Multi-light Imaging for Heritage Applications

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Multi-light Imaging for Heritage Applications
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1 Introduction

1.1 Aim
This publication provides practical guidance on reflectance transformation imaging (RTI), an innovative multi-light imaging technique, and in particular, on the polynomial texture mapping (PTM) method for fitting reflectance distribution data. 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 focus on H-RTI, an alternative recording technique that utilises a pre-fabricated dome will also be introduced, so that readers are able to decide which capture method is most appropriate for their recording project. Several case studies demonstrate how the technology can be used to understand better the cultural heritage we record. These practical examples provide solutions to some of the common challenges encountered in using this recording approach.

There are quick reference tips throughout the publication and a glossary including the abbreviations used. There are also references and useful links at the end.

1.2 Introduction to technology
Polynomial texture mapping (PTM) is a recording technique that was developed in 2001 at Hewlett Packard Laboratories by Tom Malzbender. PTM is one type of reflectance transformation imaging (RTI), a term used to describe a broader family of image-based recording methods in which information about surface reflectance is captured per pixel. A polynomial texture map (PTM) is composed of multiple photographs taken from one stationary position while the surface of the object is illuminated from different raking light positions in each shot. Using a specially developed algorithm, a computer program synthesises the images, compiling all of the information into one file. Dedicated viewing software enables the object to be interactively re-lit, revealing surface detail. The enhanced legibility of surface relief provides a powerful resource for the 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 ancient rock art. *See selection of references at the end of the guidelines.

The following is an illustrated description of how RTI technology works.

* Fig 1 (top) and Fig 2 (above) A surface normal is the vector perpendicular to the surface at any given location. 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).

1.3 Introduction to recording approaches
While there are multiple RTI capture methods, the main focus of this publication is the highlight-RTI (H-RTI) approach, which is often referred to as the ‘Egyptian Method’. The methodology 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).

1.4 Benefits of the technique
• H-RTI is a non-invasive and non-contact recording method, and therefore protects the heritage resource being recorded. H-RTI captures information about surface texture using a series of digital photographs, thus eliminating the need for contact or destructive sampling.
• Although this is a 2D recording technique, it is often described as 2½D because of the high-level visual information provided by highlighting and shadowing 3D objects. In particular, it approximates the surface orientation at each pixel, providing a relative measure of curvature known as a surface normal. 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 5).
• H-RTI is cost effective, as it can be carried out using a relatively inexpensive tool kit and freely available software. A low-end kit can be assembled for about £500. Extremely high levels of detail can be obtained with more expensive equipment, such as a professional high-resolution camera and high-quality lenses.
• 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.

1.5 Limitations of the technique
• While this technique provides detailed qualitative surface information, it does not produce quantitative metric data.

* Fig 4 Illustrates reflectance point on target (© Sarah M Duffy).

* Fig 5 Screenshots from PTM of medieval graffiti discovered in the former prior’s chapel at Durham. The inscription is revealed using specialized viewing tools in the RTI viewer (specular enhancement tool (left) and diffuse gain (right) (© Sarah M Duffy).
If 3D, metrically accurate measurements are desired, other recording techniques are suggested, such as laser scanning or photogrammetric survey (Barber 2011; Andrews et al 2010). Note that work has been undertaken to produce metrically accurate comparisons with PTM in 2D (eg Earl et al 2010 ISPRS paper).

- This approach captures information about surface texture, but does not capture visual information 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 UV or IR photography may provide the desired information. Emerging research in RTI shows that several multi-spectral datasets can be combined using the specialised PTM processing software.

- To optimise the resolution of surface information captured in the images, it is recommended that the maximum size of the subject is c 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 object is unacceptable or impractical, laser scanning or photogrammetry may be more appropriate techniques to use in such instances. RTI operators have also tried stitching multiple PTM datasets together.

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

1.6 Possible uses for the technique

- Contribute visual information about surface detail to the existing record of the heritage object.
- 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.
- Create a work product that can be used in museum and educational settings in order to bring attention to the heritage object. A museum and educational settings in order to bring attention to the heritage object.
- Provide a tool for analysis, interpretation and annotation that can be shared around the world, fostering international research collaborations.
- Capture surface properties that can be used in supplemental 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 different 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 object. 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 objects of varying size – the H-RTI capture method.

