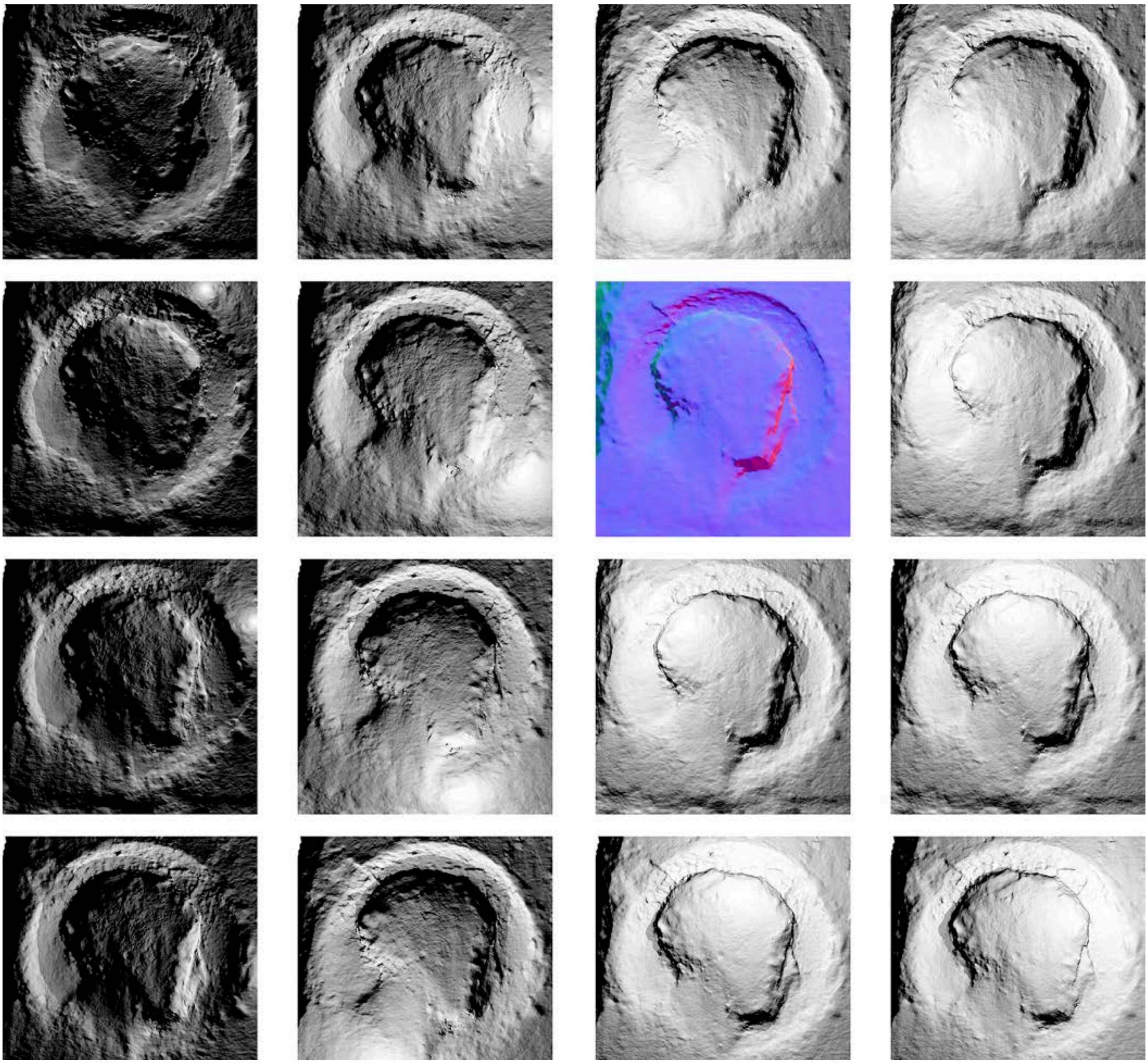
Historic England

Multi-light Imaging

Highlight-Reflectance Transformation Imaging (H-RTI)

for Cultural Heritage



Summary

This publication offers user-friendly guidelines and advice on recording cultural heritage by capturing the surface of an object through multiple photographs which, when processed, enable the enhancement of surface-level details. This technique is flexible, versatile and can be undertaken at low cost with a minimum of equipment, and has the potential to greatly enhance our understanding of heritage assets.

These guidelines focus on the equipment required and the method to produce Highlight-Reflectance Transformation Imaging (H-RTI). There are quick reference tips throughout the publication and a glossary that includes common abbreviations. References and useful links have also been provided.

A wide range of case studies have been included to demonstrate how the approach can be used to better record and understand cultural heritage. These practical examples provide solutions to some of the common challenges encountered in using this recording approach and some of the ways in which the RTI methodology can be adapted to new environments.

This document has been commissioned by Historic England and prepared by Sarah M Duffy of the University of Liverpool, Tom Goskar of Curatorial Research Centre, and Paul Backhouse and Hannah Kennedy of Historic England. It is one of a series of documents on heritage and recording.

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Front cover:
Memorial to Major John Cartwright, digitally lit using Highlight-Reflectance Transformation Imaging (H-RTI).

HistoricEngland.org.uk/advice/technical-advice/recording-heritage/

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1 Introduction

Aim

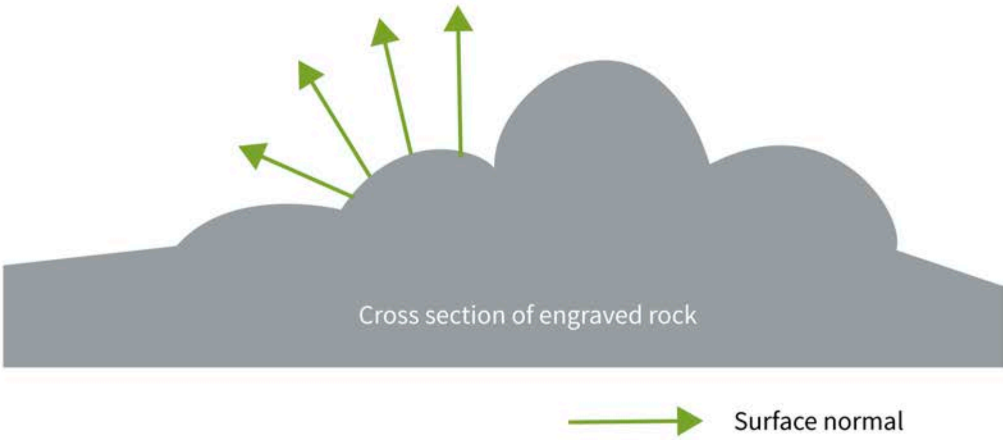
This publication provides practical guidance on Reflectance Transformation Imaging (RTI), an innovative multi-light imaging technique that compiles information about fine surface relief. It aims specifically to offer user-friendly guidelines and advice for using the Highlight-RTI (H-RTI) capture method, a flexible and low-cost RTI recording approach. Although these guidelines primarily focus on H-RTI, introduction to an alternative recording technique using a pre-fabricated dome has been included so that readers are able to determine which capture method is most appropriate for their recording project. Several case studies have also been incorporated to demonstrate how this accessible yet powerful recording tool can be used and adapted to enhance the understanding of our cultural heritage. These practical examples provide solutions to some of the common challenges encountered when using this imaging approach and highlight considerations that might not be immediately apparent.

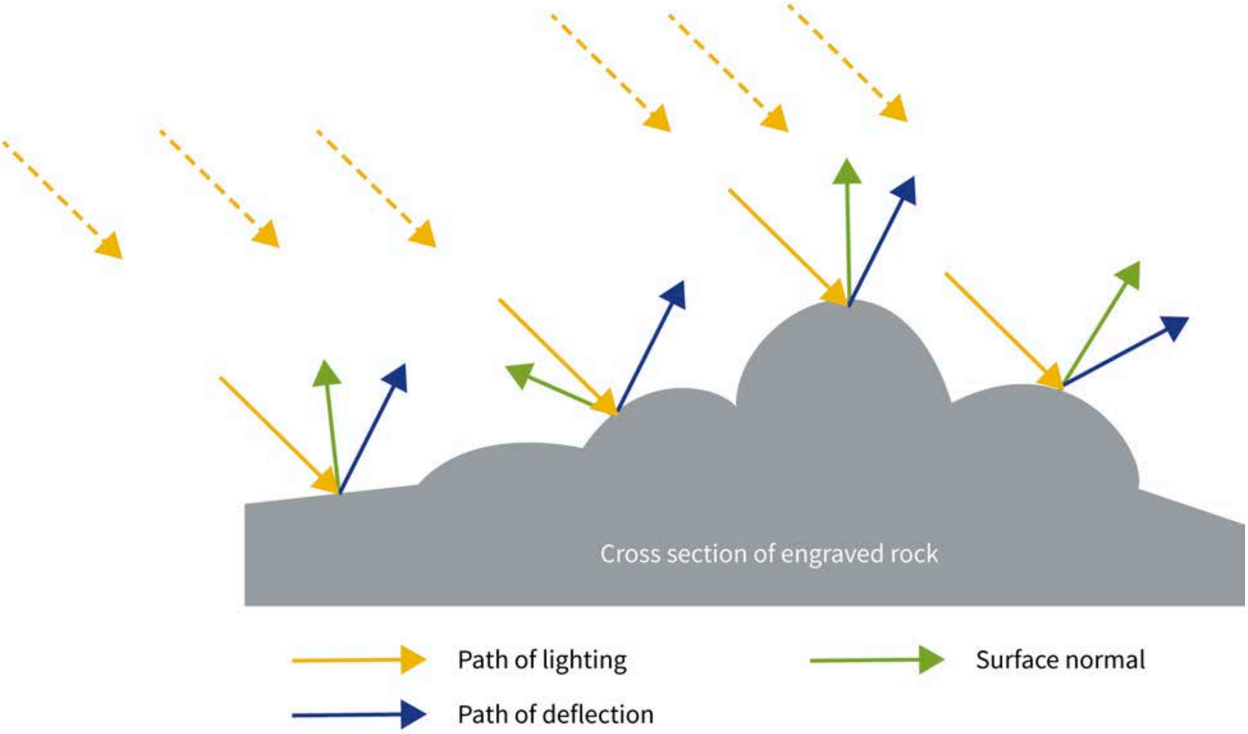
There are quick reference tips throughout the document, along with a glossary and list of abbreviations for terminology found within this publication. There are also references and useful links provided at the end of the guidance.

Introduction to technology

Reflectance Transformation Imaging (RTI) is an image-based recording method developed at Hewlett Packard Laboratories in 2001 by Tom Malzbender and Dan Gelb (Malzbender *et al* 2001). The interactive output produced from the approach is comprised of information from multiple photographs that are taken from one stationary position, while the surface of the subject is illuminated from different raking light positions in each shot. Specially developed software compiles surface reflectance and texture information from the entire image set on a pixel by pixel basis. Multiple algorithms have been developed to process the images, including the Polynomial Texture Mapping (PTM) and Hemispherical Harmonics (HSH) fitters (see Post-processing and viewing the H-RTI for further detail). The resulting output, referred to as an RTI file, can be opened using dedicated viewing software that enables the subject to be interactively re-lit. The enhanced legibility of the surface relief provides a powerful resource for the

Figure 1 (top) and Figure 2 (below): a surface normal is the vector perpendicular to the surface at any given location. Yellow arrows represent the path of the light rays before contact with the surface; blue arrows illustrate the path of light deflection.





study of faint surface detail. In addition to natural science applications, the technology has been successfully used as an analytical tool in many heritage fields of study, such as epigraphy, numismatics and art conservation, as well as in the study of rock art. The following is an illustrated description of how RTI technology works.

A surface normal is a vector perpendicular to the surface at any given location. The green arrows represent surface normals (Figs 1 and 2).

Specialised processing software utilises surface normal information in order to calculate the deflection of light rays on a virtual 3D surface. Although this is technically a 2D recording approach, it is often described as 2½D because of the high-level visual information provided by highlighting and shadowing

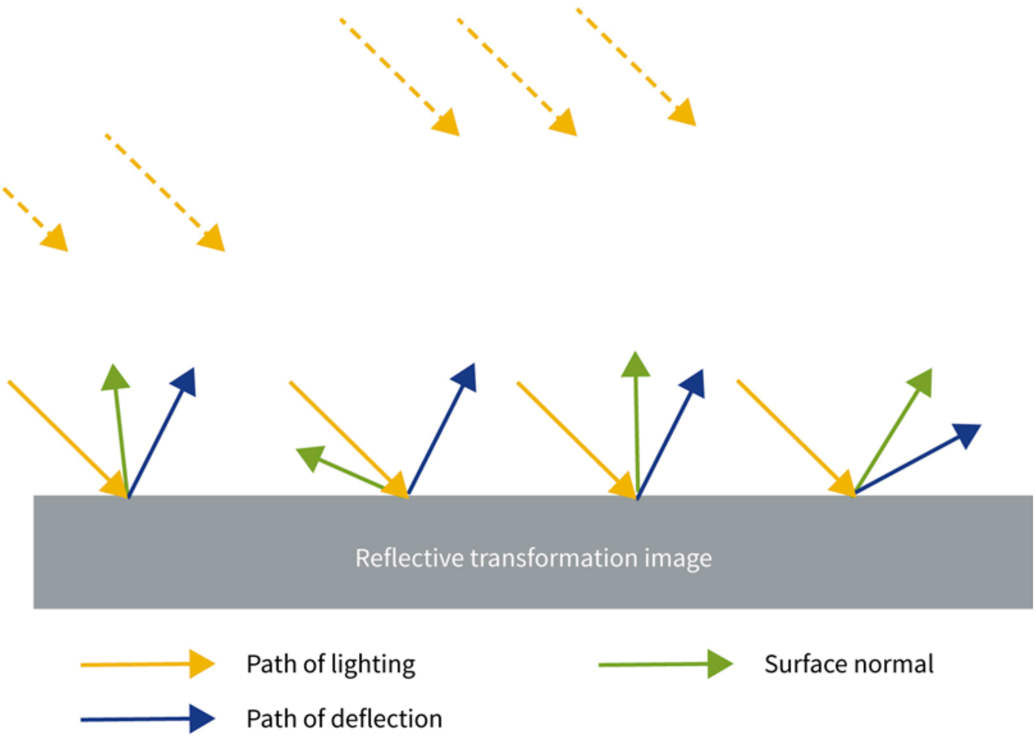


Figure 3: in addition to colour information (eg RGB values), RTI processing software is able to estimate surface normals of an image set per pixel. The surface normal data provide information about the 3D shape of the surface. © Sarah M Duffy

of 3D surfaces. In particular, it approximates the surface orientation at each pixel, providing a relative measure of curvature. Using colour data stored per pixel, as well as the captured surface normal information, this technique reveals surface texture and fine detail sometimes not captured by static photography or even obvious to the naked eye (Fig 3).

Figure 4: a reflectance point on target. © Sarah M Duffy

Introduction to recording approaches

While there are multiple RTI capture methods, the focus of this publication is the highlight-RTI (H-RTI) approach. The technique was developed at Cultural Heritage Imaging (CHI) by Mark Mudge, Marlin Lum and Carla Schroer, with technical guidance from Tom Malzbender of Hewlett Packard Labs. Using this lower-tech approach, light positions are recovered from highlights on a reflective sphere recorded in each photograph (Fig 4).

