

Digitizing the Dead Sea Scrolls

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Abstract

The Dead Sea Scrolls are objects of unrivalled importance and fragility. The Israel Antiquities Authority (IAA) invited a number of experts to provide advice to them regarding the possibility of digitising the Dead Sea Scrolls (DSS). This led to a Pilot of the imaging technology in August 2008. This paper will describe the innovative workflows and technology used in the Pilot, and further developed since then, to deliver unique perspectives on the Dead Sea Scrolls. Of particular interest is the spectral imaging of selected fragments between 650-1000 nm with a nominal bandwidth of 10 nm. This technique and the experience of the Pilot offer many lessons for other such imaging and conservation projects.

Introduction

Hidden for almost 2,000 years in remote caves in the Judean Desert, the Dead Sea Scrolls are considered the greatest archeological find of the twentieth century. The Israel Antiquities Authority (IAA) has worked for decades to preserve and make accessible these artifacts. The Scrolls have been the subject of intense scholarly investigation, much of which is based upon infra-red photography dating back to the 1950's.. Very little photography or imaging has been done in the last 20 years compared to the totality of the Scrolls. Thus, there is a gap in the detailed image information available for scholarship as well as a lack of an active image record that could be used to assist the conservation efforts of the IAA.

The IAA invited a number of experts to provide advice to them regarding the possibility of digitising the Dead Sea Scrolls (DSS). This led to a Pilot of the imaging technology in August 2008. The provisional vision statement for the digitisation of the Dead Sea Scrolls is:

"The IAA will digitise the Dead Sea Scrolls to protect the Scrolls for future generations whilst enabling all to be able to digitally view and research these artefacts of unrivalled value to world heritage".

The challenge for the Pilot was to gain a high resolution, color accurate image from the Scrolls in the color visible spectrum. This high standard has to be replicated in the Infra-Red (IR) imaging to show characters and writing not easily legible in the visible spectrum. It is well known that IR imaging provides much greater text contrast for illegible scrolls and that IR imaging is necessary to provide text for scholars. Further to this imaging there is a requirement to enable better conservation of the Scrolls through the superior monitoring that can be achieved via Imaging Spectroscopy (IS). This vision joins conservation and access together as key deliverables for the IAA. Digitising the Dead Sea Scrolls is about enabling conservation and preservation of the Scrolls with high quality surrogate images and non-invasive monitoring.

The pilot team, invited by the IAA, included Greg Bearman, Simon Tanner, Julia Craig-McFeely (Royal Holloway, University of London), Tom Lianza (X-Rite) and Yonatan Ben-Dov (University of Haifa). Many IAA staff were involved in the pilot but particularly: Pnina Shor (Head of Project and Head of the Department for the Treatment and Conservation of Artifacts), Clara Amit, Lena Libman, Tamar Rabbi, Iris Yossifon and Arcady Mutar. The authors thank and acknowledge the excellent work of the whole team that has enabled the successful pilot itself and this paper.

The Dead Sea Scrolls

The discovery of the Dead Sea Scrolls some 60 years ago has driven an extensive volume and intensity of scholarly research and investigation. These Scrolls, found in 11 remote caves in the Judean desert overlooking the Dead Sea, are of great importance to the history and development of Judaism and Christianity. The Scrolls are also a rich source for other scientific discovery. The Scrolls were found in very fragmentary condition, with some 900 or more identified Scrolls in many thousands of fragments (possibly 15,000). These fragments range from substantial and recognizable Scrolls, sometimes over a meter long, to small pieces a few centimeters across to some very fine particles a few millimeters in diameter.

