artefacts, which helps protect them from the corrosive effects of human skin contact, consequently limiting the risk of physical damage.

§ 54 By sharing our experiences and insights into using RTI technology in Byzantine sigillography, we aim not only to raise awareness of its effectiveness and numerous benefits, but also to help reduce the barriers to its use and encourage its wider adoption by institutions and collection owners.

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Competing interests

The authors have no competing interests to declare.

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References

broncolor. 2024. "Scope D50." Accessed July 2. https://broncolor.swiss/products/scope-d50.

Catalano, Maria Teresa. 2022. "Nutzen und Grenzen der RTI-Fotografie am Beispiel von zwei stark beschädigten byzantinischen Bleisiegeln." *Studies in Byzantine Sigillography* 14: 147–157. Accessed June 20, 2024. https://doi.org/10.1484/M.SBS-EB.5.132253.

Catalano, Maria Teresa, Martina Filosa, and Claudia Sode. 2021. "Byzantine Seals from the Robert Feind Collection in Cologne. Research and Publication in the Context of the Digital Humanities." *Revue des Études Byzantines* 79: 297–322. Accessed June 20, 2024. https://doi.org/10.2143/REB.79.0.3289649.

CHI (Cultural Heritage Imaging). 2011. *Reflectance Transformation Imaging: Guide to Highlight Image Processing (Version 1.4)*. Accessed June 20, 2024. https://culturalheritageimaging.org/What_We_Offer/Downloads/rtibuilder/RTI_hlt_Processing_Guide_v14_beta.pdf.

———. 2024a. *CHIforums*. Accessed June 26. https://forums.culturalheritageimaging.org/.

———. 2024b. "Process: RTIBuilder Download." Accessed June 26. https://culturalheritageimaging.org/What_We_Offer/Downloads/Process.

———. 2024c. "View: RTIViewer Download Version 1.1." Accessed June 26. https://culturalheritageimaging.org/What_We_Offer/Downloads/View.

CRS4 and CNR–ISTI Visual Computing Lab. 2022. "OpenLIME (Open Layered IMage Explorer) (Version 1.0.1)." GitHub. Accessed June 26, 2024. https://github.com/cnr-isti-vclab/openlime.

Dumbarton Oaks. 2020a. "Nicholas Bishop of Tralleis (Eleventh Century) [BZS.1958.106.135]." *Dumbarton Oaks Research Library and Collection*. Accessed July 2, 2024. https://www.doaks.org/resources/seals/byzantine-seals/BZS.1958.106.135.

———. 2020b. "Nicholas Bishop of Tralleis (Eleventh Century) [BZS.1955.1.4668]." *Dumbarton Oaks Research Library and Collection*. Accessed July 2, 2024. https://www.doaks.org/resources/seals/byzantine-seals/BZS.1955.1.4668.

Easterbrook, Jim. 2023. "Python Interface to libgphoto2 (Version 2.5.0)." GitHub. Accessed June 26, 2024. https://github.com/jim-easterbrook/python-gphoto2.

Fischer, Franz, and Stephan Makowski. 2017. "Digitalisierung von Siegeln Mittels Reflectance Transformation Imaging (RTI)." *Paginae Historiae* 25(1): 137–141. Accessed June 21, 2024. https://kups.ub.uni-koeln.de/7882.

Historic England. 2018. *Multi-Light Imaging. Highlight-Reflectance Transformation Imaging (H-RTI) for Cultural Heritage*. Accessed June 26, 2024. https://historicengland.org.uk/images-books/publications/multi-light-imaging-heritage-applications/heag069-multi-light-imaging.

HP Labs. 2001. "Polynomial Texture Mapping (PTM)." Accessed June 26, 2024. Available via the Internet Archive's Wayback Machine. https://web.archive.org/web/20141103231547/http://www.hpl.hp.com/research/ptm.

Kinsman, Ted. 2016. "An Easy to Build Reflectance Transformation Imaging (RTI) System." *The Journal of Biocommunication* 40(1): e4. Accessed June 26, 2024. https://doi.org/10.5210/jbc.v40i1.6625.

Laurent, Vitalien. 1963. *Le corpus des sceaux de l'empire byzantin*. Vol. 1, *L'église*. Paris: Centre National de la Recherche Scientifique.