Benefits of the technique

- As long as the subject being photographed can be illuminated with an artificial light source, H-RTI is a safe, non-invasive recording method in which information about surface texture is captured using a series of digital photographs, thus eliminating the need for contact or destructive sampling and protecting the heritage resource being recorded.

Figure 5: screenshots from PTM of medieval graffiti discovered in the former prior's chapel at Durham. The inscription is revealed using specialised viewing tools in the RTI viewer (specular enhancement tool (left) and diffuse gain (right)). © Sarah M Duffy

- While RTI is not technically a 3D recording method, it is often referred to as 2½D due to the visual information it provides users about the 3D surface texture of a subject (Fig 5).

- H-RTI is cost effective as it can be carried out using a relatively inexpensive toolkit and freely available software. A low-end kit can easily be assembled for around £500 or less. Extremely high levels of detail can be obtained with more expensive equipment, such as a professional high-resolution full-frame camera and high-quality lenses and lighting.

- Due to the transportable kit and robust software, the technique is flexible enough to be used in many recording scenarios, such as at remote sites and on horizontal and vertical surfaces. The method can also be virtually replicated and can even be used underwater (see case studies).

- RTI can be successfully used on surfaces from around 2m diameter down to a microscopic level (see Case Study 5). Virtual-RTI has been successfully used at a landscape scale (see Case Study 6).

Limitations of the technique

- While it provides detailed qualitative surface information, the technique, as it is outlined here, does not produce 3D metric data. If 3D, metrically-accurate measurements are desired, other recording techniques are suggested, such as laser scanning or photogrammetric survey (Barber 2011; Historic England 2018a). Note that work has been undertaken to produce quantitative information from RTI image sets (eg Earl *et al* 2010 ISPRS paper and Manfredi, M, *et al* 2013).

- This approach captures surface texture information but does not reveal any visual information (eg colour, texture) that is covered by other materials, such as lichen or paint. In other words, the technique does not enable users to see beneath overlying material if there is not a difference in surface relief. In such instances, multi-spectral imaging techniques such as ultraviolet (UV) or infrared (IR) photography may provide the desired information. Emerging research in RTI shows that several multi-spectral datasets can be combined using the specialised RTI processing software (Giachetti *et al* 2017).

- To optimise the resolution of surface information captured in the images, it is recommended that the maximum size of the subject is no more than 2m in diameter. However, with the proper equipment, the lower end of the size limit can include microscopic objects (see Case Study 5). If segmenting the surface of a larger subject is unacceptable or impractical, laser scanning or photogrammetry may be more appropriate techniques to use in such instances. RTI operators have also trialled stitching multiple RTI datasets together.

- The quality of the finished RTI is based on the quality of the captured images. While the processing software is relatively robust and enables some post-processing adjustments, users will only be able to visualise data captured during the recording phase.

Possible uses for the technique

- Contribute visual information about surface detail to the existing record of the heritage object, for example aiding the reading an eroded inscription or identifying a worn coin.

- Provide a tool that can be used for the analysis of fine surface texture and detail. With the appropriate equipment, such as a microscope and small, high-precision reflective targets, even microscopic detail can be captured.

- Document the condition of an object at the time of recording, thus generating a tool that can be used to study the deterioration and weathering of a surface over time, or inform decisions of a conservator.

- Create an output that can be used in museum and educational settings in order to engage users and bring attention to a heritage object.

- Provide a digital tool for analysis, interpretation and annotation that can that can be disseminated and shared around the world, fostering international research collaborations.

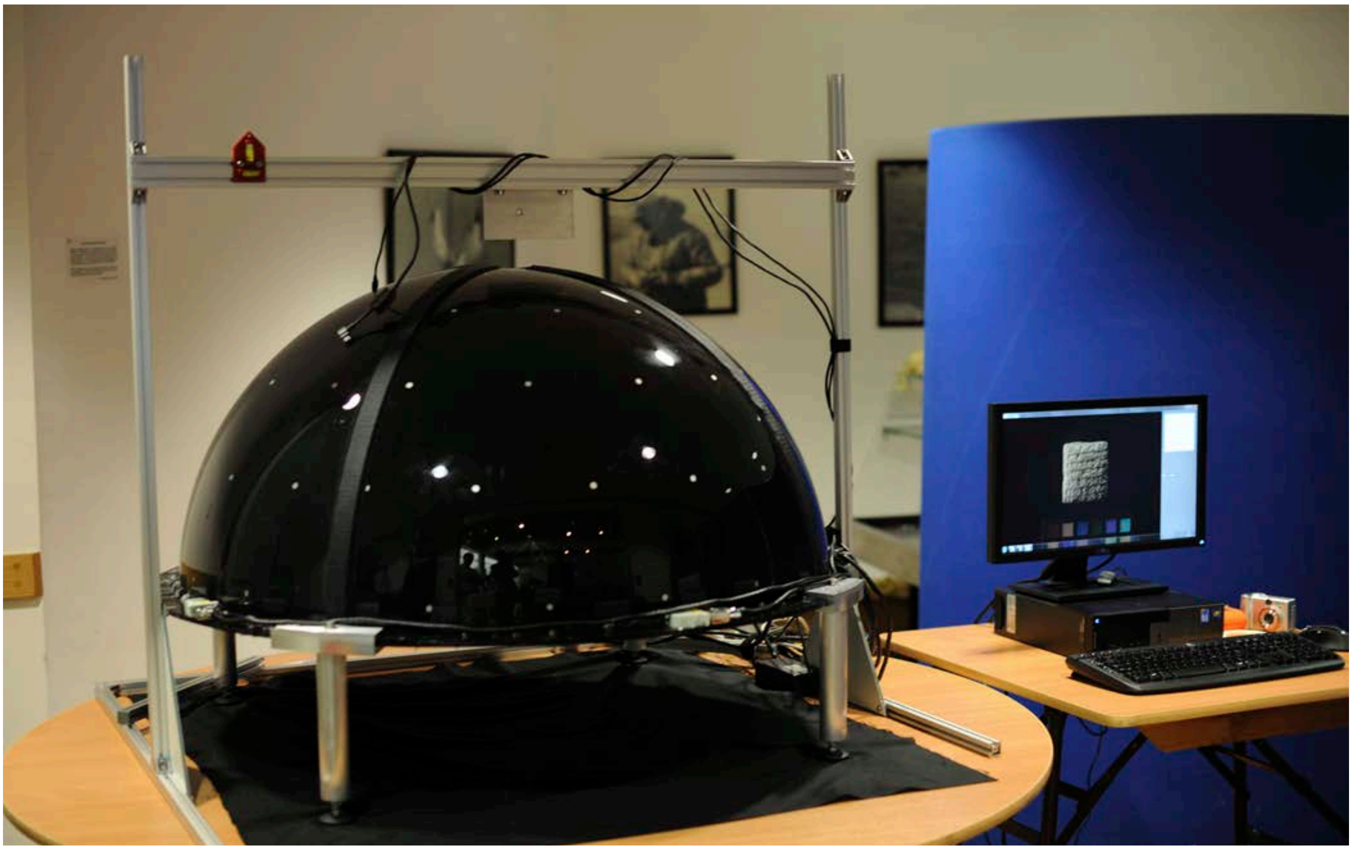


Figure 6: an RTI dome. Courtesy of Graeme Earl

- Capture surface properties that can be used in supplementary digital synthesis and enhancement of the captured surface using other innovative software (eg through computer graphic modelling).

Note that although this guidance concentrates on the H-RTI capture method, an alternative approach is described by Dr Graeme Earl in section 4. This technique uses a prefabricated RTI dome in which each highlight position is provided by a separate light source (Fig 6). One of the advantages of this approach is that the position of the light source is already established, cutting down the acquisition time and eliminating supplemental calculations during processing. Using this technique ensures systematic and thorough lighting of the subject, and can be incredibly useful when imaging large numbers of objects. In addition, the subject is completely protected throughout the recording process. While there are many advantages of the RTI dome capture approach, these guidelines aim to present readers with a relatively affordable and low-tech capture method that can be used on subjects of varying size; the H-RTI capture method.

2 Highlight-RTI capture technique

Introduction to H-RTI

As outlined above, H-RTI is a flexible, non-contact imaging approach that can be used to record subjects ranging in size from microscopic artefacts to larger objects or surfaces (up to 2m in diameter) and capture information about surface texture sometimes missed by visual inspection and other recording methods. The relatively inexpensive and portable tool kit typically includes a digital SLR camera, reflective targets, light source, tripod and string (Fig 7). In the standard set-up, the subject and the camera remain stationary while a light source is moved to a different raking light position around the surface of the subject in each photograph. The light is kept at a constant distance using a piece of string, and a reflective target is placed next to the subject and used to record the position of the light in each image.

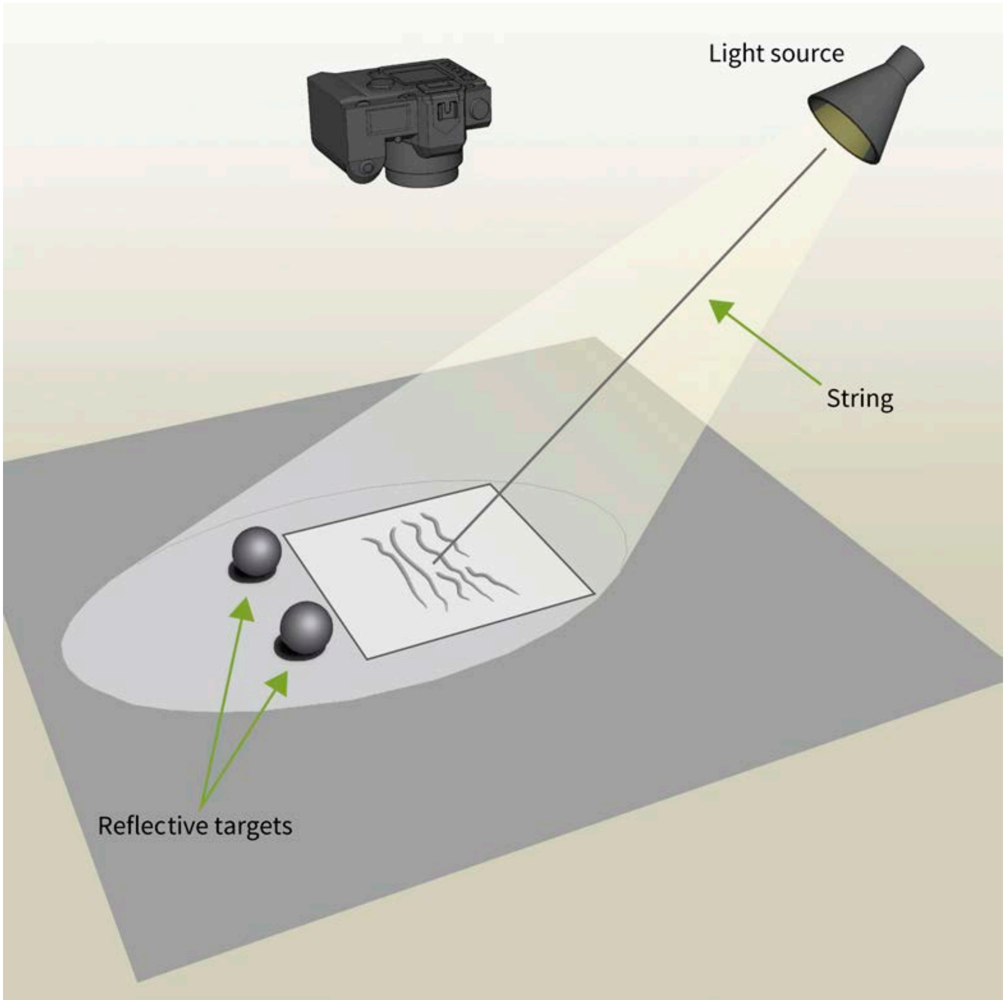


Figure 7: a H-RTI approach illustrating horizontal capture configuration. © Historic England, illustrated by John Vallender

In order to optimise the reflectance information, additional ambient lighting – such as overhead lights or sunlight – should be controlled. This can be achieved by recording in a dark room or use specialised filters. In the post-processing phase, a certain degree of adjustment can be made to the image set before they are fed through the specialised software that produces an interactive RTI file.

Note: Most of the software required in the processing workflow is freely available (see Post-processing and viewing the H-RTI).

Toolkit

Camera

There are three main considerations to make when selecting a digital camera.

1. The camera must be able to photograph in RAW, an image format in which the data is minimally processed by the image sensor of the camera, thus enabling image adjustment during post-processing (Historic England 2015).

2. The camera needs a manual setting in which aperture, exposure, speed and flash can all be manually controlled.

3. Remote capture capability is a must-have, as it is crucial that the camera remains absolutely still once the photo sequence has begun. This is because the images are processed per pixel so any variation in pixel registration from shot to shot will render the finished image blurry and inaccurate.

Many of the newer digital cameras come with a 'live view' option which means that the camera can be linked directly to a computer through a USB cable, Bluetooth or Wi-Fi. Using this functionality, the photographer has a real-time view of the subject on a monitor and is able to make adjustments to the camera settings from the computer. This can prove particularly helpful when making fine adjustments to the focus of the camera. Alternatively, if the camera is not controlled by computer, a wireless remote or cable release can be used instead. In certain situations, for example when the photographer is unassisted, a timed, sequential shutter release may be effectively used, although this requires careful set up and planning. Where a heavy shutter is employed, it is also important that the camera is tightly fixed in place on the tripod as even this can cause slight movement and affect per-pixel registration. A blurred RTI file is usually the result of camera movement.

In order to minimise image distortion, a normal lens (also known as a standard lens) is recommended. It is acceptable to use the auto-focus setting on a lens. However, once focused on the subject, the lens should be set to manual. If a wide-angle lens is used, lens calibration is suggested during the post-processing phase in order to correct image distortion.

Furthermore, since the camera cannot be touched after a capture sequence has begun, the data-storage card must be large enough to hold at least one set of RAW photographs (approximately 24–60 shots). Since RAW images are a substantially larger format than JPEGs, a card of at least 4GB is recommended; although this will ultimately be determined by the size of the camera sensor and number of photographs taken.

Tip: Most digital SLR (D-SLR) cameras will meet the requirements of the H-RTI capture method. However, in selecting the size of the image sensor, it is helpful to consider the trade-offs between higher and lower resolution cameras. For example, high megapixel cameras (eg full frame) capture large amounts of information and will produce high-resolution outputs. However, a larger data storage card and more computer processing power will be required to handle the image sets produced during the capture sequence.

Tip: Depending on the camera make/model, there is a selection of software available on the internet that provides 'live-view' functionality for older cameras.

Filters

If it is necessary to record outdoors during the day, or there are other sources of ambient light that cannot be eliminated, neutral density (ND) filters can be fitted to the lens. These filters reduce the light that passes through the lens and are available at varying intensities (see Case Study 2).

Tripod(s)

The primary requirement for the tripod is that it must be stable enough to ensure that the camera remains absolutely still throughout the imaging sequence. If recording takes place in windy conditions or the tripod needs further stabilisation, weights are suggested (Fig 8). You may need to invest in a boom or horizontal arm to allow a top-down view of the surface.