Shuka Dorfman, IAA Director General, describes the Israel Antiquities Authority's role and the Scrolls thus: 'Since its establishment, the IAA has promoted and supported an intensive research and publication program... [and] established a conservation laboratory dedicated to the preservation of these outstanding 2000-year-old manuscripts for future generations... Another objective is the presentation of the scrolls to the public, without endangering their preservation... The Scrolls, biblical and sectarian, were written as early as the third century BCE, but most date to the first century BCE and the first century CE. They contain fragments of all the books of the Hebrew Bible (with the exception of the Book of Esther), as well as a complete text of Isaiah. Especially significant are the fragments of the Apocrypha... The sectarian texts reflect the beliefs and apocalyptic expectations of the community that wrote them'. [4]

The Scrolls were written on both parchment and papyrus. The parchment mostly has writing on one side only. The smaller fragments are stored and arranged in an alignment known as Plates. The legibility of the text on fragments ranges from the clear to totally invisible to the naked eye; with many of the fragments so dark in tone that it isn't easily possible to tell there is text at all. It is for this reason that the Scrolls have been the subject of infra-red photography in the past, in an attempt to be able to see the previously hidden text. The only complete photography of the Scrolls was made some 50 years ago and includes infra-red photography of most of the fragments.

Pilot Imaging Process

The imaging pilot took place over two weeks in August 2008 at the IAA. Using borrowed and leased equipment we set up three imaging stations in the imaging studio located just a few meters from the IAA Conservation Laboratory to ease movement of the Scrolls. The room was specially prepared and the set-up to broadly comply with the ISO 3664:2000 standard, "Viewing conditions - Graphic technology and photography".

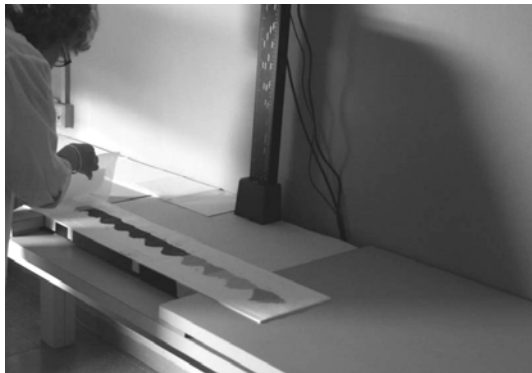


Figure 1: The Imaging Lab uses specially made tables to support the Scrolls during imaging (Job, Plate 638).

The reasons for setting up three stations was partly for conservation reasons and mainly to enable the specialist imaging technologies for each form of imaging to have its optimal setting.

- The visible spectrum imaging utilized a Phase One camera for both the Color and the Infra-Red imaging stations with interesting implications for workflow and image consistency.
- The Munsell Color Division within X-rite provided a unique and bespoke linear Color Checker target. This target consists of a twenty four patches in a row, reduced in size to fit across an approximate 250mm width.
- The Pilot project tested a completely cold light source, namely 940 nm LEDs, to illuminate the texts for IR imaging.
- The major driver for the project is conservation issues. We will use spectral imaging as part of a monitoring program for the scrolls.
- Another motivation for acquiring spectral images is that it has been proposed to borrow some techniques from biomedical skin imaging to measure the water content of the scrolls with an optical method; non invasive, non-contact and one that may work for scrolls or other objects in glass or other transparent mountings.

Images will be captured at 600 dpi or greater. All images will be shot at a fixed height so as to produce a consistent image across the collection. Images are captured in 48-bit RGB color for color and 16-bit grayscale for IR.

One key principle decided in the Pilot was that only one Scroll Plate will be allowed into the imaging process at one time. So each Plate will pass from visible to IR and then possibly to image spectroscopy in one continuous workflow with all handling

done by an IAA conservator and the imaging by an IAA photographer.

Color Imaging

The color imaging used a Phase One Camera medium format back with a Hasselblad camera body. The Pilot worked with the P45 model of camera, but the latest P65+ is now available offering a 60.5 megapixel resolution. The illumination was provided by cold lighting and two systems were tested with DeSisti Broadlights providing the optimal pool of light for color imaging. The camera was operated tethered to a computer. Images of the AF resolution target showed we were almost at diffraction limited imaging with the camera body and macro lens (Hasselblad 120 mm macro).

For the Dead Sea Scrolls Pilot project, the Munsell Color Division within X-Rite provided an experimental linear Color Checker target based upon the classic Macbeth Color Checker target. This target consists of a twenty four patches in a row. The target patches have been reduced in size to fit across an approximate 250mm width. A 200 mm scale is also printed on the target.