2 Highlight-RTI capture technique

2.1 Introduction to H-RTI

H-RTI, also known as the ‘Egyptian Method’, is a flexible recording approach that is able to capture information about surface texture sometimes missed by visual inspection. It can be used to record both very small and large objects (up to c 2m in diameter). One of the most important advantages of the technique is the non-contact recording approach. As long as the object being photographed can be lit using an artificial light source (eg continuous or flash), H-RTI is safe and non-invasive. In a museum context, attention can be paid to emission by the chosen light source and length of exposure, both of which can be kept within standard conservation guidelines. An additional benefit of H-RTI is the relatively inexpensive and transportable tool kit required, which typically includes a digital camera, reflective targets, light source, tripod and string (Fig 7). Moreover, the processing software, much of which is freely available, enables a certain degree of post-processing adjustment (see section 3).

2.2 Tool kit

Camera

There are three main considerations to make when selecting a digital camera. First, it must be able to photograph in RAW, an image format in which the data has been minimally processed by the image sensor of
the camera. RAW format, therefore, enables adjustment during post-processing. Second, the camera needs a manual setting in which aperture, exposure and flash can all be manually controlled. Finally, as the camera cannot be moved after the photo sequence has begun, it needs remote capability. 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. Using this function, the photographer has a real-time view of the object and is able to make adjustments to the camera settings from the computer. However, if the camera is not controlled by computer, a wireless remote or cable release can be used instead. Where a heavy shutter is employed, it is also important that the camera is tightly fixed in place as even this can cause slight movement and affect per-pixel registration.

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 object, the lens should be set to manual. If a wide-angle lens is used, lens calibration is suggested in order to correct image distortion.

Furthermore, the camera cannot be accessed after a capture sequence has begun. Therefore, if a data-storage card is being used, it must be large enough to hold at least one set of RAW photographs (approximately 24–60 shots). As RAW is a substantially larger format than JPEG, a card of at least 4GB is recommended.

**Tip:** Most digital SLR (D-SLR) cameras will meet the requirements of the H-RTI capture method. However, for best results, an 8-megapixel or higher camera is recommended.

**Tip:** If you are using an older camera that did not originally come with a ‘live-view’ option, there is a selection of software available that provides similar functionality (eg DIY Photobits Camera Control is a freely available software that operates many Nikon D-LSR camera models).

### 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 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 still throughout the imaging sequence. If recording takes place in windy conditions or the tripod needs further stabilisation, weights are suggested (Fig 8).

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

**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.

### Light source

A light source is used to illuminate the surface of the object 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. Additionally, it 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 available sources of power. The light source can be continuous or flash, but it should be powerful enough to illuminate the surface of the object 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 destabilize 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. The alternative, a continuous light source, is often 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 object is being accurately highlighted in each shot. A further consideration regarding the selection of lighting equipment is how the light source will be powered (eg remote recording will likely require a battery-operated light source).

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

**Tip:** The light should be separated from the surface of the subject at least 4× its diameter. Therefore, for larger objects, try mounting the light source to an extendable pole (eg a monopod).

### String

By illuminating the object 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 object at a consistent distance of 4× the object’s diameter. A pre-measured piece of string can be used as a flexible aid to determine the distance that the light should be separated from the surface of the object. Although the lighting distance does not have to be exact, in order to maintain a consistent distance around the object, 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 geodesic pattern is the most efficient distribution, a pattern with radial spokes is easier to implement in practice (Fig 11).

#### Greyscale card

Using the RTI workflow highlighted in these guidelines, an 18 per cent greyscale card is incorporated into the capture sequence and later used during image processing in order to adjust the colour of the photographs. This step ensures 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.

### 2.3 Recording technique

#### Accessing and handling the object

In many cases, recording work has 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 by using a specific protocol. It is essential to follow precisely any handling instructions provided.

#### Assembling a team

A further advantage of the H-RTI capture approach is that it requires a relatively small team. Many projects can be completed by just two – one person operating the camera and the second illuminating the surface of the object. For larger objects, a team of three is sometimes necessary, with two people properly positioning the light source.

#### 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 should also be taken throughout the recording process. Information such as project date, name and/or number of the object and site, the size of the object, equipment details (eg lens type), the length of the string, the names of each team member and their corresponding task, recording conditions and any errors encountered should be also noted. The RTI format itself provides an expanded opportunity for meta-tagging.
Selection of recording location
There are three primary considerations to make when choosing a recording location. First, 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 wood floors, which can shake as the light source is moved around the object (Fig 12). Second, the space should allow for the light source to be separated by c. 3x to 4x the diameter of the object on all sides. One final consideration to make about location is the presence of other light sources. Unless specialised filters are used, 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 object cannot be moved and thus requires being photographed 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 surrounding features (eg architectural features) that prevent the capture of all desired lighting positions. Additionally, recording in daylight may affect the success of H-RTI photography or produce very bright PTMs. In such instances, neutral density filters should be used to offset the effects of unavoidable ambient light.