Depending on the placement of the object, additional tripods may be required to secure the reflective targets in a vertical position.

Figure 8: tripod stabilised by attaching a hand weight to the boom arm with a piece of string. Courtesy of Dr Kate Sharpe

Tip: Tripod legs sometimes create unwanted shadow during a capture sequence. If available, a copy stand can be used to stabilise the camera and eliminate additional sources of shadow.

Reflective target(s)

Reflectance points recorded on a target are used to locate the lighting angle in each photograph. The requirements for a target are that it has a reflective (or glossy) surface, is unmarked and is spherical. While it is more common to use a black target, the processing software is also able to identify red, glossy targets.

The size of the reflective target is relative to the size of the subject being photographed. For example, a black marble can be used to record a smaller subject, while a snooker ball is often a good solution for larger subjects. Microscopically small objects can be recorded using a black, glass-headed sewing pin. The rule of thumb is that the diameter of the target should span at least 250 pixels in the image (Fig 9).

The target must be placed in the field of view with the subject and remain stationary throughout the recording phase. This can be accomplished by attaching a mounting assembly to the target, as shown in figure 10, and then attaching it to a tripod. For horizontal photography on relatively flat surfaces,

Figure 9: reflective targets of varying size – note the reflectance points. © Sarah M Duffy

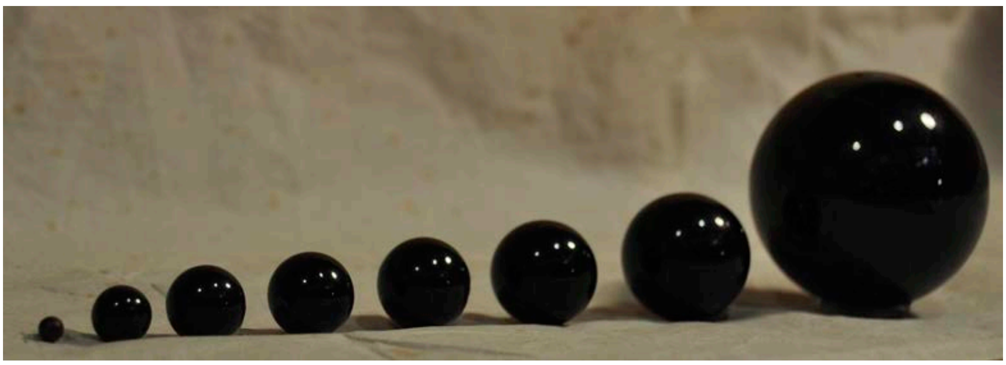


Figure 10: a mounting assembly incorporating a black snooker ball, which has been attached to 1⁄4 inch dual threaded female screw connector. A small piece of grey card has been attached to the mount using Velcro. © Sarah M Duffy

a tripod might not be necessary for placing the target(s). In such instances, the target can be mounted on a stable item, such as the bottom of a flat, rubber end-cap and placed next to the subject (as in Fig 8).

For various reasons, it is sometimes difficult for the software to process one of the targets. Therefore, it is recommended that two targets be included in the capture sequence.

Tip: In order to maximise the surface information captured about the subject, avoid filling the image frame with a target that is significantly larger than is required. Remember, it needs to fill at least 250 pixels of the image.

Light source

A light source is used to illuminate the surface of the subject from oblique angles, as well as to produce the highlight point in the reflective targets. It should have a small enough aperture that it is able to create distinct reflectance points on the targets and should be a broad-spectrum light for good colour rendering. During the capture sequence, the primary considerations regarding lighting include the required intensity and exposure time, the relationship with the camera, and the power requirements. The light source can be continuous or flash, but it should be powerful enough to illuminate the surface of the subject consistently and thoroughly.

If a flash is used, it must be synchronised with the camera so that it flashes automatically with each photograph; this can be accomplished using a sync-cord or wireless transmitter. A wireless control system is often preferred, as the cable can inadvertently destabilise the camera when the light source is moved. Flashes are useful in situations in which a high level of light intensity is required, such as in outdoor, daytime recording or photography of large subjects. The alternative, a continuous light source, can be easier to work with because it does not need to be connected to the camera. Additionally, with continuous lighting, the person operating the lamp is able to ensure that the surface of the subject is being accurately highlighted in each shot. However, portable continuous lamps require relatively large batteries and can become quite hot during an image sequence. When using continuous lamps consider using LED lighting to negate these problems.

A further consideration regarding the selection of lighting equipment is how the light source will be powered (eg recording on remote sites will likely require a battery-operated light source); flash systems tend to be less power hungry.

Tip: If using a sync cable, it is advisable to secure the cord to the tripod using tape or a cable tie to avoid inadvertently destabilising the camera.

Tip: It is recommended that the light should be separated from the surface of the subject by two to four times its diagonal diameter. Therefore, for larger subjects, try mounting the light source to an extendable pole (eg a monopod) and tying the string to the base of the light.

String

By illuminating the subject in the round from multiple raking light positions, a ‘virtual dome’ is created. Using this capture technique, lighting angles should range between 15° and 65° above the surface of the subject.
The highlight and shadows captured as a result of the oblique lighting provide valuable information about surface texture. For best results, it is recommended that the light be separated from the surface of the subject at a consistent distance of two to four times the diagonal diameter of the area to be recorded (eg for an object measuring 20mm diameter, the light source should be 40 to 80mm from the subject). A pre-measured piece of string attached to the light can be used as a flexible aid to determine the distance that the light should be separated from the surface of the subject in each photograph. Although the lighting distance does not have to be exact, in order to maintain a consistent distance around the subject, the string should be as inextensible as possible. The arrangement of the virtual dome has an impact on the quality of the RTI data captured. Ideally the light positions should be evenly spaced. While a pattern with radial spokes is often easier to implement in practice, a geodesic pattern produces the best light distribution (Fig 11 and 12).

Figure 11: a virtual lighting dome based on the 'spines' of an imagined umbrella – note lighting positions at 15°, 40° and 65° above 'horizon' (0°). © Historic England, illustrated by John Vallender

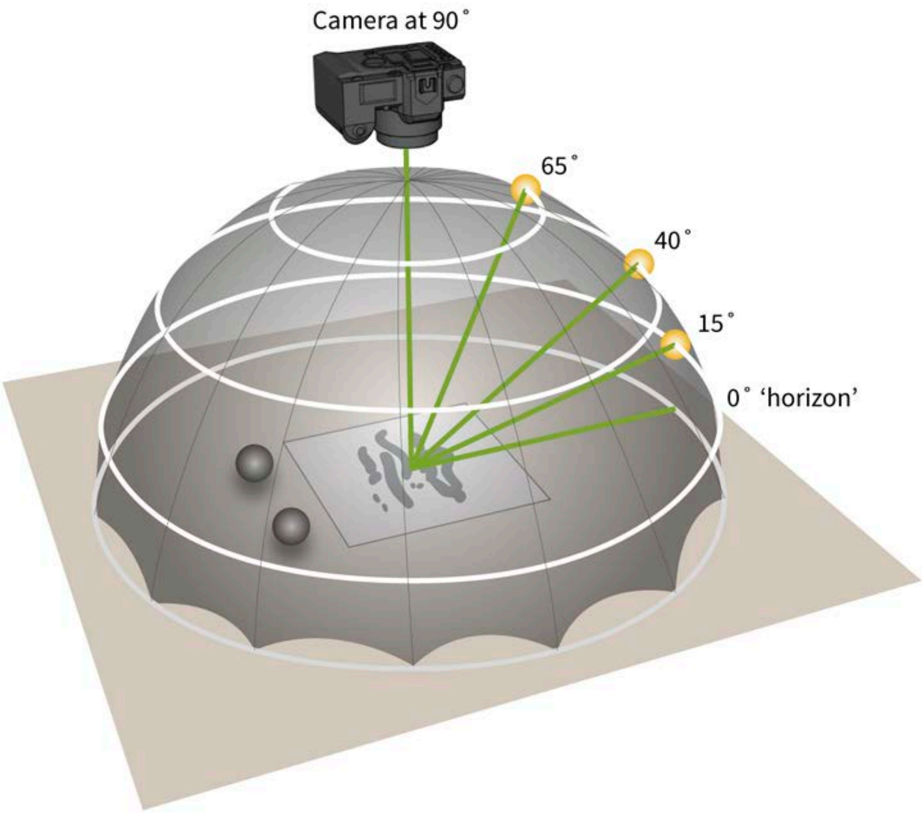
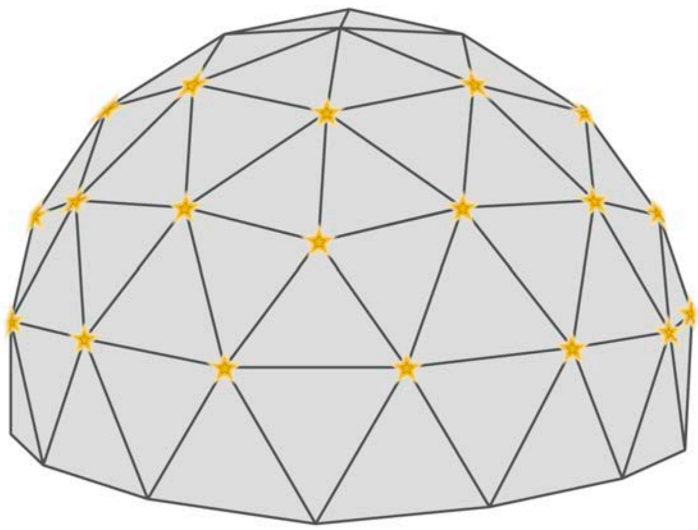


Figure 12: a virtual geodesic lighting dome.



Greyscale or colour-balance card

Using the RTI workflow highlighted in these guidelines, a greyscale or colour-balance card is incorporated into the capture sequence and used later in the post-processing phase to adjust the colour of the photographs and ensure accurate colour by offsetting the effects of the colour temperature of the light source. The greyscale card can either be photographed at the beginning of a capture sequence or incorporated into the staging of the photographs (ie recorded in each shot).

Tip: The following is a list of additional equipment that, although not required, can prove quite useful during the capture phase:

- While this RTI workflow does not provide metric data, including a scale ruler into the capture sequence informs users about the size of the subject. Furthermore, it can be used to enable dimensional calibration of the images using additional processing software.
- It is important to control cables and power cords so that they do not affect an image sequence (for example, by destabilising the camera or creating safety hazards). Therefore, have a selection of supplies, such as cable ties or tape, available to secure any loose cables.
- 'Blu Tack', 'White Tack' or similar can be used for multiple tasks, including stabilising smaller reflective targets. Note, unless given explicit instruction by the owner or curator, never apply adhesive material of any kind to the object being recorded.
- Bubble levels can be helpful when trying to properly align the camera over or in front of the subject.
- Finally, in order to avoid forgetting equipment, create a checklist that can be consulted prior to departure for fieldwork. The list might also include tasks such as ensuring that batteries are charged and data-storage cards have been cleared.

Recording technique

Accessing and handling the object

In many cases, recording work will have been commissioned by the organisation or person who manages or owns the object. If this is not the case, it is often necessary to consult with the appropriate parties in order to gain access to the object or site before recording. Furthermore, some heritage objects are fragile and should only be handled by a professional or using a specific protocol. It is essential to follow precisely any handling instructions provided and note specifically any lighting restrictions in relation to the condition of the object. In such cases, attention should be paid to emission of the light source and length of exposure of the object to the light source, both of which can be kept within standard conservation guidelines.

Assembling a team

A further advantage of the H-RTI capture approach is that it requires a relatively small team. In the case of smaller objects and with the right remote equipment, some projects can be completed by either a one-person (operator uses remote release while moving the light source around the surface of an object) or two-person team (one person operates the camera and the second illuminates the surface of the object). For larger subjects, a team of three is sometimes necessary, with two people properly positioning the light source and a third operating the camera.

Capturing data and taking notes

Metadata is generally defined as 'data about data' and is essential to the creation of a robust and informative archive. In addition to the data automatically generated by the camera, it is advised that detailed notes be taken throughout the recording process. It is recommended that additional information such as project date, name and/or number of the subject and site, the size of the subject, equipment details (eg lens type), the length of the string, the names/tasks of team members, recording conditions and any errors encountered also be noted as part of the record. The RTI format itself provides an expanded opportunity for meta-tagging and many of these details can be coded into the dataset during post-processing (see An alternative approach).

Tip: Designing a standardised form – either electronic or hard-copy – is an easy way to ensure that no information is missed out during fieldwork.

Selection of recording location

There are three primary considerations to make when choosing a recording location.

It is essential that nothing but the light source moves. Even the slightest vibration can affect the success of a capture sequence. Therefore, it is important to consider the stability of the flooring at the recording location. Concrete slab floors are preferred over wooden floors, which can shake as the light source is moved around the subject (Fig 13).

The space should allow for the light source to be moved around the surface of the subject at a consistent distance of two to four times the diagonal diameter of the subject on all sides.

Consider the presence of other light sources. Unless specialised filters or a high intensity flash is used, additional ambient light should be eliminated during photography. This can be accomplished by turning off lights, by covering windows or by photographing at night.

Obviously if the subject cannot be moved and therefore requires photography in place or *in situ*, recording conditions cannot always be controlled. Factors that can affect successful in situ H-RTI photography include distortion of the 'virtual dome', caused by awkwardly positioned

Figure 13: screenshot of PTM from Durham graffiti recording project – note the blurriness of the image caused by movement introduced by the wood floor. © Sarah M Duffy

surrounding features (eg architectural features; beams, walls etc) which prevent the capture of all desired lighting positions. Additionally, recording in daylight may affect the success of H-RTI photography or produce very bright RTIs. In such instances, neutral density filters and/or a high-intensity flash should be used to offset the effects of unavoidable ambient light. Shelters such as umbrellas or gazebos may be able to provide a degree of control over the lighting conditions.

Preparation and placement of the object

Once the recording location has been selected, prepare a secure area to place and position the object so that it can be lit on all sides from the appropriate distance (two to four times the diagonal diameter).

In some instances, it may be necessary to prepare the surface of an object (clearing away dust or dirt, for example). However, make sure to consult the proper professionals before touching or making any contact with the surface of the subject.

Tip: Portable objects can be placed on a plain piece of matt (non-reflective) fabric (eg black) in order to forefront the subject in the images and create the effect of a neutral background.

Placement and set-up of the camera

The flexibility of the H-RTI capture method enables the technique to be carried out on both vertical and horizontal surfaces. Depending on the orientation, the camera should be mounted over or in front of the subject and incorporate both the subject and reflective target(s) in the frame. Next, it is necessary to ensure that the camera will not be inadvertently moved during the photo sequence. Therefore, it should either be connected to a computer, cable release or wireless remote. If the camera is controlled by computer, designate an image-naming system and destination folder. It is important not to include spaces in the names of folders or images. This point cannot be emphasised enough throughout the entire process, as spaces will almost certainly result in an error during processing. If the camera has a power-save mode (eg automatically shuts off after a certain amount of time being idle), this function should be disabled.

Tip: If the camera is moved or touched after recording has begun, the images should be retaken, starting from the original lighting position. Therefore, make sure that there is sufficient battery power and room on the SD card to complete an entire imaging sequence.