Figure 2: X-Rite linear Color Checker target

The size and shape of the color target means that it can be included in every shot without reducing the scale of the object being photographed.

Deciding to use separate Color and IR imaging stations

The imaging technology was considered carefully by the Pilot leaders and the best practice, most preferred equipment from the international community of use was fully assessed. The challenge is to gain a high resolution, color accurate image from the Scrolls in the visible color spectrum. The IR imaging must replicate this to show characters and writing not easily legible in the visible spectrum. They must be closely equivalent images to allow accurate comparison between visible and IR image outputs.

The Phase One was used by both the Color and the IR imaging stations in the Pilot. The Infra-Red imaging capability is achieved by removing the IR blocking filter from the Phase One. Phase One has offered to build a camera back with that filter removed and with the Bayer filter array also removed (actually simply not added during manufacturing). Using the same camera model for both modes of imaging provides benefits for simplifying workflow, standardization of imaging technique, maintenance and skills; plus ensuring a Color and IR image of matching resolution.

It possible to use the same camera for both color and IR by removing the IR blocking filter and then placing it over the lens in order to take a color image. In that case, the IR filter does the same job of blocking IR, but it does so at the beginning of the light train, rather than just in front of the sensor. The IR image is taken with a long pass at ~ 900 nm, 940 nm LED illumination in a completely dark room or a bandpass filter. The appeal of this lies less in cost

reduction but in the notion that the color and IR image are now perfectly registered. However, that is not true and there many significant downsides to this method:

1. Any photographic lens designed for visible color imaging (such as the Hasselblad macro) will have to be refocused at 940 nm. Doing that means automatically the images would have to be registered in post processing anyway, if one required that the color and IR be registered. So, compared to the two cameras, there is no advantage.
2. More importantly, the system is always being refocused, which means that ALL images are slightly different in size. It may be only a few pixels, but a fixed camera and lens means that they are all identical for all the color and separately all the IR.
3. Without autofocus, IR focusing requires homing in on the focus with multiple images and can be time consuming. We were not able to get autofocus to work in the IR, perhaps due to not enough illumination (the auto focusing algorithm most likely requires more image contrast than we could provide with the 940 nm LED lights).
4. One would have to use the same lighting system for both the color and IR – our tests suggest this was most likely not a good idea.
5. One has to either manually slide filters on and off or build an automatic device of some sort. Since one does not want to risk dropping the filters on the scrolls (moving them in and out only adds to the risks and time costs), one now has to make a mechanical device and interface it to the camera software.

In short, the cost saving is minimal and the disadvantages are significant; the project team recommend against this approach.

Infra-Red Imaging

High-resolution IR imaging is required to provide clearly legible text for scholars. It has been known for years that the best images for legibility are provided by IR; the Palestine Archaeological Museum (PAM) photographs were all shot with an IR filter, most likely a Kodak 87C, and IR black and white film. Combined with the spectral performance of the film, this imaging yielded a broad bandpass of ~780-900 nm. At the same time, not much was known about why IR photography worked sometimes and not others. Work in the mid 1990s showed that better results can be obtained with a single relatively narrow spectral bandpass (~10-20 nm) with a wavelength about 940 nm or longer [2-4]. Spectral imaging has provided clues into the mechanism of IR imaging and will be discussed later.

A Phase One P45 digital back was used for the IR imaging. The IR blocking filter was removed and we relied on the fact that the on-chip Bayer color filters used by all color cameras to create color images turn on again in the infrared and transmit all the out to 1000 nm although with reduced throughput.

So, although the signal is reduced, these digital camera backs can be used to obtain IR images. The pilot project tested a completely cold light source, namely 940 nm LEDs, to illuminate the texts. It had a bank of nominally 940 nm LEDs, arranged in a

rectangle. The LED bandwidth is not tightly controlled and it typically is ~30-40 nm. Since this is an extended source, hot spots in the digital image output were a potential problem. An 80° diffractive diffuser was used to spread out the light. At a distance of 18-24", the light was able to illuminate an area of ~ 8x11", the field of view specified by the November 2007 expert committee meeting.