Preparation and placement of the object
Once the recording location has been selected, prepare a secure area to place the object. Position the object in the space so that it can be lit on all sides from the proper distance.

In some instances, it is necessary to prepare the surface of an object. However, make sure to consult the proper professionals before any contact with the subject.

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

Tip: Portable objects can be placed on a plain piece of fabric (eg black) in order to forefront the object in the images and create the effect of a uniform background.

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

Tip: Think carefully about the orientation of the object. Positioning the object so that it is facing the correct direction and aligned straight in the frame eliminates the necessity of some post-processing adjustment.

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

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 object, and incorporate both the object 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. If the camera has a power-save mode (ie automatically shuts off after a certain amount of time being idle), this function should be disabled.

Placement of reflective targets
The targets should be placed and stabilised next to the object close enough to be incorporated in the photographs but far enough away from the object 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 (eg see Fig 7).

Eliminating or controlling ambient light
Optimal H-RTI recording conditions call for complete darkness, so indoor or nighttime recording is best. For indoor recording, this means turning off overhead and supplemental lighting sources as well as covering windows.

As was previously mentioned, in the case of outdoor, daytime recording, neutral density filters of the appropriate intensity should be fixed to the lens. Umbrellas can be placed over the capture area to further control ambient lighting. If daytime recording is required, photographing on an overcast day is preferable.

Making final adjustments to the camera
After the camera is in the correct position over the object and targets, and ambient light has been eliminated or minimised, the camera should be set to photograph in RAW format. Next, focus the camera on the surface of the object and set the lens to manual in order to ensure that it is in a ‘locked’ position. If the camera is not connected to a computer, take test shots in order to adjust the focus, exposure and aperture. These test shots should include images at the highest and lowest light angles (ie 65° and 15°). Aim for a histogram curve in which no whites are blown out and no shadows are too dark (Fig 13). Finally, the camera itself should be set to manual in order to ensure that the settings will not change throughout the photo sequence.

If neutral density filters are being used, take a test shot without lighting the object. The histogram should read to the far left. If the image is still bright, increase the intensity of the filters, re-adjust the camera

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

Tip: Think carefully about the orientation of the object. Positioning the object so that it is facing the correct direction and aligned straight in the frame eliminates the necessity of some post-processing adjustment.

Fig 12 (left) 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).

Fig 13 (below) For H-RTI, the histogram should read toward the left, avoiding blow-out of whites (© Sarah M Duffy).
settings (eg focus, aperture, etc) and return to the manual setting.

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

- It is best to keep the aperture set between f/5.6 and f/11. Avoid an aperture setting narrower than f/13.
- Keep the ISO setting as low as possible in order 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, setting it to manual after accuracy has been confirmed in test shots.
- The longer the exposure time, the greater the opportunity to introduce movement into a shot. Try to achieve a shutter speed of 1/60 or faster.

**Tip:** Spend some time learning how to read histograms. The better you understand what they mean and how to make adjustments to the camera settings accordingly, the easier it will be to take higher-quality photographs and produce better quality PTMs (Fig 13).

**Tip:** One of the benefits of photographing in RAW format is that it allows some adjustment of images during post-processing.

### 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 card. Alternatively, a small greyscale card can be incorporated into the frame of the shot. As with the reflective targets, this card should be placed so that it can be cropped out during post-processing.

**Tip:** It is easy to forget to take a photograph with the greyscale card. In order to avoid inadvertently missing out 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).

When deciding how to illuminate the object during the photo sequence, it is helpful to imagine photographing around a virtual dome oriented on a virtual clock. Depending on how many photographs of an object are desired, establish how many locations around the dome will be photographed and then decide what angles above the surface of the object will be used. As PTMs offer information about highlighting and shadowing, it is not necessary to capture photographs directly above the object (‘high noon’ or 90°). However, it is recommended that the subject be lit from at least three positions between 15° and 65° above the surface of the object (the ‘horizon/0°’). As an example, in order to capture 24 shots, pick eight equidistant locations around the clock (eg 12, 1:30, 3, 4:30, 6, 7:30, 9 and 10:30) and then photograph at 15°, at 40° and at 65°above the object at each location around the object (see Fig 11).

During this final phase of the capture sequence, one person operates the camera directed by the person lighting the object. The light should be focused on the surface of the object and held as still as possible in each shot. Again, it is important to be mindful of shadows created by tripod legs, umbrella can provide a good means of eliminating direct light. If recording during the day outside, neutral density filters are required.