Tip: Photographs in which shadow obscures the surface of the subject will be discarded during post-processing. Therefore, try to avoid positioning equipment (such as the tripod) in ways that will introduce shadowing when the subject is lit in the round.

Tip: Think carefully about the orientation of the subject. Positioning the object so that it is facing the correct direction and aligned straight in the frame eliminates additional post-processing adjustment. Using bubble levels can be a helpful way to achieve proper camera alignment.

Placement of reflective targets

Although not essential, it is recommended that two targets should be placed and stabilised next to the subject close enough to be incorporated fully in the photographs, but far enough away from the subject that they can later be cropped out of the frame during post-processing. They should also be placed at a height that eliminates or reduces shadowing on the surface of the subject during photography (for example, see Fig 7).

Eliminating or controlling ambient light

Optimal H-RTI recording conditions call for complete darkness, so indoor or night-time recording is preferable. For indoor recording, this means turning off overhead and any additional light sources, as well as covering windows. Fire exit signs may need to be covered, as they usually cannot be turned off.

As was previously mentioned, in the case of outdoor, daytime recording neutral density filters of the appropriate intensity should be fixed to the lens. Photographing on an overcast day is preferable, and umbrellas or a gazebo can be placed over the capture area to further control ambient lighting. If lighting conditions change during a photo set (eg the sun comes out on an overcast day) the software may struggle to process the image set successfully. Keep in mind that daytime photography will require a higher intensity light source.

Making final adjustments to the camera

After the camera is in the correct position over the subject, the targets have been stabilised and ambient light has been eliminated or minimised, the camera should be set to photograph in RAW format. Next, set the camera and lens to manual mode to ensure that settings will not change through the photo sequence. Then focus the camera on the surface of the subject, making sure at least the top third of the reflective target(s) is in focus.

Figure 14: for H-RTI, the histogram should read toward the left, avoiding blow-out of whites.
© Sarah M Duffy

In the following step, exposure is set by taking three test shots. In the first two, the subject should be illuminated from the highest and lowest light angles (ie 65° and 15°) with consistent shutter speed, aperture and lighting conditions. Aim for a histogram curve in which no whites are blown out and no shadows are too dark (Fig 14). Finally, to confirm that ambient light has been eliminated, after the exposure has been set an image is taken without flash. This should appear completely dark and the histogram should read to the far left. If the image is still bright, increase the intensity of the neutral density filters and/or re-adjust the exposure and return to the manual setting.

Tip: Every recording project will be different. However, the following are a few helpful guidelines regarding camera adjustments:

- CHI recommends that it is best to keep the aperture set between f/5.6 and f/11 and avoid using an aperture setting narrower than f/11.
- Keep the ISO setting as low as possible to minimise image noise. A sensitivity setting of 100–200 is optimal.
- It is sometimes possible to use the auto-focus function on the lens to set up the camera, setting it to manual after accuracy has been confirmed in test shots.
- Remember, the longer the exposure time, the greater the opportunity to introduce movement into a shot.

Tip: If your lens has an image stabilisation feature, make sure to disable it to avoid inadvertent camera shake.

Tip: Spend some time learning how to read histograms. The better you understand what they mean and how to adjust the camera settings accordingly, the easier it will be to take higher-quality photographs and produce better quality RTIs.

Tip: Remember, one of the benefits of photographing in RAW format is that it allows some adjustment of images during post-processing (Fig 15).

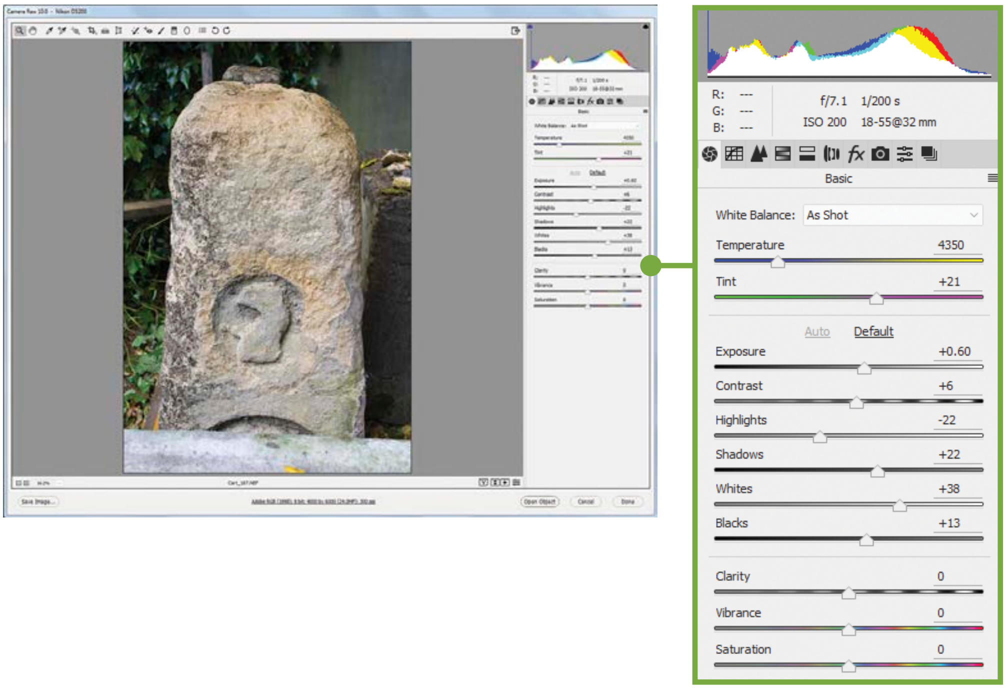


Figure 15: DNG to JPEG conversion using Adobe Camera Raw in Photoshop.

Photographing the greyscale card

Once the camera has been set to manual and before each recording sequence begins, one photograph should be taken that includes a greyscale or colour card. Alternatively, to avoid missing out this step, the colour card can be incorporated into the photo set-up and recorded in each image. If the latter approach is selected, consider positioning the card so that it can be cropped out during post-processing.

Tip: It is easy to forget to take a photograph with the colour card. In order to avoid inadvertently forgetting this step, one suggested solution is mounting a small piece of card to the target assembly so that it is automatically captured in each shot (eg see Fig 10).

To summarise:

1. Place the object on a stable surface (if portable).
2. Mount the camera over the selected capture area.
3. Position the target spheres in the shot, far enough away from the subject that they can be cropped during post-processing.
4. Ensure remote system is in place for camera and flash (if applicable).
5. Place the camera and lens in manual mode and set to capture photographs in RAW format.
6. Take test shots to determine proper camera settings.
7. If it has not been incorporated into the photo set-up, take one image with a greyscale or colour card.

Creating a 'virtual dome' and photography

The final step of the recording phase is illuminating and photographing the subject. RTIs can be successfully generated on as few as 16 photographs. However, more raking-light images mean greater acquisition of data and higher quality RTI output. In addition, photographs are sometimes discarded during the post-processing phase if errors occurred during the capture sequence (eg if they contain shadow or if the flash did not fire). For best results, taking at least 24–60 shots is recommended.

The light source should be separated from the surface of the subject by two to four times its diagonal diameter. Using a measuring device such as a pre-measured piece of string ensures that the distance between the light and subject is consistent in each photograph, although this measurement does not need to be metrically exact. If a larger object is photographed, it is sometimes necessary for two people to operate the light source – one person positioning a light source with the piece of string attached and the other holding the end of the string in front of the surface of the subject prior to image capture. It is also possible to use an electronic distance meter. Once the light is at the correct distance move the string from the camera's field of view.

Tip: It may be useful to attach the light to a pole (eg telescopic monopod) to extend the operator's reach.

Tip: If using an electronic distance meter, select one with an audible alarm that sounds at a pre-set distance and attach the meter to the flash so that it remains in a constant relative position to the subject.

When deciding how to illuminate the subject during the photo sequence, it is helpful to imagine shooting the light from around a virtual dome based on the spines of an umbrella. Depending on how many photographs of a subject are desired, establish how many locations around the dome will be photographed and then decide what angles above the surface of the subject will be used. As RTIs offer information about highlighting and shadowing, it is not necessary to capture photographs directly above the subject ('high noon' or 90°). However, it is recommended that the subject be lit from positions between 15° and 65° above the surface of the subject (the 'horizon'/0°). For the optimal capture of lighting information, it is recommended that instead of taking images in a linear formation up and down the spines, that the light source be staggered horizontally between spines (ie a virtual geodesic lighting dome; imagine the Crystal Dome from The Crystal Maze). This provides an even spread of lighting positions around the virtual dome (see Fig 12).

During this final phase of the capture sequence, one person operates the camera. They are directed by the person lighting the subject. The light should be focused on the centre of the surface of the subject and held as still as possible in each shot. Again, it is important to be mindful of shadows created by tripod legs, targets or other objects around the capture area. Also remember to remove the string in each shot. Note that if a photograph contains shadow or the flash misfires, it can easily be removed from the image set later. However, if possible, take an additional photograph duplicating that light position. Finally, if surrounding features prohibit the desired lighting positions, capture as many raking light positions around the virtual dome as possible. As long as it is consistent, the lighting distance is somewhat flexible (two to four times the subject's diagonal diameter) and can be adjusted to fit the recording conditions.

Tip: Use a systematic approach to lighting the subject in order to avoid any gaps in coverage. If there is any question about an image, simply reshoot.

Tip: If photographing multiple RTI image sets, consider using a white board or chalk board to indicate when image sequences stop and start. This will make it easier to identify image set breaks during the post-processing sequence.

Quick reference to H-RTI

Below is a quick reference list of considerations to make prior to recording:

- **Size of subject:** For best results, the size of the object should be limited to approximately two metres in diameter. If the subject is larger, consider creating multiple RTIs.

- **Recording location:** The subject should be photographed in a space with stable flooring (ie not wooden planks) that is large enough for the light source to be separated from the subject by at least two to four times its diagonal diameter.

- **Ambient light:** Think about windows and sources of artificial light. An umbrella or gazebo can provide a good means of eliminating direct sunlight. If recording during the day outside, consider neutral density filters and a high intensity light source.

- **Weather conditions:** If winds are strong, the tripod must be stabilised so that there is no movement of the camera during photography. Sometimes it may be more time and cost effective to reschedule a shoot than attempt to work with inadequate images.

- **The tripod:** The tripod must be strong enough to bear the weight of your camera and lens. Consider the load weight of your tripod before you set up. You may need to consider the purchase of a boom or horizontal arm to allow placement of the camera over the subject.

- **The camera:** The selected digital camera should have the capability to be set to photograph in RAW, have a manual mode and be able to be controlled remotely.

- **The light:** This can be continuous or flash but must be bright enough to illuminate the entire surface of the subject. Large objects or outdoor, daytime recording may require a higher intensity light (eg flash). Alternatively, the surface of the subject can be segmented into smaller sections and recorded in multiple phases. If a flash is used, it must have the capability to be remotely controlled by the camera release.

- **The targets:** The targets should be reflective, unmarked and spherical. If using the automated highlight-RTI software, the spheres should be black or red and glossy. Their size is relative to the size of the subject and should take up roughly 250 pixels of the image. The targets must be stabilised in each shot and photographing two reflective targets is recommended.

- **Power sources:** Consider how equipment will be powered (eg the light source, computer – if used, camera battery).

- **Data storage:** Ensure the data-storage card is large enough to hold one complete set of RAW photographs.

- **Shadows:** Minimise inadvertent shadowing caused by tripod legs, the reflective targets, surrounding objects and the position/shape of the subject itself.

3 Post-processing and viewing the H-RTI

Introduction to processing

In brief, there are two main processing stages:

1. batch image manipulation and conversion and
2. RTI production

During the first stage, images are converted from camera RAW (file type varies by camera manufacturer; NEF, CLR, DCR and so on) to DNG (digital negative; a universal RAW format developed by Adobe), adjusted in synchronised or batch operations, then converted to JPEG and saved in a dedicated folder. The resulting JPEGs are then processed by specialised software that detects the target and highlight position in each image and generates a light position file. In an optional step, the software can be used to crop the targets out of the photographs and generate a cropped set of JPEGs. In the final stage of processing, the software synthesises the information from the light position file and the JPEGs to generate an RTI. Most of the software required to generate and view RTI files is freely available for download on the internet. Note that processing time is heavily dictated by image size and computer processing power. The RTI software is compatible with both Apple Macs and PCs.

Introduction to CHI

Cultural Heritage Imaging (CHI) is a non-profit company that 'supports the development and adoption of new tools and methods that apply the power of digital technology to humanity's cultural legacy' (CHI website). The San Francisco-based organisation creates and fosters worldwide research collaborations among cultural heritage communities, and emphasises and encourages the use of freely available, open-source tools in cultural heritage recording projects. CHI was established in 2002 by Carla Schroer and Mark Mudge who, with the input of Marlin Lum and technical guidance from Tom Malzbender (HP Labs), developed the H-RTI capture approach. Further information about CHI and the technologies it promotes, as well as access to software downloads, can be found on their website. The team also hosts helpful web-based forums that provide guidance on a range cultural heritage imagining topics, including RTI.

Software requirements and access

There are three pieces of software necessary to generate and view an RTI file:

1. image post-processing software
2. specialised RTI builder, and
3. dedicated RTI viewer

Additionally, if polynomial texture mapping (PTM) processing workflow is desired, a specialised fitter will need to be downloaded separately. The RTI builder and viewer are freely available for download from CHI's website; the PTM fitter is freely available from HP Labs and the HSH fitter (© University of California, Santa Cruz and CHI, Inc) is downloaded automatically with the RTI building software.

Irrespective of which image processing software is selected (No 1 above), it should include functionality that allows a user to convert RAW images to DNG (although this can be done with Adobe DNG converter; see Converting the Images and Post-Processing, below), batch image manipulation (eg changes to rotation, white balance, exposure), and the capability to convert DNG to JPEG (.jpg). Since the information from the image set is processed per pixel, synchronised batch operations are particularly important.

Tip: As with other innovative recording technologies, RTI technology is ever advancing. It is advisable to periodically check resources, such as the CHI website, for updates on the most recent processing and viewing software.

Processing workflow

A step-by-step processing workflow, *Reflectance Transformation Imaging: Guide to Highlight Image Processing*, is available from Cultural Heritage Imaging, alongside the software download.

What follows is a more general outline of the stages involved in the processing sequence.

File formatting

The RTI processing workflow is based on a standardised file format system, with the parent or project folder containing several sub-folders, including 'assembly-files', 'finished-files', 'cropped-jpegs', 'original-files', and 'jpeg-exports'. All but the final two are generated by the processing software; the 'jpeg-exports' folder, which contains the final jpeg image set, must be present when initiating the processing sequence.

Tip: Create a template file structure for your RTI projects. This will ensure you always have the correct file structure.

Converting the Images and Post-Processing

RAW files have the advantage of being a 'lossless' (or near lossless) format and allow a certain degree post-processing adjustment. However, because the format varies by camera make and model, there is no universal RAW file format. RAW files are, therefore, not a suitable archive format. To solve this problem, the original RAW photographs are converted to digital negative (DNG) files, an Adobe open-archival format that is considered archivally stable and eliminates the issue of varying RAW formats. Therefore, the image processing software needs the functionality to covert RAW images to DNG. It is recommended to save the new images using a naming convention that provides information regarding the project and/or subject and date. (Remember not to use spaces in the file names.) If your imaging software does not have the ability to convert RAW files, or is not up to date with your camera's RAW format, you can use Adobe DNG converter to batch convert your image set.