In addition to the 940 nm LED illumination, we tested using both flash and HID lights in the form of the DeSisti lamps as used for all of the color imaging. A Kodak 87C filter over the macro lens provided some spectral filtering so that those images were looking at ~790 nm to 1000 nm, where the silicon detector cuts off. The flash illumination was tested with a modified Canon SLR (IR blocking filter removed and replaced with a long pass) and the built-in camera flash. The same setup was used for imaging with the DeSisti lights.

Both the flash and the DeSisti illumination provided sufficient light for imaging, as shown below for the autoflash. However, it is important to note that the bandpass was quite large due to the 87C filter and that a narrower bandpass filter would most likely require a longer exposure time. It is difficult to estimate how much longer the exposure would need to be without experimentation. One of the conclusions for IR imaging with the Desisti lights is that using them for color imaging means we do have to worry about leakage over to the IR imaging setup.

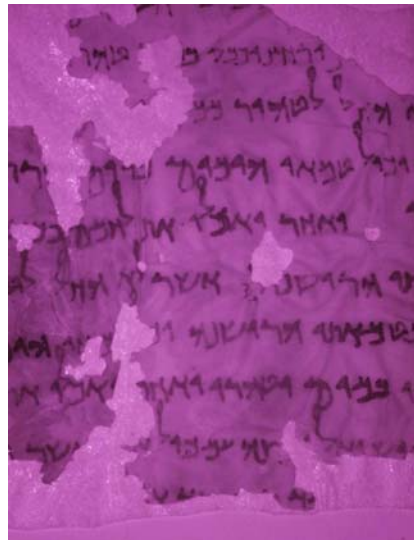


Figure 3: IR image with modified Canon SLR taken with the Canon autoflash . Unmodified image with no post processing to enhance legibility.

For the main digitisation project, we would recommend:

- Purchase a Phase One without the Bayer filters. This will increase sensitivity in the IR and also make it easier to take large format images at other wavelengths with bandpass filters, if desired, for other applications.
- 940 nm LED illumination with two banks on each side and diffusers over LEDs
- Acquire a background white for all the IR images and use it to flatten any illuminating gradients in post processing.

Image Spectroscopy

The major reason for acquiring spectral data is that such data will become the linchpin of a conservation monitoring method. As demonstrated again in the Pilot project, it is the changes in the parchment reflectance that degrade the text legibility and reflect physical changes in the scroll. There have been papers in the conservation literature on using spectral reflectance as a proxy for detecting changes in texts, art or other artifacts [5-8]. In addition, there is a body of work on what is known as the “microfader”, a measuring device that artificially ages a small (~ 100 μm) spot and measures the reflectance spectra of the spot [9-14]. It takes a few hours to expose the spot to the equivalent of decades of museum lighting and measure the spectral changes simultaneously. Spectral data from the microfader is converted into L^*a^*b color space, which can be used to calculate ΔE , which tracks changes visible to the human eye.

As part of the Pilot project, the team acquired spectral images of selected fragments between 650-1000 nm. While there was some previous data [2], we could obtain more data and image further in the infra-red with current technology than was available 12 years ago, when the last spectral data was obtained. For dark and illegible fragments, the ink reflectance spectrum is relatively constant, while that of the parchment typically increases with wavelength. In short, the parchment becomes brighter and the contrast with the black ink is improved. Note that we calculated the Michelson contrast ratio $C = (\text{parchment-ink}) / (\text{parchment+ink})$ (<http://www.stonesc.com/pubs/Contrast Metrics.htm>), and that relatively small visual differences in visible color and single wavelength images in the range of human vision lead to large differences in the contrast ratio. In general, this data tells us that single wavelength IR images provide a larger contrast ratio than do ones taken with an 87C filter, for example, as they do not integrate the lower contrast ratio at lower wavelengths.

The conservation methodology for the Scrolls will be to image fragments on a regular basis and use both colorimetry and spectral data to monitor changes in the parchment reflectance. The goal is to use spectral changes as proxies to detect changes before they are visible to the human eye. The project goal was to obtain some preliminary spectral images, mostly as a guide for image acquisition, since it will require imaging over an extended period to measure a baseline and look for trends.