- **Weather conditions:** If winds are strong, the tripod must be stabilised so that there is no movement of the camera during photography.
- **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 object. Large objects or outdoor/daytime recording may require a higher intensity light (eg flash). Alternatively, the surface of the object 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 in order to be detected. Their size depends on the size of the subject and should take up roughly 200 pixels of the image. The targets must be stabilised in each shot. Photographing two reflective targets is recommended.
- **Power sources:** Consider how equipment (eg the light source) will be powered.
- **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 shape of the object itself.

To summarise:

- Place the object on a stable surface (if portable).
- Mount the camera over the selected capture area.
- Position the spheres in the shot far enough away from the object so that they can be cropped during post-processing.
- Set the camera to photograph in RAW, focus it on the object and then set the camera and the lens to manual.
- If it has not been incorporated into the photo set-up, take one image with a greyscale card.

Creating a ‘virtual dome’ and photography

The final step of the recording phase is illuminating and photographing the object. PTMs can be successfully generated on as few as 16 photographs. However, more raking-light images mean greater acquisition of data and a higher-quality finished PTM. In addition, photographs are sometimes discarded during the post-processing 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 object by c 3× to 4× its diameter. Using a measuring device such as a pre-measured piece of string ensures that the distance between the light and object is consistent in each photograph. (This measurement does not have to be metrically exact.) If a larger object is photographed, it is sometimes necessary for two people to operate the light source – one person holding the end of the string and the other positioning the lamp. It is also possible to use an electronic distance meter.

**Tip:** If using an electronic distance meter, use one with an audible alarm that sounds at a pre-set distance and attach the meter to the flash so that they remain in a constant relative position.
3 Post-processing the H-RTI

3.1 Introduction to processing
RAW files have the advantage of being a ‘lossless’ (or near lossless) format and allow some 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 eliminates the issue of varying RAW formats. In the next stage of processing the DNG files are adjusted in synchronised operations and exported as a set of JPEGs. The resulting JPEGs are processed by specialised software that detects the highlight position in each image and generates a light position file. In an additional step, the software is used to crop the targets out of the photographs and generate a final set of JPEG image files. Finally, additional software synthesises the information from the light position file and the JPEGs to generate a PTM.

3.2 Introduction to CHI
Cultural Heritage Imaging (CHI) was established in 2002 by Carla Schroer and Mark Mudge. Based in San Francisco, California, it 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 creates and fosters research collaborations throughout the world among cultural heritage communities. They emphasise and encourage the use of freely available, open-source tools in cultural heritage recording projects. Further information about CHI and the technologies it promotes can be found at http://culturalheritageimaging.org.

3.3 Software requirements and access
CHI provides free access to all software required to process a PTM except that needed to convert the original photographs from RAW to JPEG format (via DNG). These guidelines feature a processing workflow that incorporates RTIBuilder developed by Universidade do Minho and the PTM Fitter developed by Hewlett-Packard Company. Note that certain licensing restrictions apply to the current version of RTIBuilder which require the fitting software to be downloaded separately.

In this processing approach, RAW files are converted using Adobe products (eg Adobe Camera Raw in Photoshop CS3 or higher or Lightroom). If you are considering using alternative software, the requirements are that it include the functionality for RAW photographs to be rotated, white balanced and adjusted for exposure as a synchronized batch jobs. The software should also be able to convert RAW images to DNG, and then DNG to JPEG format.

Finally, Java 6 or higher is also required for this workflow.

Tip: Various plug-ins are available that will provide the required functionality to earlier versions of Adobe Photoshop (eg Adobe DNG Converter and different versions of Adobe Camera Raw). Note that the applicability of these depends on the model and make of the camera that was used to capture the original RAW files.

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

3.4 Processing workflow
Directory structure
The processing software uses a preformatted directory structure, which is also available through CHI.

The name of the primary folder can be changed to provide information regarding the recording project. However, it may not contain spaces. The names of the files within the main directory folder should not be changed, as they are used by the processing software (ie assembly files, finished files and JPEG exports).

Apple Mac users should place the folder in the top directory.

Convert RAW to DNG
Once the original RAW photographs have been transferred from the camera’s storage card, they must first be converted into DNG files using software such as the Adobe Camera RAW plug-in. In this step, discard any unwanted images and convert the entire set of photographs to DNG. It is recommended that the raw data be embedded in this step. Doing so eliminates the necessity of archiving the original RAW images. Save the new images using a naming convention that provides information regarding the project and/or object. (Remember not to use spaces in the file names.)