Meissner, Marcus, Lutz Müller, Scott Fritzinger, and Hubert Figuiere. 2024. "The libgphoto2 Camera Access and Control Library." GitHub. Accessed June 26. https://github.com/gphoto/libgphoto2.

Malzbender, Tom, Dan Gelb, and Hans Wolters. 2001. "Polynomial Texture Maps." In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques*, 519–528. Accessed June 26, 2024. http://doi.org/10.1145/383259.383320.

Nesbitt, John, and Nicolas Oikonomides. 1996. *Catalogue of Byzantine Seals at Dumbarton Oaks and in the Fogg Museum of Art*. Vol. 3, *West, Northwest and Central Asia Minor and the Orient*. Washington DC: Dumbarton Oaks Research Library and Collection.

Neuefeind, Claes, Jan Bigalke, Maria Teresa Catalano, Sviatoslav Drach, Sofia Efthymoglou, Pia Evening, Martina Filosa, Christos Malatras, Marcel Schaeben, and Claudia Sode. 2024. "Signed, Sealed, Delivered – Digital Approaches to Byzantine Sigillography." *it – Information Technology*. Accessed June 17. https://doi.org/10.1515/itit-2023-0030.

Palma, Gianpaolo. 2024. "Reflectance Transformation Imaging (RTI): RTIViewer." Accessed June 26. https://vcg.isti.cnr.it/rti/rtiviewer.php.

Pawlowicz, Leszek. 2017. "Affordable Reflectance Transformation Imaging Dome." Revision 3b4488a8. Accessed June 26, 2024. https://artid.readthedocs.io/en/latest/index.html.

PBW (Prosopography of the Byzantine World). 2016. "Nikolaos 20191." Accessed July 23, 2024. https://pbw2016.kdl.kcl.ac.uk/person/Nikolaos/20191/.

Perathoner, Marcello. 2018. "RTI Documentation." RTI (Reflectance Transformation Imaging) project at CCeH. Accessed June 26, 2024. https://cceh.github.io/rti.

Ponchio, Federico. 2019. "Relight: An Efficient and Versatile RTI Compression Format." CNR-ISTI Visual Computing Lab. Accessed July 31, 2024. https://vcg.isti.cnr.it/vcgtools/relight/comparison/index.html.

———. 2024. "Relight: Relightable Images." CNR-ISTI Visual Computing Lab. Accessed July 23. https://vcg.isti.cnr.it/vcgtools/relight/.

Ponchio, Federico, Massimiliano Corsini, and Roberto Scopigno. 2019. “RELIGHT: A Compact and Accurate RTI Representation for the Web.” *Graphical Models* 105: 101040. Accessed June 26, 2024. https://doi.org/10.1016/j.gmod.2019.101040.

RTI Dome. 2023. “Home.” Accessed July 2, 2024. https://www.rti-dome.com/.

Schaeben, Marcel. 2023. “Byzanz RTI Capture Tool.” Universität zu Köln. CCeH GitLab. Accessed June 26, 2024. https://gitlab.cceh.uni-koeln.de/Marcel/byzanz-capture.

Schlumberger, Gustave. 1884. *Sigillographie de l’Empire byzantin*. Paris: Ernest Leroux.

Schroer, Carol [cdschroer]. 2012. Reply to “HSH or PTM – How to Choose the Best Fitter,” *CHIforums*, September 17. Accessed June 26, 2024. https://forums.culturalheritageimaging.org/topic/190-hsh-or-ptm-how-to-choose-the-best-fitter/#comment-202.

———. 2023. “RelightLab to Replace RTIBuilder,” *CHIforums*, March 27. Accessed July 2, 2024. https://forums.culturalheritageimaging.org/topic/3849-relightlab-to-replace-rtibuilder.

Truvis. 2024. “Helios S53.” Accessed July 2. https://www.truvis.ch/authentica/helios.html.

Wagensonner, Klaus. 2015. “On an Alternative Way of Capturing RTI Images with the Camera Dome.” *Cuneiform Digital Library Notes* 1. Accessed June 26, 2024. https://cdli.mpiwg-berlin.mpg.de/articles/cdln/2015-1.

Wang, Oliver, Prabath Gunawardane, Steve Scher, and James Davis. 2009. “Material Classification Using BRDF Slices.” In *2009 IEEE Conference on Computer Vision and Pattern Recognition*, 2805–2811. Accessed June 26, 2024. https://doi.org/10.1109/CVPR.2009.5206558.