The image processing software is also used to perform batch image manipulation such as rotation, adjusting exposure and white balancing using the colour correction. Any changes should be made as synchronised (batch) operations to the entire image set. Unwanted images (eg that contain shadow, in which flash has misfired or the string was left in view) can be deleted at this stage.

In one final step, the DNG files are converted into JPEGs (note that these should be exported as .jpg rather than .JPG or .jpeg files) and saved in a designated folder ('jpeg-exports'). Note that the size and quantity of the JPEGs will dictate the resolution of the final RTI file and the processing time.

Tip: Adobe DNG converter is free to use and contains colour control which will minimise colour casts on the image. It is also continually updated with the latest RAW file formats.

Using the Specialised RTI Builder

In the next stages of processing, the specialised RTI software (RTIBuilder) is used to locate the target and highlight position in each image (JPEG), generate a highlight position file (.txt), crop the reflective targets and produce a new image set (JPEG), and finally generate an RTI. As mentioned previously, the images can be processed using several fitting algorithms; the two Highlight-based options are Polynomial Texture Mapping (PTM) which produces a .ptm file and Hemispherical Harmonics (HSH) which produces an .rti file.

It is worth taking a moment to consider the fitting options: PTM and HSH. HSH, a more recent development, is particularly useful for visualising reflective, 3D surfaces and generates more accurate surface normals. Alternatively, PTM, an older fitting approach, offers more enhancement options in the viewer, which can be used to further examine the visual information captured during an imaging sequence. Keep in mind that image set can be processed using both fitting options, so experimentation is possible.

4 An alternative recording approach and software innovations

by Graeme Earl

The Archaeological Computing Research Group at the University of Southampton has been working with RTI and PTM for many years (Earl *et al* 2010). Most recently they have been funded by the UK Arts and Humanities Research Council (AHRC) under the Digital Equipment and Database Enhancement for Impact (DEDEFI) scheme to develop RTI systems. This project, in collaboration with the University of Oxford, has trialled RTI on a great many cultural heritage datasets.

In addition to the highlight method, a great deal of RTI capture takes place using lighting rigs of various kinds. The first PTM research employed a geodesic dome and subsequent applications have used robotic arms and arcs, hemispherical domes (including portable systems) and other motion-control systems. These have also employed a range of imaging devices including digital SLRs, firewire or Ethernet cameras directly connected to a PC, microscope cameras and, most recently, as part of the RTISAD project, gigapan-mounted D-SLRs. Each of these has advantages and disadvantages. For example, firewire cameras are significantly more expensive for equivalent resolution to a D-SLR, but automated control of them is much easier.

At Southampton we employ a hemispherical rig with computer-controlled LED lights, adapted from a dome built by Tom Goskar at Wessex Archaeology in 2009. This replaces an earlier robotic rig using a rotating light arc. This dome system can capture and process a 76-image RTI dataset in about four minutes, with significant speed improvements for lower resolution capture and for a reduced capture set of 60 images. The hemispherical system employs a loading scissor lift for positioning objects.

The RTISAD project has also explored software innovations. It has generated a means to annotate RTI datasets (see Other RTI formats and emerging software). It has also developed two versions of a camera control system – one using proprietary Nikon camera drivers and another using entirely open source, the code for which can be found here. Finally, it has explored ways to use off-the-shelf imaging and modelling software to make further analytical use of RTI data. This has included automated contouring of 'RTI normal' maps (Mudge *et al* 2010), metric comparison of RTI surfaces in assessment of conservation treatment including surface normal matching (Karsten and Earl 2010), automated matching of RTI data to 3D laser scan data (Earl *et al* 2010), use of RTI data in production of computer graphic simulations of archaeological material (Beale and Earl 2011), microscopic, multi-spectral and gigapixel RTI (see Case Study 5) and in the museum presentation of objects with complex surface properties (Bridgman and Earl 2012).

A sequence of photographs and videos illustrating the creation of a dome by Tom Goskar at Wessex Archaeology can be found on Flickr.

5 The RTI viewer

The RTI viewer opens multiple RTI formats and is Mac and PC friendly. It was developed primarily by the Italian National Research Council's Institute for Information Science and Technology Visual Computing Laboratory. The viewer enables users to interactively manipulate the data captured during photography. Users can move a virtual light around the surface of the subject, zoom in/out, adjust and enhance the RGB values and surface normal information. Manipulating this information often provides an enhanced perception of surface texture and detail. The viewer also provides an opportunity to save and annotate lighting positions and to capture screenshots. A download of the viewing software and a detailed instruction manual are freely available on CHI's website.

Annotating an RTI dataset

The AHRC RTISAD project extended the RTI viewer and format to enable annotation of RTI datasets, as of version 1.1. These annotations are linked to the viewer settings and can be shared as a separate annotation file. A subsequent user can load and amend the annotations, and view the RTI data under exactly the same conditions as the creator. Multiple annotations can be attached to a single RTI file. For example, in annotating a rock art panel, it is possible to mark bounding boxes around particular features of interest that only appear with given light orientation and filter settings.

An illustrated user guide for RTIViewer is available on the CHI website.

6 Other RTI formats and emerging software

Virtual RTI and landscape

Using supplemental processing software, 3D data generated using other capture techniques (eg laser scan or Structure from Motion - SfM) can be virtually illuminated using the RTI technology.

For example, landscapes can be virtually rotated and illuminated on screen using 3D processing software, lidar datasets and RTI technology (Earl *et al* 2010; Goskar and Cripps 2011). This approach can also be useful when working with an object is geometrically complex or is too large for traditional RTI capture, as the 3D model can be rotated to different positions and Virtual RTIs can be generated from multiple views. See Case Studies 6 and 7.

Surface normals and 3D surface representation

As previously discussed, surface normals are the vectors perpendicular to the surface. RTI processing software is able to estimate surface normals per pixel of an image set. The recorded normals provide 3D shape information about the object's surface. Current research is highlighting the importance of surface normals as an intermediary between RTI and 3D surface representation and work is being done to extract 3D data from RTI using surface normals. However, the process is very difficult and still experimental. No easy tools yet exist for using normal maps generated by RTI to enhance a 3D model (for further information, see MacDonald and Robson 2010; MacDonald 2011).

Underwater RTI

One of the more exciting advancements over the past few years has been the development of an underwater RTI capture approach. As a component of a post-graduate project and in connection with the Archaeological Computing Research Group (ACRG) computer lab at the University of Southampton, an underwater lighting rig has been fabricated that can capture images for RTI processing (Selmo *et al*, 2017). This work is discussed in more detail in Case Study 7.

Disseminating RTI online

An HTML5 web viewer has been developed by Gianpaolo Palma at the Visual Computing Lab, National Research Council of Italy. This allows RTI or PTM (HSH) images to be embedded into websites and viewed on tablets and mobile devices. More information is available from the Visual Computing Laboratory website.

7 Case studies

Case Study 1: RTI as a method of digital preservation for worked antler from Star Carr

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Figure CS1.1: Star Carr 2010 excavations. This re-excavated trench contained barbed antler points. © Nicky Milner

Type: reflectance transformation imaging using H-RTI capture method (indoor)

Keywords: non-contact, reflectance transformation imaging (RTI), polynomial texture mapping (PTM), highlight-RTI (H-RTI), Mesolithic, Star Carr, antler, degradation of organic material

Introduction (site and resource)

Star Carr is an early Mesolithic archaeological site on the Vale of Pickering in north-east Yorkshire, dating to about 9000 BC. In recent excavations, the site has been researched collaboratively by The Vale of Pickering Research Trust, University of York and University of Manchester (Fig CS1.1). Among the rare organic finds were several barbed antler points (average size around 15mm by 80mm). As part of his doctoral research focusing on the manufacture and use of antler tools within the British Mesolithic, Dr Ben Elliott was interested in testing RTI on a group of antler artefacts from the site.

The selection of antler barbed points was scheduled to be dated using an invasive technique that required a sample of the material be removed. Additionally, there are specific preservation issues related to on-going drainage at Star Carr, which have caused accelerated deterioration of many of the organic materials at the site. Various techniques are being deployed to slow the degradation of artefacts from Star Carr, but it remains crucial that fragile materials such as the antler points are recorded at the earliest opportunity. In addition to creating a record before dating or further deterioration, there was also an interest in what could be learned through RTI regarding how the antler had been worked by early Mesolithic people.

Figure CS1.2 (left) and Figure CS1.3 (right). Mesolithic barbed antler points from Star Carr. © Sarah M Duffy

Justification for using RTI

In this case study, the non-invasive approach proved the principal advantage of the H-RTI capture method (Figs CS1.2 and CS1.3). In addition to more traditional recording techniques such as hand-drawing, survey and static digital photography, the antler points had previously been laser scanned with less than satisfactory results, possibly owing to the nature of the material (it is dark and porous). This survey offered an opportunity to test the use of RTI technology on the artefacts without spending additional funds on a supplementary recording technique. If the approach proved successful, the research team planned to add the finished multi-lighting work products to a larger suite of innovative methods trialled to record the antler artefacts, which included laser scanning and image stitching.

Discussion of fieldwork

The tool kit comprised a Nikon D60 (10.2mpx) camera and compatible wireless remote alongside a Lowel Pro iD lamp (continuous, dimmable and battery operated), two black snooker balls, and an 18% greyscale card. Recording conditions were optimal as the capture sequence was undertaken indoors. A team of two photographed three antler points, front and back, in one afternoon. As the objects were relatively small, the light was dimmed to the minimum setting. Special considerations were made to protect the fragile material (eg handling the objects under specialist supervision and keeping the points in a stable environment (water) when they were not being photographed).

Figure CS1.4: screenshot of PTM generated from fieldwork, viewed with diffuse gain. Possible tooling revealed.
© Dr Dav Smith

Discussion of results

Problems encountered and how they were addressed

Although the lamp was dimmed to the lowest setting, when the small objects were lit from four times their diameter, the test photographs were still too bright. Therefore, it was necessary to position the light source farther away than the usual recommended distance. Additionally, although the size of the objects called for a smaller reflective target to be used during the capture sequence, it was necessary to use a snooker ball since there was nothing more suitable available. As a result the target occupied more of the photographic frame than was required. The results were, nevertheless, satisfactory. Finally, because of the asymmetrical shape of the artefacts, it was necessary to prop up one side of the barbed points in order to create a more level surface. This eliminated most of the shadows created by their irregular 3D shape (Fig CS1.4).

Final product and what was gained through RTI

Six RTIs were generated that recorded both sides of three antler barbs. The work successfully proved the feasibility of using H-RTI as a method to record fragile antler finds from Star Carr. As well as recording the condition of the artefacts before the invasive dating technique was carried out, the RTI files have enabled examination of the surface of the points in a way that had not previously been possible. In particular, osseous technology specialist Dr Ben Elliott found that the manipulation of raking light highlighted the surface in a way other techniques had not permitted.

The outputs were used to examine working marks, as well as to attempt to decipher which marks were man-made and which were the product of natural erosion. Since the first publication of these guidelines, this particular application has been developed, with the use of RTI on barbed points excavated from Star Carr in 2015 proving particularly useful in identifying finely incised and ephemeral decorative motifs (Elliott and Little In Press). Finally, because the high acid content and oxidation of the soil at Star Carr have caused organic materials to degrade at an advanced rate, the RTIs provide a valuable account of the objects as they existed at the time of recording, as well as a more comprehensive record of the fragile artefacts.

Case Study 2: Daytime survey of prehistoric rock art at Roughting Linn, Northumberland

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Type: reflectance transformation imaging using H-RTI capture method (daytime/outdoor)

Keywords: non-contact, reflectance transformation imaging (RTI), polynomial texture mapping (PTM), highlight-RTI (H-RTI), British rock art, remote recording

Introduction (site and resource)

Named for a nearby waterfall, Roughting Linn (or 'roaring pool') is considered the largest decorated rock in northern England, measuring around 20m by 15m (Fig CS2.1).

The site is near Doddington in Northumberland County, close to the Scottish border, and is accessed by right of way using a footpath that leads from the road. It is a scheduled ancient monument (list entry 1006601), decorated with prehistoric incised artwork – comprised primarily of cup and ring marks. Researchers speculate broadly that Northumberland rock art originated in the Neolithic and Early Bronze Age and there are no definitive interpretive explanations of these ancient motifs.

The massive, whale-back shaped rock has a long history of investigation. It was first noted in the 1850s by Rev William Greenwell, then recorded by Dr Stan Beckensall as part of his extensive rock art survey in the 20th century, and later included in the Northumberland and Durham Rock Art Pilot Project (NADRAP).

Figure CS2.1: recording in process at Roughting Linn. Neutral density filters were used to off-set daytime lighting conditions. Courtesy of Dr Kate Sharpe

The English Heritage Metric Survey team initiated this recording project; the request was for practical H-RTI training, including the opportunity to test the application of the capture technique during the day at a representative rock art site in England.

Justification for using H-RTI

In order to see the often subtle and shallow surface detail of rock art, motifs are best viewed under specific lighting conditions, such as oblique or raking light. Although the recording programme at the site has been varied, ranging from traditional techniques, such as tracing and rubbing, to more innovative techniques such as photogrammetry, none of the methods has offered the (interactive) surface relief information that RTI provides. For example, John Price, a retired English Heritage conservator, created a fibreglass replica of a particularly eroded section of the rock. One of the most substantial benefits of the model he created was that it could be viewed under varying lighting conditions. RTI offers this opportunity digitally and without potentially harmful methods of capturing the carvings.

The H-RTI capture method was used at this ancient rock art site for several reasons. First, as Roughting Linn is a relatively remote site, the transportable tool kit was particularly appealing. Additionally, there was no available funding to construct an RTI dome, and furthermore, the research team did not want a frame to dictate the size of area that could be photographed.

Discussion of fieldwork

The recording equipment included a Canon 22mpx EOS-1Ds Mark III camera and compatible wireless remote-controlled flash, cable-release remote, neutral density filters of varying intensities, Manfroto tripod, two black snooker balls, scale ruler, string mounted on PVC pipe and 18% greyscale card.

The conditions at the site were less than optimal, primarily because recording was done during the day (Fig CS2.1). Additionally, the terrain was uneven and the wind picked up due to impending rain. However, in one afternoon, two people successfully photographed two rock art panels, each around 0.75m in diameter. One person operated the camera by remote control, while the other lit the rock surface. A piece of string was mounted on a thin piece of PVC pipe so that the person positioning the light source was able to hold both the flash and the end of the string.

Discussion of results

Problems encountered and how they were addressed

As previously noted, logistical challenges included daytime lighting, windy conditions and the relatively remote location of the site. To lessen the effects of the sunlight, filters were attached to the camera lens and a high-intensity flash was selected. Additionally, weights were added to the tripod to offset the wind and to stabilise the camera during photography. There was no access to mains electricity, so all the equipment was self-powered and properly charged. Finally, during the photographing sequences, a remote-

Figure CS2.2:
Left: traditional static photograph of carving.
Middle: screenshot of PTM viewed with specular enhancement.
Right: normal map generated from a PTM-fitted RTI. © Sarah M Duffy

controlled flash was used to highlight the rock. However, since recording occurred during the day, it was difficult to see the reflectance on the surface of the rock and, therefore, assure that the light was illuminating the correct section of the rock panel. In order to increase the likelihood that all the light positions were successfully recorded, more photographs were captured than is typically necessary (approx. 50–60 shots).