Convert DNG to JPEG
Adjustments to the images can be made in this step. In synchronised operations, the entire set of photographs should be ‘zeroed out’ (ie all settings but the first three are adjusted to zero) and white balanced using the photographed grey scale card. If necessary, modifications can also be made to the exposure and orientation. Once the images have been adjusted, export the DNG files as JPEGs in the desired size to the ‘jpeg-export’ folder. Note that the size of the JPEGs dictates the resolution to which the PTM can be processed.

Figure 14 provides a brief overview of this step using Adobe Camera Raw in Photoshop CS3.

Using RTIBuilder
In the final stages of processing, RTIBuilder is used to locate the highlight position in each image (JPEG) and generate a highlight file (.txt), crop the reflective targets and produce a new image set (JPEG), and finally generate a PTM using the specialised fitting software, images and the light position file.

The following provides illustrated guidance on how to use RTIBuilder.

Screen 1: RTIBuilder page
A Input the name of the project.
B Select the ‘Highlight Based’ pipeline.
C Move to the next screen by selecting ‘Start New Project’.

Screen 2: Open images
D Select ‘Open Folder’ and map to the folder that contains the JPEG files previously converted from DNG. This should be the ‘jpeg-export/’ folder. Open this at the higher folder level (ie the parent folder).
E Add metadata in the ‘Project Properties’ section (bottom left) by clicking ‘Add’ and then inputting field and value information. If revisions or additions are made, click ‘Save’.
F Images can be removed during this step if they contain shadows, or are too dark or too bright. If an image is removed, note the reason for deletion in the ‘Removal Reason’ text box. Then click ‘Remove Picture’.

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

Tip: All images contain spaces. The names of the files should also be able to convert RAW images to DNG, and then DNG to JPEG format.

Figure 14: Use a systematic approach to lighting the object to avoid any gaps in coverage. If there is any question about an image, simply reshoot.

3.4 Processing workflow
Directory structure
The processing software uses a preformatted directory structure, which is also available through CHI.

The name of the primary folder can be changed to provide information regarding the recording project. However, it may not contain spaces. The names of the files within the main directory folder should not be changed, as they are used by the processing software (ie assembly files, finished files and JPEG exports).

Apple Mac users should place the folder in the top directory.

Convert RAW to DNG
Once the original RAW photographs have been transferred from the camera’s storage card, they must first be converted into DNG files using software such as the Adobe Camera RAW plug-in. In this step, discard any unwanted images and convert the entire set of photographs to DNG. It is recommended that the raw data be embedded in this step. Doing so eliminates the necessity of archiving the original RAW images. Save the new images using a naming convention that provides information regarding the project and/or object. (Remember not to use spaces in the file names.)

Screen 1: RTIBuilder page
A Input the name of the project.
B Select the ‘Highlight Based’ pipeline.
C Move to the next screen by selecting ‘Start New Project’.

Screen 2: Open images
D Select ‘Open Folder’ and map to the folder that contains the JPEG files previously converted from DNG. This should be the ‘jpeg-export/’ folder. Open this at the higher folder level (ie the parent folder).
E Add metadata in the ‘Project Properties’ section (bottom left) by clicking ‘Add’ and then inputting field and value information. If revisions or additions are made, click ‘Save’.
F Images can be removed during this step if they contain shadows, or are too dark or too bright. If an image is removed, note the reason for deletion in the ‘Removal Reason’ text box. Then click ‘Remove Picture’.

Tip: Use a systematic approach to lighting the object in order to avoid any gaps in coverage. If there is any question about an image, simply reshoot.
a) select all and synchronise actions  
b) white balance using greyscale card  
c) zero out settings (note exposure can be adjusted approx. 2 stops +/-)  
d) export as JPGs

Fig 14 Screenshot from DNG to JPEG conversion using Adobe Camera Raw in Photoshop CS3.

Fig 15 Post-processing in RTIBuilder: Screen 1 (RTIBuilder software is copyright Universidade do Minho and Cultural Heritage Imaging 2007–2011 and is made available under the Gnu General Public License version 3. The required PTM Fitter is copyright Hewlett-Packard Company).

Fig 16 Post-processing in RTIBuilder: Screen 2.

Fig 17 Post-processing in RTIBuilder: Screen 3.

Fig 18 Post-processing in RTIBuilder: Screen 4.
G. Select ‘Next’ to proceed to the next screen.

Screen 3: Selecting the target (Fig 17)
H. Use the mouse to highlight the area around the target (i.e., the black or red sphere). A transparent green box will appear over the selected area.
I. Select ‘Add Area’. The highlighted box will turn red and can be adjusted using the handles provided. Note that this software currently only processes PTMs using one target.
J. In the ‘Process Configuration’ section, select either ‘black’ or ‘red’ target from the drop-down menu.
K. Then click ‘Detect Sphere’. This step may take a while to complete.