There is no consensus on the number of bands required for the conservation monitoring methods we plan to implement. Photo induced artificial aging with a microfader is measured by looking at changes in reflectance spectra, sampling typically ~ 1 nm spacing across the visible. However, microfader data is usually converted into a CIE color space such as L^*a^*b , and calculating Delta E (ΔE). Depending somewhat on the definition (see http://www.colorwiki.com/wiki/Delta_E:_The_Color_Difference), a $\Delta E = 1$ is the minimum change detectable by the human eye. Since we plan to convert the data into a color space anyway, that suggests using an XYZ tri-stimulus camera to image the scroll directly in L^*a^*b color space. With this approach we would get, in effect, imaging microfader style data. Since the scrolls are very heterogeneous, point spectroscopy is not sufficient to track all the possible changes. Since we know that changes in reflectance for

the scrolls continue out as far as 1000 nm, we need to be sure to cover that region spectrally with some other method.

Another motivation for acquiring spectral images is that it has been proposed to borrow some techniques from biomedical skin imaging to measure the water content of the scrolls with an optical method; non invasive, non-contact and one that may work for scrolls or other objects in glass or other transparent mountings. One of the team members, Dr. Bearman, has collaborated with a group at the University of California-Irvine on combining a technology developed there with spectral imaging that is being applied to human skin for clinical applications. We did some preliminary experiments on modern parchment that show water content; this data is unpublished. This work will be a later part of the project.

The Pilot Project used a commercially available spectral imaging system primarily sold for applications in biology and microscopy (<http://cri-inc.com/products/nuance-ex.asp>). The particular system in the Pilot covered from 650 nm-1100 nm with a nominal bandwidth of 10 nm. A common problem with spectral imaging is the chromatic shifts in focus as the wavelength range is spanned. Over the visible part of the spectrum, any well designed C-Mount or photographic lens will work well; above ~720 nm, though, lenses begin to show significant defocus with wavelength as they are not designed to work at those wavelengths. We used a recently introduced hyperspectral lens from Coastal Optical optimized for performance over the visible and near IR (http://www.coastalopt.com/index.php?option=com_docman&task=cat_view&Itemid=&gid=24&orderby=dmdate_published&ascdesc=DESC). This lens required no refocusing, often done during spectral imaging in the near infrared. Not only is this time consuming, it also requires significant post processing of the images to re-register and morph the images into the same size. Images of the AF resolution target showed 1-2 pixels of defocus which could be cleaned up with a point-spread function deconvolution method, such a Lucy-Richardson deconvolution.

The conservation goal would be reliable and repeatable measurements of an absolutely calibration image cube. As with the IR imaging, illumination is a critical issue. There are two major approaches to spectral imaging; filter on the detection side or filter the illumination. Practically speaking, this means either broadband illumination (at least over the right spectral range) and filtered imaging or narrow band illumination via some method and imaging with a standard unfiltered monochrome camera. For the pilot project, we chose to filter on the detection side, as we were able to borrow a commercial spectral imager. We have recommended obtaining the spectral data required with two systems, a XYZ camera and an LED illumination system that covers the visible and NIR with about 13-14 bands. XYZ cameras can go up to 3 K x 2 K images.

Measurement of Water Content

Water has an absorption band overtone at ~ 980 nm that can be used to measure water content; this has been applied to human skin imaging. We propose to use the same method to measure water content in the Dead Sea Scrolls. In addition, the measurement technique provides information on photon scattering, which in turn

may also mirror physical changes in the parchment. Some preliminary experiments at the University of California-Irvine suggest that this is a feasible extension of the human clinical imaging. The approach still needs to be demonstrated on controlled parchment samples and calibrated. Prof. Bruce J. Tromberg, director of the Beckman Laser Institute at UCI, and Greg Bearman have worked on combining the spatial modulation technology from UCI with spectral imaging methods from JPL. This work is as yet unpublished. Implementation of this measurement would come later in the Digitizing the Dead Sea Scrolls project and is experimental.