Final products and what was gained through RTI

Three RTIs of varying resolution were generated from this work. Successfully producing multiple outputs from the datasets gathered through the fieldwork demonstrated the feasibility of using H-RTI capture at remote rock art sites in daylight. The RTIs have been incorporated into the existing site documentation, possibly aiding specialists interested in future conservation of the ancient rock art motifs. The outputs also provide additional interpretive and analytical tools, and show the potential to answer questions about relative chronology, tooling techniques and tools, the stylistic programme, as well as aid in deciphering whether incisions are natural or man-made.

Case Study 3: Extreme RTI at Ughtasar rock art site, Armenia

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Type: reflectance transformation imaging using H-RTI capture method (outdoor)

Keywords: non-contact, reflectance transformation imaging (RTI), polynomial texture mapping (PTM), highlight-RTI (H-RTI), rock art, petroglyphs, remote, Armenia

Introduction (site and resource)

Ughtasar is a remote rock art site in the Syunik mountains in southern Armenia, around 3,200m above sea level (Fig CS3.1). A majority of the pecked motifs are located in ancient volcanic boulder streams, and the 0.5m to 0.75m diameter carved panels include animals, anthropomorphic figures and geometric shapes. Although the rock art has not been definitively dated, it is estimated to date to the 5th–2nd millennium BC. Since 2009, a small, self-funded international research team has been intensively investigating and recording the site. In the summer of 2010, a pilot project was initiated to test the use of RTI technology on Ughtasar's rock art. The PTMs produced were intended to complement an assorted recording programme that includes specialised photography, photogrammetry, topographical survey using high-accuracy GPS devices, as well as rapid measured survey.

Justification for using RTI

The H-RTI technique was chosen primarily due to the extreme conditions and rugged terrain at Ughtasar, which demands light-weight and portable equipment. In addition, since the project is largely self-funded, the relatively inexpensive toolkit was particularly attractive. Finally, this technique has been successfully employed to record subtle surface relief of rock art at other remote sites. If pilot work at Ughtasar proved the multi-lighting approach to be a feasible and sustainable recording tool, the intention was to add it to the already established suite of recording techniques.

Figure CS3.1: Ughtasar, southern Armenia. © Sarah M Duffy

Discussion of fieldwork

The H-RTI toolkit comprised a Nikon D60 (10.2mpx) camera and compatible wireless remote, a Lowel Pro iD lamp with continuous, dimmable and battery operation, neutral density filters of varying intensities, two black snooker balls, a Benbo tripod, supplemental lighting to be used for setting up the camera and safety equipment (eg a bear bell and horn) (Fig CS3.2).

Challenging conditions at the site included low temperatures, wind, dangerous wildlife and the uneven, rocky terrain made it difficult to position the tripod. Additionally, it was decided to carry out the recording at night, to allow the maximum control of lighting conditions.

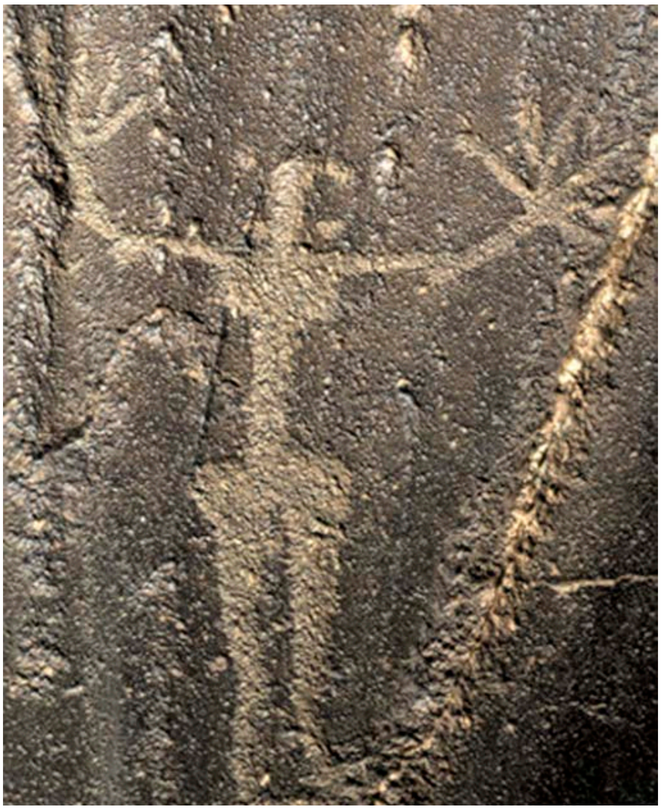
On the first night of recording, training was provided to the research team, which included students and specialists. It took more than an hour to set up and photograph the first panel. However, as the team became more familiar with the equipment and conditions, the recording pace accelerated. During six nights of fieldwork, more than 20 panels were successfully recorded by a team of three or four on each occasion. One panel was photographed several times under varying conditions in order to test the flexibility of the technique.

Discussion of results

Problems encountered and how they were addressed

Predictably, many challenges were encountered at this remote site. The terrain was difficult to traverse and made set-up time consuming, which necessitated leaving camp and travelling to the recording locations before

Figure CS3.2 (left): night-time fieldwork at Ughtasar, Armenia. CS3.3 (right): screenshot of PTM generated from fieldwork, viewed with diffuse gain. © Sarah M Duffy



dusk. By incorporating neutral density filters, it was possible to photograph the panels before sunset, thus allowing the team to record more panels than was originally anticipated.

Furthermore, it was not always possible to satisfy H-RTI lighting requirements at Ughtasar. However, the team captured as many raking light images as possible and the results were satisfactory.

A continuous light source was used for this research and proved easier to control than flash lighting. This did cause some power complications as no mains electricity was accessible. As a solution, all equipment, including the lamp used for RTI photography, was charged using an innovative makeshift solar power system.

To off-set the threat that the wind might destabilise the camera, the tripod was weighed down with a rucksack.

Finally, dangerous wildlife (eg bears and wolves) on Ughtasar become more active at night. Accordingly, the team took extra care to be aware of their surroundings, and packed appropriate safety equipment.

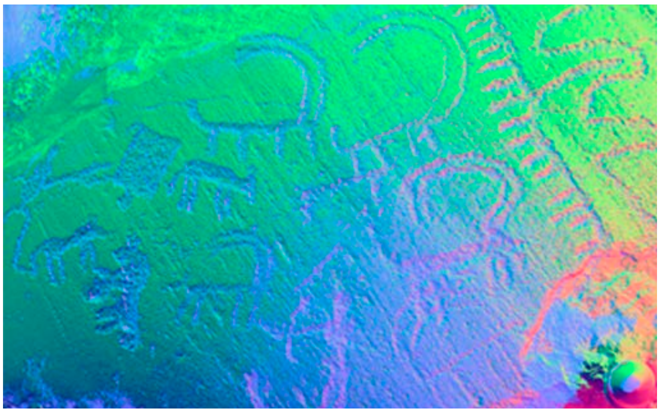
Final product and what was gained through RTI

Despite the challenging recording conditions, the technique proved to be a robust and effective recording method at Ughtasar. More than 20 RTIs were successfully generated from the data gathered during the summer fieldwork, providing remote digital access to the ancient rock art (Fig CS3.3).

The team was encouraged by the results of the pilot work, and the technique was able to highlight aspects of the motifs that had not been previously identified. In addition to supplementing the record at the site, the team plans to use the outputs to further analyse the recorded panels. For example, they hope to use the RTIs to study the deterioration of the ancient motifs.

Where differential carving depth and the occasional superimposition is detected, the outputs will be examined in an attempt to determine phasing and relative chronology. The RTIs will also be reviewed to differentiate between natural and man-made features and investigate how the ancient carvers incorporated natural features into their inscriptions (Fig CS3.4).

Figure CS3.4: a screenshot of normal map generated from a PTM-fitted RTI. © Sarah M Duffy



Case Study 4: Roman painted statue head from Herculaneum

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Type: RTI dome recording of a painted Roman statue head from Herculaneum in Italy

Keywords: RTI, dome, Roman, statue

Introduction (site and resource)

The object recorded was the painted head of a Roman statue of a young woman – identified as a Sciarra-type Amazon from Herculaneum (inventory number 4433) (Fig CS4.1). It is made from fine-grained, pentelic marble – white with very pale yellow streaks – and is roughly 380mm tall.

The head was discovered in 2006 in the vicinity of the Basilica Noniana. At the time of recording it was housed in the on-site museum at Herculaneum. As the research project was based in England, access to the statue was limited.

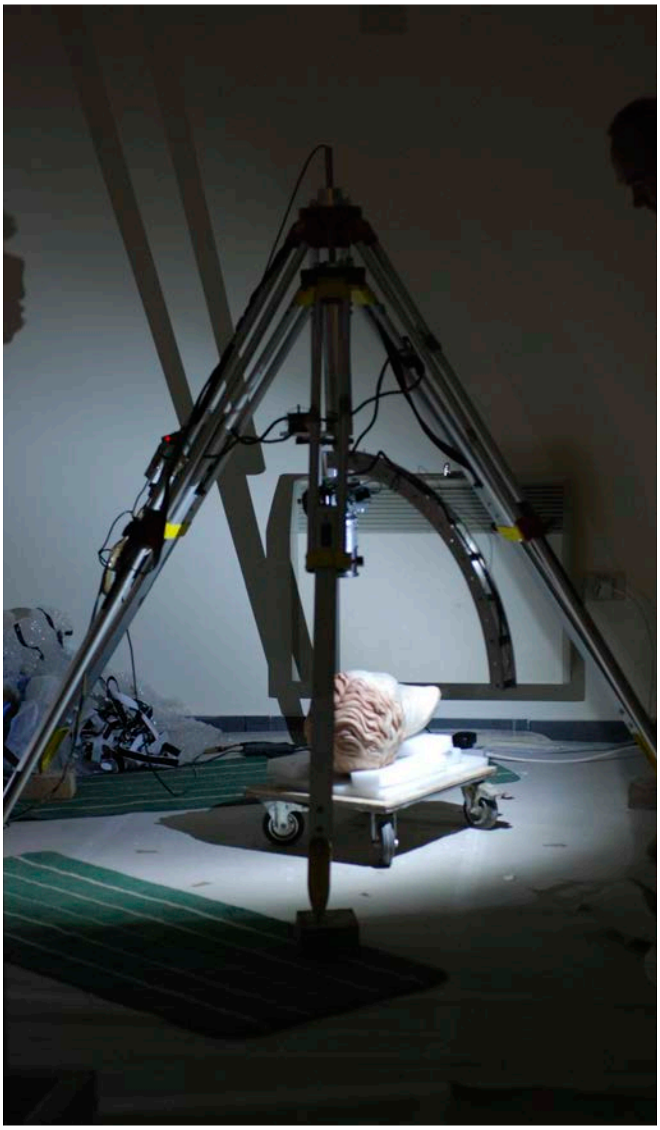
Figure CS4.1: close-up image of the statue. Note the well-preserved paint. © Hembo Pagi

Justification for using RTI

The statue head was recorded as part of a larger project, the goal of which is to record and use metrically accurate 3D computer graphics to virtually reconstruct examples of Roman polychrome statuary from Herculaneum. To achieve these goals it was necessary to create a comprehensive digital record of the object, so that computer graphics work could take place off site. The object was recorded using RTI, laser scanning and conventional digital photography.

The RTI data were invaluable in their ability to provide a record of the influence of light positions upon the surface appearance of the object, an essential component of any virtual reconstruction. The technique enabled us to observe changes in colour and reflectance. RTI data were captured from several angles, providing an excellent record of the surface detail of the object. Where necessary, 'normal' maps derived from the RTI were used to supplement laser scan data. The RTI data was matched to laser scan data using an approach described in Earl *et al* 2010.

Figure CS4.2: the statue head was recorded with a portable dome-type RTI rig. © Hembo Pagi



Discussion of fieldwork

The data was collected using a dome-based RTI system developed at the University of Southampton (Fig CS4.2). The images were captured in two sessions using a Nikon D300 and a Nikon D3X with a 200mm zoom lens and several fixed lenses. This combination enabled the capture of high-resolution images and close-up RTIs, which gave excellent surface detail. Two people conducted the work, undertaking the entire recording session within four hours, during which several RTI datasets were captured.

Discussion of results

Problems encountered and how they were addressed

Few problems were encountered. There were unique challenges recording an object with this much depth. RTI has generally been applied to flat objects or to smaller objects. Consequently it was necessary to take great care in selecting which areas of the image were to be in focus during each capture.

Final product and what was gained through RTI

Consultation of RTI images enabled a visual inspection of the object to continue beyond the short period of access. The painted areas of the statue were examined using the RTI outputs and information on the application and layering of paint was revealed. RTI provided an excellent record of the influence of light position on the appearance of the object. This in turn enabled the production of a far more complex and accurate virtual reconstruction of the statue. Rendered images from the virtual scene were compiled into a virtual RTI to enable comparative verification.

RTI data enabled the generation of ‘normal’ maps, providing an extremely detailed 3D record of the surface of the object.

The RTI records provide a virtual record of the object that can be consulted when the real object is unavailable. This has been of particular benefit when working collaboratively with colleagues at multiple institutions.

Case Study 5: Microscopic RTI of gilded silver discs from the Derveni tombs, Macedonia, Greece

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Type: microscopic RTI

Keywords: RTI, microscopic examination, conservation, silver

Introduction (site and resource)

The Derveni tombs in Thessaloniki, Macedonia, were discovered in 1962 by P Themelis. They are considered one of the most significant archaeological sites in northern Greece because of their numerous rich grave offerings and their important location in the ancient Mygdonian city of Lete, on the pass of Via Egnatia. The cemetery comprises seven graves and, according to the excavation publication, dates to 320–290 BC (Themelis 1997, 192).

The Derveni collection includes vases and vessels, weapons, harness equipment, sport and training objects, furniture, jewellery, cosmetics, figurines, toys, and coins, either exhibited or stored in the Archaeological Museum of Thessaloniki under stable and controlled environmental conditions.

The conservation and interpretation of a large number of artefacts from this collection raises interesting questions, especially in cases of heavily deteriorated fragments. A characteristic example is a group of circular pieces of gilded silver sheet with repoussé (hammering from the reverse side) scenes of a Macedonian shield (A19; diameter approximately 36mm) (Themelis 1997, 47).

Why was RTI selected?

Considering the objectives of a conservation project, including accessibility to the objects, their durability and integrity, and other practical considerations (Watson 2011, 12), RTI was selected for its contribution in the following actions:

1 Preservation

These silver discs were distorted, in fragmentary condition and poorly conserved (Fig CS5.1). Their fragility caused significant handling problems, even from the first stage of the project to assess their condition.

Repeated physical examination of these objects during their museum life may endanger their integrity. RTI was selected as a preventive conservation measure, in order to protect the artefacts, and because visual records of artefacts using RTI can minimise the amount of physical handling necessary for the study of them and thus limit damage.