Screen 4: Confirming the target (Fig 18)
L. Once the target has been detected, adjust the red circle outlining the sphere using the available handle so that it accurately outlines the shape of the target. If the target is too large to fit the screen, the size can be adjusted using the ‘Image Scale’ bar.
M. If adjustments are made, click ‘Set New Center’.
N. If the highlights or the ball have not been detected properly, restart the highlight detection step by selecting ‘Redo Process’ (bottom right).
O. Select ‘Next’ to proceed to the next screen.

Screen 5: Highlight detection (Fig 19)
P. Click ‘Highlight Detection’. This step may take a while to complete.

Screen 6: Highlight detection (Fig 20)
Q. Once completed, the highlight distribution can be reviewed by clicking on the image marked ‘blend’. An archival copy of this image is located in the ‘assembly_files/’ folder along with the light position file generated during this step.
R. Click ‘Next’ to proceed to the next screen.

Screen 7 (left): Select cropping area (Fig 21)
S. To crop the images, click on the ‘Use Crop’ option under ‘Crop Properties’.
T. Select either the ‘Free’ form or ‘Rectangular’ cropping option from the drop-down menu.
U. Select the area to be cropped by drawing either a rectangle or free form area on the image. The area will be highlighted with a transparent green box. Clicking ‘Clear Crop’ will restart the cropping procedure. Note the area selected will be the frame of view for the PTM.

Screen 7 (right): Fitting the PTM (Fig 22)
V. The first time RTIBuilder is used to generate a PTM, it is necessary to map to the PTM Fitter in the ‘PTM Fitter Location’ under ‘Data’. Remember that the fitter will have been downloaded separately. This step should not need to be repeated as long as the fitter is not moved.
In the next step, the output PTM can be formatted for size and colour. Note that PTMs processed using the RGB option will result in a larger output file, but will also have more colour accuracy. The PTM can also be named in the ‘Output File Name’ field. (If creating multiple PTMs of the same subject, then it is useful to give the files meaningful names.)

If multiple target areas were previously processed (see Screen 3), then select the preferred sphere number.

Next select ‘Execute’. A dialog box located on the right side of the screen tracks the progress of processing and a message box will pop up when complete, which, if successful, will announce ‘Fitting Completed’. The finished PTM file will have been written to the ‘finished_files/’ folder.

Note that a ‘Back’ button option is available throughout the processing sequence and is located on the bottom right-hand corner of most screens. The above steps can be repeated using the same image set and different parameters to create multiple PTMs.

4 An alternative recording approach and software innovations by Graeme Earl

The Archaeological Computing Research Group (http://www.soton.ac.uk/archaeology/acrg) 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. More can be learned about the AHRC RTISAD project at http://www.southampton.ac.uk/archaeology/acrg/AHRC_RTI.html.

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. 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 scissors lifter for positioning objects.

The RTISAD project has also explored software innovations. First, it has generated a means to annotate RTI datasets (see section 6). Second, it has produced a prototype RTI repository hosted by the Archaeology Data Service (ADS) in York. This prototype includes workflow management for documentation and deposit of RTI archives, and a costing process for future deposits. Third, it has developed two versions of a camera control system – one using proprietary Nikon camera drivers and another using entirely open source. 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).

5 Viewing RTI and PTM files

5.1 Introduction to the viewer

RTIViewer is a specialised software that can be used by both Apple Macs and PCs, and opens multiple RTI formats, including PTMs. It was developed primarily by the Italian National Research Council’s Institute for Information Science and Technology Visual Computing Laboratory. The viewer and a detailed instruction manual are freely available on CHI’s website (see Web links cited). The viewer enables users to manipulate the data that were captured during photography. Users can move a virtual light around the surface of the object, adjust and enhance the RGB values and surface normal information. Manipulating this information often provides an enhanced perception of surface texture and detail.

To find out more information about RTIViewer, as well as about the developers and sponsors, click on the blue info button under the configuration icon.

5.2 Opening a PTM

Although this software is capable of opening multiple RTI formats, these guidelines outline its functionality with PTMs (Fig 24).

To open a PTM from a file, click on the top folder icon to the left of the green sphere and browse the local directory until the desired PTM file is located. If the file to be opened is on a shared network, it can be viewed remotely by selecting the second folder icon.

The PTM will open in the main viewing panel on the left of the screen. Configure the size of the main panel using the wrench/screwdriver in the toolbox to the left of the green sphere (Fig 24A). Checking the ‘full size’ tick box will maximise the size of the image.