Conclusions and applications to other projects

The pilot demonstrated that the imaging of the Dead Sea Scrolls can be achieved safely and would have significant conservation benefits for the IAA. Text was revealed in IR imaging not previously recorded by scholars. This demonstrates that the IR digital imaging and image spectroscopy hold new possibilities for scholarly discovery not possible with the previous IR analog photography. The pilot successfully showed that very high resolution color and IR imaging can be done in tandem to produce comparable results that enable further analysis by scholars.

The IAA would need to consider a 3-year project for the complete imaging of the Scrolls. The imaging is a tractable project, whilst the repository and delivery options for the Scrolls are varied and complex to conceive and implement in an open and inclusive fashion.

The X-Rite provided experimental linear Color Checker target based upon the classic Macbeth Color Checker target proved to be a real success in delivering accurate color management with a minimal footprint in the image output. As this target is developed it could become a standard tool for manuscript imaging because of the sophistication and small footprint

The image spectroscopy technologies proposed here could provide a strong exemplar to other projects for conservation monitoring. The further experimentation proposed to monitor water content could become an important non-invasive testing mechanism for other manuscript collections to enable them to proactively measure and then acclimatize according to the water content of their parchment objects.

References

- [1] D.T. Ariel, H. Katz, S. Sadeh and M. Segal (eds) *The Dead Sea Scrolls*, Forward by S. Dorfman, Israel Antiquities Authority, Jerusalem, 2008.
- [2] G. Bearman, Stephan Pfann and Sheila Spiro, Ed., *Imaging the Dead Sea Scrolls*, vol. Vol. 1 (1998), vol. Vol. 1, pp. 472-495.
- [3] G. Bearman, Zuckerman, Ken, Zuckerman, Bruce and Joseph Chiu, in *Society of Biblical Literature* (Washington DC, 1993).
- [4] G. a. S. S. Bearman, *Biblical Archeologist* 59, 56 (1996).
- [5] S. Baronti, A. Casini, F. Lotti, Simone Porciniai, *Chemometrics and Intelligent laboratory Systems* 39, 103 (1997).

- [6] E. Marengo, M. C. Liparota, E. Robotti, M. Bobba, *Vibrational Spectroscopy* 40, 225 (2006).
- [7] E. Marengo, M. C. Liparota, E. Robotti, M. Bobba, M. C. Gennaro, *Analytical and Bioanalytical Chemistry* 381, 884 (2005).
- [8] E. Marengo, E. Robotti, M. C. Liparota, M. C. Gennaro, *Analytical Chemistry* 75, 5567 (2003).
- [9] L. Andrew, H. T. Joyce, L. Haida, H. Stephen, T. Jacob, 2007.
- [10] A. Lerwill, Joyce H. Townsends, Haida Liangb, Stephen Hackneya, *Jacob Thomasa SPIE* 4402, 66181G (2007).
- [11] H. a. w. Morris, Paul, *Journal of the American Institute for Conservation* 46, 215 (2008).
- [12] P. Whitmore, Catherine Bailie and Sandra Connors, Ed., *Microfading Test to Predict the Result of Exhibition: progress and Prospects*, (International Institute for Conservation, 2001), pp. 200-205.
- [13] P. Whitmore, *PNAS Sackler NAS colloquiem*, (2005).
- [14] P. Whitmore, X. Pan and C. Bailie, *Journal of American Insitute for Conservation* 38, 395 (1999).

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Tanner is an independent member of the UK Legal Deposit Advisory Panel and Chair of its Web Archiving sub-committee, he is also a member of the UK JISC's Digitisation Advisory Group. Tanner authored the book, *Digital Futures: Strategies for the Information Age*, and edited the book, *Digital Preservation*, both with Prof Marilyn Deegan.

Greg Bearman is a physicist formerly with NASA'S Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. An optical physicist, Bearman has worked on imaging and spectroscopy of archeological artifacts and ancient texts over the last 15 years and is a consultant to the IAA on imaging. He was among the first to apply modern digital imaging and spectroscopy to archeology. Aside from working in archeology, he has published widely on applications of spectral imaging to biology and medicine.