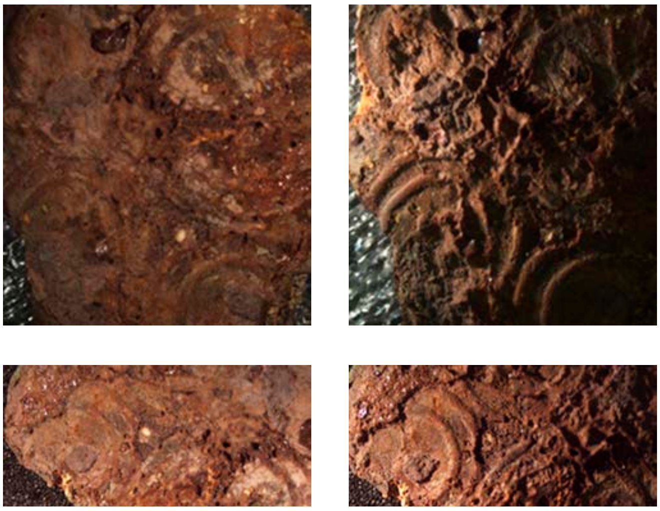

Figure CS5.1: details of heavily deteriorated fragment of silver sheet: comparison of microphotograph (left) and microscopic RTI visualisation (right). Visible area is 15mm.

2 Investigation

Initial physical and visual examination and analysis of an object is the first stage in interpretation before applying any other techniques or further treatment. Raking light in addition to magnification are valuable examination tools (Appelbaum 2007, 12). Microscopic examination with double-sided lighting and in raking light from 5° to 45° to the plane of the object is used to reveal the basic materials of construction, tool marks, traces of gilding, details of assembly, evidence of use and of damage (Caple 2006, 30). Successful visual analysis reveals important features and can guide future choices in an artefact's investigation and analysis.

3 Documentation and communication

RTI can replace the traditional, insufficient documentation, mainly hand drawings and photographs, because it better fulfils documentation, communication and dissemination needs. It is the improved digital analogue to traditional documentation approaches, while the cost remains affordable.

Discussion of fieldwork

The RTI data capture took place in the conservation department of the Archaeological Museum of Thessaloniki. Each recording took less than an hour.

The equipment used included:

- microscope equipped with a camera
- a pen light
- straight sewing pins with ball-shaped, glossy, plastic heads, either red or black, and sharp point
- plastazote foam sheet (material commonly used in museums for storage of fragile items)
- modelling clay or plasticine

Discussion of results

Problems encountered and how they were addressed

The application of highlight image capture technique under magnification is much more demanding than normal RTI.

1. Setting up the scene for microscopic RTI capture requires the best use of the available space. Pieces of jewellery, pearls, pills, pins and parts of mechanical assembly painted with red or black acrylic paint were tested for their efficiency as highlight targets. The glossy plastic-headed pins proved to be the best option because of their variety of head sizes (1 to 4mm diameter) and lengths (20 to 50mm), the low price and the easy positioning with plasticine or modelling clay, or by sticking the pin into a sheet of polyethylene (plastazote) foam sheet. A polyethylene sheet is recommended because it also provides the necessary support for the object being examined.

2. The millimetre-level accuracy in light-to-subject distance required for microscopic RTI is extremely difficult to achieve, considering that the light-to-subject distance should be four times the diameter of the subject. A rotation ring would speed data acquisition and increase the quality of captured data. Another problem is that the microscope arms block some of the light from specific directions. Alternative types of microscope should be considered.

3. In practical terms the use of microscopic RTI in conservation labs may conflict with other conservation activities that require different lighting conditions. Neither switching off the lights (for long periods) nor moving the microscope is practical; therefore, cardboard sheets were used to block the light from other sources.

4. The presence in a museum of a camera-equipped microscope capable of RTI data-capture cannot be assumed.

5. Micro-dome lighting would better address the problems listed above, so it is recommended.

Final product and what was gained through RTI

Microscopic RTI proved to be a valuable tool for documentation and condition reporting of surface variation. It reveals minor anomalies, scratches, gaps and pits, and helps to examine and characterise physical damage. Low-relief decorations become apparent and are distinguished from depositions, encrustations or corrosion.

Figure CS5.2: detail of fragment of silver sheet, backside. Microscopic RTI reveals the horizontal striped texture, which may indicate the contact with another material, possibly organic, such as textile.

Microscopic RTI's ability to emphasise surface variation can be considered an investigation tool. For example, areas with striped texture on the backside of the Derveni silver discs may indicate contact with textile (Fig CS5.2). Such information is important archaeological material evidence, and can aid the interpretation of the object and its characterisation, possibly as an element of decorative apparel.

The morphological analysis of depositions and encrustations helps to identify its nature, and aids treatment proposal. With knowledge of the findings in this study conservators will proceed with further cleaning and removal of the depositions.

The application of other methodologies in conjunction with RTI can confirm the results of the latter as well as further develop finds studies.

Case Study 6: Virtual views of endangered archaeology – the Happisburgh Footprint Project

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Type: virtual-RTI using photogrammetric capture methods (outdoor)

Keywords: non-contact, structure from motion photogrammetry (SFM), virtual reflectance transformation imaging (V-RTI), Palaeolithic Archaeology

Introduction (site and resource)

Located on the Norfolk coast, Happisburgh, UK, has been recognised over the last decade as a key Lower Palaeolithic site for understanding the earliest occupation of northern Europe. In May 2013, a series of storms revealed large areas of laminated sediment which led to the significant archaeological discovery of the oldest known hominin footprints outside of Africa (Ashton *et al* 2014). The prints, which date to between 1 million and 780,000 years ago, were situated in a laminated silt deposit (12m length) in an intertidal zone exposed to daily tidal erosion. Over the course of the following days, specialists visited the site to record and take samples of the prints. Included with this work was Structure from Motion Photogrammetry (SfM), a recording technique in which 3D models are produced from a set of digital images and virtual-RTI (v-RTI), a processing approach in which 3D models are virtually-illuminated and processed using RTI software. Within just a couple of weeks of their discovery, the footprints had completely disappeared, highlighting the pressures of coastal erosion and the importance of the team's quick response.

Justification for using v-RTI

SfM is an imaging technique in which 3D models and metric data are generated from a set of digital photographs that overlap by at least 60%. In a subsequent step, it is possible to generate images of the model being virtually illuminated from different positions and then process the resulting

Figure CS6.1: the recording location in the intertidal zone at Happisburgh. © Simon Parfitt/Martin Bates

Figure CS6.2: in preparation for an exhibition, the Natural History Museum filmed a short documentary about the project; it records the conditions of the day and explains the significance of the discovery in more detail. © NHM

images with the same RTI software used for traditional RTI, thus creating a virtual-RTI. This approach allows users to work with larger subjects (eg landscapes) and interactively select the area to be illuminated, the latter proving especially helpful with more complex 3D surfaces. Other than the software required for processing and re-lighting the 3D models, the SfM recording approach, which is based on digital photography, requires no additional equipment. Furthermore, SfM photography provides an opportunity for fast data acquisition and does not come with the same lighting requirements as RTI. At Happisburgh, the team needed a flexible, rapid imaging technique to capture a record of the disappearing prints.

Discussion of fieldwork

During a tidal window on one very wet afternoon, the photographer systematically moved around the subject area, capturing overlapping images. A team of five undertook this survey with one person taking the images of a section of the prints using a Nikon D5300 (24.2mpx) camera, another shielding the camera from rain and three preparing the next area for recording (Fig CS6.1).

Discussion of results

Problems encountered and how they were addressed

Wind, rain and an encroaching tide were the most notable challenges. Although the tide retreated, the prints were constantly filling up with water so the team worked in tandem, bailing out one set of prints with buckets and sponges as another area was being photographed. It was the intention of the photographer to take images directly above the prints using a ladder, but as rain and sand do not provide a stable substrate, this approach had to be abandoned. Furthermore, the site was located at the base of a 10m cliff, so access became more of an issue as the rain persisted (making the portable toolkit particularly attractive). Finally, since the processing software relies on matching points of interest in the image set, features that change during a capture sequence can cause processing errors (eg rain droplets in the prints and the team's own footprints around the site). As much as possible, any areas of change were masked out of the image set in post-processing.

Figure CS6.3: ortho-rectified image produced from the 3D model of the recording area at Happisbursh.
© Sarah M Duffy

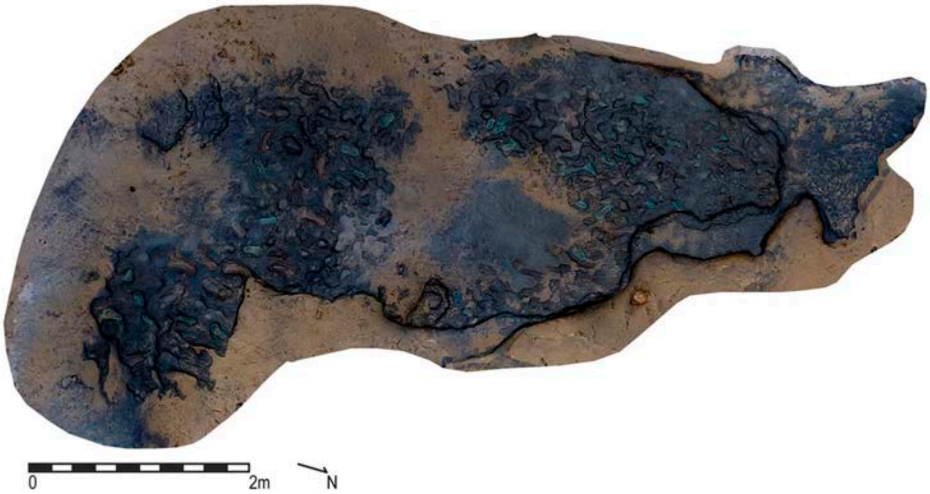
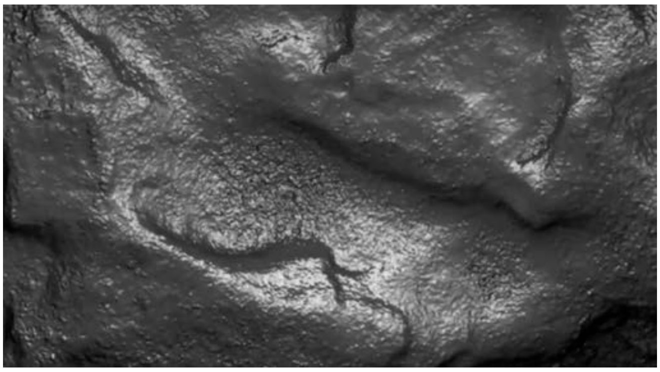


Figure CS6.4: screenshot of V-RTI viewed with specular enhancement.
© Sarah M Duffy



Final product and what was gained through v-RTI

Despite the challenges on the day, SfM proved to be a successful recording approach at Happisburgh and several 3D models of the prints were produced. In a subsequent stage and using an additional piece of software, an image set of a model of a single print was virtually illuminated from different lighting angles was generated. A virtual target was placed next to the model to provide the necessary reflectance information. In a final step, the resulting images were processed using the same RTI workflow outlined in this guidance to produce a virtual-RTI of the print.

As compared to traditional methods, such as taking plaster casts or block lifting, SfM photography provided an opportunity for rapid recording in a challenging environment. Furthermore, due to the conditions at the site and the size of the subject, traditional RTI photography would not have been practicable for this project. However combining these two techniques has enhanced the record and provided users the ability to virtually and interactively re-interrogate the intertidal features which have long since disappeared. The resulting v-RTI provides a new perspective of the ancient footprints, highlighting areas which appear to be toes and foot arches, their relative depths and size, and direction of movement (Figs CS6.3 and CS6.4).

Case Study 7: Underwater Reflectance Transformation Imaging (URTI)

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Type: reflectance transformation imaging conducted underwater (URTI) using H-RTI capture method and scuba diver-directed free-form illuminating.

Keywords: URTI, scuba, underwater, in situ, UCH

Introduction (site and resource)

In the summer of 2013, a proof of concept MSc dissertation was submitted to the University of Southampton's Center for Maritime Archaeology by David Selmo, confirming the viability of using RTI to record in situ underwater cultural heritage (UCH); underwater-RTI (URTI). Selmo developed a semi-submersible RTI imaging dome and conducted experiments generating PTMs of submersed objects in varied turbidity conditions. Over 10,000 underwater images were captured during the research and dozens of successful PTMs generated of submerged cultural material. As part of the research, scuba diver acquired PTMs were successfully generated on archaeological wood from two historically significant shipwrecks, the HMS Invincible and the Cap del Vol. Presented here is a PTM from the Cap del Vol, a 1st-century BC Roman cargo vessel wrecked in 26 meters (86 ft) of relatively clear, warm water in the western Mediterranean, off the northern coast of Catalan, Spain.

Justification for using URTI

An anomaly in the moulded side (face) of a portside floor frame timber just aft of amidships was of particular interest. Two triangular indentations on either 90° edge of the frame appear to both the naked eye and the camera lens to resemble an exterior hull-plank lashing-point transverse to the frame member. This is a lashing method associated with ancient Iberian naval architecture of northern Spain. This ancient lashing method is known from written records but has never been observed in the surviving archaeological

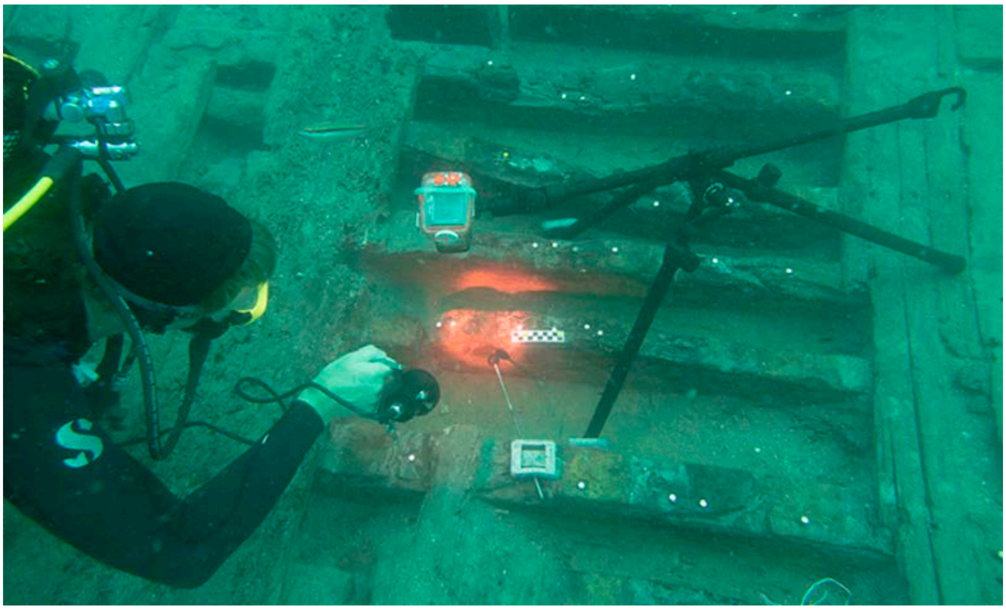


Figure CS7.1: the author performing URTI on the *Cap del Vol* 1st century BC Roman shipwreck. © Dr. Gustau Vivar