Property information about the PTM (eg name, size and format) can be found on the right of the screen (Fig 24B). A control panel in the bottom right corner provides...
tools for zooming and moving the selected viewing area (Fig 24C).

**5.3 Interactive tools**

**Moving the light source**
The light source can be moved interactively around the surface of the object by pressing and holding the left mouse button and by moving the cursor around the green sphere on the top right-hand side of the screen (Fig 24C). The screen displays the lighting information captured in the photographs. The virtual light starts in the ‘high noon’ position (without raking light). The farther the cursor is moved towards the edge of the sphere, the more oblique, or raking, the light will become. Users of computers with other means of cursor movement will need to move the cursor according to their equipment.

**Zoom**
The viewer also enables users to zoom into specific areas of the object. This is done in several ways (Fig 24D), for example, by increasing or decreasing the zoom ratio with the arrows to the right of the highlight sphere. A red box outlines the area being displayed in the control panel at the bottom right-hand corner of the screen. By dragging the triangular handle in the bottom right of the box, the zoom ratio can also be adjusted. Finally, if you are using a mouse, the scroll-wheel can be used to adjust the zoom in both the control and main panels. Move the area selected by moving the cursor in the main viewing panel or by moving the red box in the control panel.

**5.4 Rendering modes**
There are several rendering modes that enable the user to modify the visual characteristics of a PTM. Each tool uses mathematical transformation calculations in different ways to maximise the information gathered during the recording phase. A list of applicable rendering modes is displayed in the drop-down menu under the highlight sphere (Fig 24E and Fig 25). Each enhancement tool has a set of associated adjustable parameters. The rendering mode options may change with different RTI formats.

Figure 25 provides a list of rendering options that are compatible with PTMs. However, a more detailed, technical description of each of the enhancement tools can be found in the previously mentioned RTIViewer guidelines made available by CHI.

**5.5 Creating a snapshot**
A screenshot of what is being displayed in the main viewing panel can be created by using the ‘camera’ icon to the left of the highlight sphere (Fig 24A). In order to generate a snapshot, choose a location to save the file and select the desired image format (either JPEG or DNG).

**6 Alternative RTI formats and emerging software**

While these guidelines outline the H-RTI capture approach and PTM fitting method, there are alternative RTI capture and fitting techniques as well as RTI formats.

**6.1 Hemispheric harmonics (HSH)**
HSH is a more recently developed technique for fitting reflectance distribution data. It is particularly useful for visualising reflective, 3D surfaces. The necessary fitting software can be downloaded with the most recent release of RTIBuilder (version 2.0.2). HSH fitting can be completed using the same directory structure and images captured for PTM fitting, by choosing the ‘Highlight Based (HSH Fitter)’ workflow option in RTIBuilder and either starting a new project or opening an existing project previously processed with the PTM fitter (Fig 26). (HSH Fitter is copyright University of California, Santa Cruz and CHI, Inc.)

**6.2 Annotating an RTI dataset**
The AHRC RTISAD project extended the RTI viewer and format to enable annotation of RTI datasets. These annotations are linked to the viewer settings and can be shared as a separate annotation file. A separate 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.

6.3 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 (for further information, see MacDonald and Robson 2010; MacDonald 2011).

6.4 Virtual PTM and landscape
Landscapes can be virtually rotated and illuminated on screen using 3D processing software, lidar datasets and RTI technology (for further information, see Earl et al 2010; Goskar blog).

Glossary and abbreviations

**CHI** Cultural Heritage Imaging, Inc.

**DNG** Digital Negative, a lossless Adobe format considered to be a stable raw 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 on the target created when the light source illuminates the object

**HSI** 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

**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 reflectance dome created by lighting an object from a consistent distance at varying degrees above and around its surface

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CASE STUDY 1
Digital preservation of worked antler (Star Carr) using RTI
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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 c 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 c 15mm × 80mm). Ben Elliott, a PhD student at University of York specialising in the manufacture and use of antler tools within the British Mesolithic, 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 ongoing 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.

Justification for using RTI
In this case study, the non-invasive approach proved the principle 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 been laser scanned previously, with less than satisfactory results, possibly owing to the nature of the material (eg 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 supplemental 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 per cent greyscale card. Recording conditions were optimal since 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).

Downloads
Adobe updates/plug-in downloads: www.adobe.com/support

Fig CS1.1 Star Carr 2010 excavations. This re-excavated trench contained additional barbed points (© Nicky Milner).