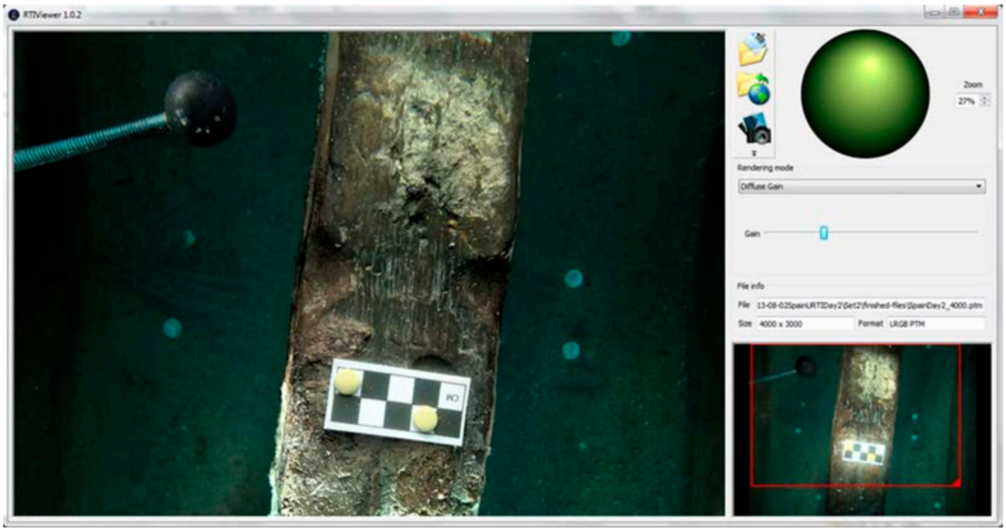


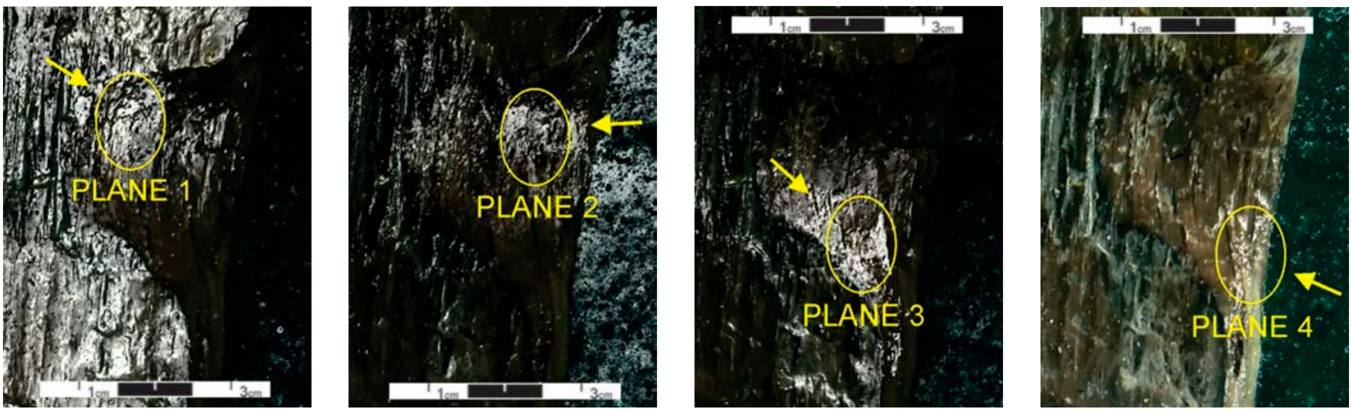
Figure CS7.2: screen-capture from RTIViewer software render of a URTI off the *Cap del Vol* 1st century BC Roman shipwreck. © David Selmo

record. The Cap del Vol may be of Iberian origin but instead features a parallel (through-timber bore hole) lashing method characteristic of Roman built vessels of the time period. Therefore, to help inform maritime archaeologists as to the nature of the anomaly, URTI was used to analyse the surface to determine if its cause was characteristic of impact, abrasion, or tooling.

Discussion of fieldwork

Images for this underwater PTM were captured by a scuba diver utilizing a common point-and-shoot digital camera (Fuji FinePix F200EXR 12 M Pixel) in a proprietary Fuji waterproof housing. A thick rubber band was used to hold down the camera housing shutter button to activate the interval shooting capability. The remaining ancillary items consisted of a tripod (Benbo Trekker MK3), a 1000 lumen high-intensity discharge (HID) torch (Diverite) and a 25.27mm sphere twisted onto a threaded metal rod, 20 cm in length, to facilitate positioning the sphere underwater. The tripod-mounted camera was positioned above the anomaly with a focal length <1.0 m. The reflective sphere was placed in the field of view. With the camera aperture set to F11, interval shooting then took place while the HID torch was introduced into the field of view by the scuba diver. An exposure-batch of 200–300 pixel-

Figure CS7.3: re-lighting the URTI produces four distinct planes of ‘mirror-like’ reflection under specular enhancement. © David Selmo



registered digital images was captured. As the camera fired, the diver free handed the torch to distinctly different lighting angles of incidence, pausing long enough for a minimum of three exposures per incidence.

Discussion of results

Problems encountered and how they were resolved

As a result of free-form torch movement, not every image in the exposure-batch was of equal quality. Therefore, the image-set of roughly 35 to 48 images required to produce this PTM was sub-selected from the available 3 images at each position of light incidence, based on three criteria:

1. best focus;

2. best torch beam position (center on the anomaly);

3. and images that collectively characterized the widest distribution of lighting angles for the set. Priority was given to images with lower grazing angle lighting. This typically produces better RTI results.

Final product and what was gained through URTI

A successful PTM was generated of the anomaly using images captured on a single 30-minute scuba dive. The image-set was sub-selected from an batch of over 200 photos and processed in less than an hour following the dive. An illustration of the PTM of the right-side of the anomaly depicted under varied degrees of specular transformation enhancement and relighting reveals four distinct planes of "mirror-like" reflection. These planes are characteristic of marks made by a straight bladed tool. As such, URTI revealed that this was not an abrasion characteristic of an ancient Iberian lashing point but instead an intentional modification of the timber with a wood working tool.

An article featuring the body of research adapting RTI to the subaquatic environment is available open access in the 2017 edition of the *Journal of Electronic Imaging*'s Special Section on Image Processing for Cultural Heritage.

Case Study 8: Reading an early medieval inscription at Tintagel, Cornwall

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Type: reflectance transformation imaging using H-RTI capture method

Keywords: H-RTI, inscription, epigraphy, medieval

Introduction (site and resource)

In 2017 a 60cm long stone inscribed with Latin writing and Greek letters as well as Christian symbols – all dating from the 7th century – was excavated at Tintagel Castle in Cornwall by Cornwall Archaeological Unit (CAU). Known for its mythical association with King Arthur, and combined with the rarity of inscribed writing from the early middle ages, made this a particularly exciting find. The find was announced in summer 2018 to much excitement from the media. However, when it was first found, the writing was indistinct. Thomas Goskar was commissioned to study the stone and produce enhanced images of the writing to allow further study.

Why was RTI selected?

The writing was lightly incised into a large piece of Cornish slate which once formed a window ledge in an early medieval building. The lettering was indistinct and there was a great deal of excitement and speculation about what it may say. Some large letters were more deeply incised, but no sense could be made of the writing. RTI was selected for several practical reasons. Firstly, RTI is able to enhance very fine details such as light incisions

Figure CS8.1: the inscribed stone, freshly excavated, and before cleaning and conservation.
© Thomas Goskar

into slate. Secondly, it is relatively quick and therefore cost-effective to undertake. Photogrammetry (SfM) would generate a huge dataset beyond the resources of the project.

Discussion of results

RTI capture

The RTI capture was completed in a morning. The inscribed surface of the stone was lightly cleaned and the room set for photography, excluding all light. The camera was mounted on a short boom attached to a stout tripod to allow for a position directly above the inscribed part of the stone, which was positioned on a table. A continuous LED light source was used, along with string to ensure a roughly consistent distance from the centre of the frame. A laptop was used to trigger the 18 megapixel Canon 550D camera by CAU archaeologist and Tintagel excavation director Jacky Nowakowski. Thomas Goskar positioned the light source and asked for the shutter to be released. Images were captured in RAW.

Figure CS8.2: frame from RTI capture sequence. Not every environment has to be perfect!
© Thomas Goskar

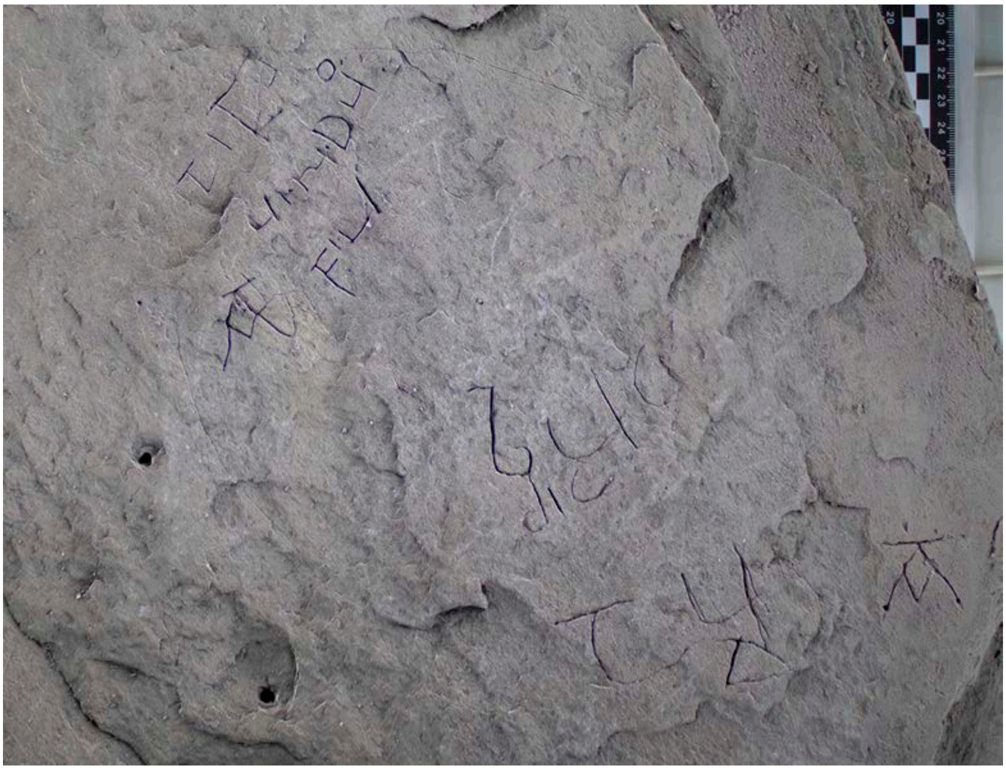

Figure CS8.3: screenshot of the RTI file. The shadows have brought the lettering into sharp relief allowing them to be easily read. © Thomas Goskar

Reading the writing

The images were reviewed on-site, but processed off-site. The HSH fitter was used in the RTIbuilder software to create the RTI file. The resulting interactive image was as required – clear and blur-free, clearly producing the desired enhanced view of the writing. The inscriptions were identified and grouped into three areas. Clear interpretation images were created in RTIviewer, using the annotations feature to mark other potential features. Other features included a lightly incised line encircling all three groups of letters. This was not noticed on the slate during capture.

The stone includes Roman and Brythonic names 'Tito' (Titus) and 'Budic'. The Latin words 'fili' (son) and 'viri duo' (two men) also appear. The excitement of reading personal names for the first time in over a millennium is incredible. The enhanced images and RTI file were passed to medieval writing specialists Professor Michelle Brown and Oliver Padel for the next stage of interpretation.

English Heritage released the story to the press in June 2018, and the stone was featured in the BBC documentary *King Arthur's Britain: The Truth Unearthed*, aired in October 2018.

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Downloads

RTIBuilder

RTIViewer User Guide and HSH Fitter (CHI, Inc.):
http://culturalheritageimaging.org/What_We_Offer/Downloads/

PTM Fitter (HP Labs):

http://www.hpl.hp.com/research/ptm/downloads/agreement.html

Adobe DNG converter:

https://helpx.adobe.com/photoshop/using/adobe-dng-converter.html

Web RTI Viewer

http://vcg.isti.cnr.it/rti/webviewer.php

9 Glossary and abbreviations

CHI	Cultural Heritage Imaging, Inc.
DNG	Digital Negative, a lossless Adobe format considered to be a stable, open file archive format
D-SLR	digital single-lens reflex camera
histogram	a graphic representation that shows the pixel distribution between black and white
H-RTI	highlight-RTI, a flexible RTI capture option that relies on digital photography and a reflective target; highlight refers to the reflectance point captured on the target created when the light source illuminates the subject
HSH	hemispherical harmonics – an alternative approach for fitting reflectance distribution data
ISO	measure of image sensor sensitivity; the lower the number, the lower the sensitivity of the film and finer grain the image
lossy/lossless	terms that refer to the degrees in which the information captured by the image sensor of a camera is compressed
JPEG	Joint Photographic Experts Group – one of the most common lossy digital image formats
metadata	information recorded about the data during the capture or processing phases that can be added to the archive of the project
normal	line or vector orthogonal to the tangent plane of a 3D surface
PTM	polynomial texture map
RAW	(also referred to as 'digital negatives'). This format contains data that have been minimally compressed by the image sensor of the camera; the format varies for different camera makes and models. RAW has been capitalised through this guidance to distinguish it as a generic file type.
RGB	red-green-blue colour model; used for the electronic representation and display of colour images
RTI	Reflectance Transformation Imaging
reflective target	see target
specular reflective	having the properties of a mirror

target glossy black or red sphere used to locate the lighting angle in each photograph during post-processing

virtual dome a virtual 3D lighting dome created by illuminating a subject from a consistent distance at varying degrees above and around its surface

10 Where to get advice

Cultural Heritage Imaging, Inc
http://culturalheritageimaging.org/
CHI is a non-profit organisation, founded in 2002 to advance digital capture and documentation of cultural heritage by creating robust, low-cost imaging tools. They are responsible for the development and distribution of open-access RTI software. They provide instruction and discussion on RTI and photogrammetry and continue to work in partnership with organisations world-wide to develop and improve recording and imaging strategies. They also offer training sessions and consultation on digital imaging in heritage.

CHI forums
http://forums.culturalheritageimaging.org/ (free registration is required)
CHI Forums hosts discussion on all aspects of RTI and photogrammetry in the heritage environment. It is a good trouble-shooting resource as there is an active community of RTI and photogrammetry users who willingly share their research and any and all troubles and solutions they have encountered through their experiences.

The Archaeological Computing Research Group
http://acrg.soton.ac.uk/
ACRG carry out multidisciplinary research in the cultural heritage applications of computer graphics, geographic information systems, web science, geophysics, data management, imaging and survey. They are based at the University of Southampton. The site features an active blog where research students post their ongoing findings.

HP Labs Polynomial Texture Mapping Research
http://www.hpl.hp.com/research/ptm/?jumpid=reg_r1002_usen_c-001_title_r0001

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