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

Lucet, C, Pitzalis, D, and Ribes, A (eds) VAST10: The 11th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage – Short and Project Papers, 111–37
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Web links cited
Cultural Heritage Imaging, Inc: http://culturalheritageimaging.org/
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 4× 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 PTMs 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 PTMs have enabled examination of the surface of the points in a way that had not previously been possible. In particular, specialist Ben Elliott found that the manipulation of raking light highlighted the surface in a way other techniques had not permitted. The PTMs 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. 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 PTMs 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 c 20m × 15m (Fig CS2.1). The site is close to the Scottish border, in Northumberland County near Doddington. It is accessed by right of way using a footpath that leads from the road. It is a scheduled ancient monument, decorated with prehistoric incised artwork – primarily cup and ring marks. Researchers speculate broadly that Northumberland rock art
originated in the Neolithic and Early Bronze Age. There are no definitive interpretive explanations of these ancient motifs.

The massive, whale-back-shaped rock has a long history of recording. 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).

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 light 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 benefit digitally.

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. 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, Manfrotto tripod, two black snooker balls, scale ruler, string mounted on PVC pipe and 18 per cent 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 with impending rain. However, in one afternoon, two people successfully photographed two rock art panels, each $0.75m \times 0.75m$. 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. 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-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). For future daytime rock art recording, consideration is being given to the use of a self-powered, high-intensity continuous light source.

**Final products and what was gained through RTI**

Three PTMs of varying resolution were generated from this work. Successfully producing multiple PTMs from the datasets gathered through the fieldwork demonstrated the feasibility of using RTI technology at remote rock art sites in England in daytime lighting. The PTMs have been incorporated into the existing site documentation, possibly aiding specialists interested in future conservation of the ancient rock art motifs. The PTMs also provide additional interpretive and analytical tools, and show the potential to answer questions about relative chronology, tooling techniques and instruments, and the stylistic programme, as well as aid in deciphering whether incisions were natural or man-made.
CASE STUDY 3
Extreme RTI at Ughtasar rock art site
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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, c. 3,200m above sea level (Fig CS3.1). A majority of the pecked motifs are located in ancient volcanic boulder streams. The carved panels include animals, anthropomorphic figures and geometric shapes c. 0.5m–0.75m diameter. Although there has been no definitively established date, the rock art is estimated to date to the 5th–2nd millennium BC. A small, self-funded international research team began an intensive survey of the site in 2009. 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 at Ughtasar primarily because the site is difficult to access and because the required equipment is easily transportable. In addition, since the project is largely self-funded, the relatively inexpensive tool-kit 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.

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 when setting up the camera and safety equipment (e.g. a bear bell and horn) (Fig CS3.2).

Challenging conditions at the site included low temperatures, wind, dangerous wildlife and the difficulty of positioning the tripod on multiple rocks. 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 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.

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. However, this did cause some power complications as no mains electricity was accessible. As a solution, all equipment, including the lamp used for PTM photography, was charged using a 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 (e.g., bears and wolves) on Ughtasar becomes 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 PTMs were successfully generated from the data gathered during the summer fieldwork, providing remote digital access to the ancient Armenian rock art (Fig CS3.3).

The team was encouraged by the results of the pilot work. 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 PTMs to further analyse the recorded panels. For example, they hope to use the PTMs to study the deterioration of the ancient motifs.

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

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 Sciarrà-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 c. 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. As the research project was based in England, access to the statue was limited.

Why was RTI selected?
The statue head was recorded as part of a larger project, the goal of which is to record and use physically 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, we used ‘normal’ maps derived from the RTI to supplement laser scan data. We matched the RTI data to laser scan data using an approach described in Earl et al. 2010.

Discussion of fieldwork
We collected the data 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 us to capture high-resolution images and close-up RTIs, which give 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. We scrutinised painted areas of the statue using RTI and acquired information on the application and layering of paint. RTI provided an excellent record of the influence of light position on the appearance of the object. This in turn enabled us to produce a far more complex and more accurate virtual reconstruction of the statue. We compiled rendered images from the virtual scene into a virtual RTI to enable comparative verification.

RTI data enables us to generate ‘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, discovered in 1962 by P. Themelis, 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 scenes of a Macedonian shield (A19; diameter c. 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) Prevention
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.

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 (Fig CS5.2). 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 plasteline

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 (1–4mm diameter) and lengths (20–50mm), the low price and the easy positioning with plasteline 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 4× 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
1 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

Fig CS5.2 Laboratory set-up showing microscope and light source.

Fig CS5.3 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.
become apparent and are distinguished from depositions, encrustations or corrosion.

2 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 CS5.3). 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.

3 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.

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