

Searching for Changes: The Use of High-Resolution Multispectral Imaging for the Very-Long-Term Monitoring of the 2,000-Year-Old Dead Sea Scrolls

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Abstract

In 1991, with the establishment of the Israel Antiquities Authority, a unique laboratory was formed, dedicated to the long-term monitoring and preservation of the Dead Sea Scrolls. A unique multi-spectral imaging system and protocol was implemented, using a carefully chosen set of wavelengths and exposures, in order to image and monitor the documents. The wavelengths chosen spanned the near infrared and visible spectra, avoiding the ultraviolet ranges, in order to avoid exposing the fragments to damaging light: 445 nm, 475 nm, 499 nm, 540 nm, 595 nm, 638 nm, 656 nm, 706 nm, 728 nm, 772 nm, 858 nm and 924 nm. The exposures used a set, never-changing positioning of camera, lens, lighting units and table on which the objects were placed. The Dead Sea Scrolls imaging project is the first museum collection in the world to be monitored for long-term changes, and the first collection in the world to be imaged and monitored using multispectral imaging.

The Discovery and History of the Dead Sea Scrolls

Between the years 1947 and 1956, one of the greatest archaeological discoveries ever made came about by chance. The process began with the discovery of seven relatively well-preserved scrolls stored in pottery jars and wrapped in linen cloth in a naturally formed cave near the ancient site of Qumran in the northern Dead Sea Region. With an elevation of 440 meters (1,443 feet) below sea level, the Dead Sea is the lowest place on Earth.

The Dead Sea Scrolls include texts previously known from the Hebrew Bible, such as two copies of the Book of Isaiah, as well as additional literary texts, clearly belonging to the Jewish Second Temple Period literature, albeit representing a different outlook and ideology known to us from other historical and textual sources. These texts, initially associated to a group known as the Essenes and later more broadly defined as sectarian, included important texts, such as the Community Rule (describing the ideology, customs and behavior of the sect that composed it) and the War Scroll (describing the final battle between the sons of light and the sons of darkness). The discovery of these texts, written on parchment with carbon-based ink and opening new windows into the study of ancient Judaism and Early Christianity, led to the belief that if seven could be found, there were more to be discovered.

At the Qumran site, this culminated with the discovery of a total of eleven caves that yielded some 930 scrolls, written primarily on leather and some on papyrus in Hebrew, Aramaic and Greek, which included the earliest copies of the Biblical text with the rep-



Figure 1. A composite of four photographs showing Ken Boydston at the new Israel Museum facility in Jerusalem that was established in 2011 to image and monitor the Dead Sea Scrolls. The photographs show four of the twelve narrow-band wavelengths of the LED illumination employed with the multispectral imaging system. (Photographs and digital composite by Shai Halevei)

resentation of all but one of the books of the Hebrew Bible, as well as extensive literature kept by communities some 2,000 years ago.

The scrolls revealed copies of extra-biblical books (such as Enoch), known to us from somewhat later monastic libraries, as well as a large group of texts broadly defined as sectarian and specifically focusing on the beliefs and practices of a group of Jews, living in Second Temple times, which detached itself from mainstream Judaism and established its home at the site of Qumran, storing these scrolls in the caves surrounding the site.

Although no further scrolls or documents have been found at the Qumran site, many more documents and scrolls continued to be discovered in the Judean desert, spanning from the seventh century BCE through to the twelfth century BCE, exposing us to knowledge of diverse communities that settled in the desert, with documents written in ancient Paleo-Hebrew, Greek, Latin, Nabatean, Latin and of course square Hebrew script used to write both Hebrew and Aramaic. These documents continue to be found, with a growing collection of manuscripts under the care of the Israel Antiquities Authority, the governing body in Israel charged with the preservation of archaeological materials and, in particular, the scrolls.

The scrolls, written on leather and papyrus, were preserved as a result of the dry desert climate, which allowed the organic materials to survive. Yet, as opposed to the initial seven scrolls, most of the other scrolls were not found in ceramic jars and wrapped in linen, which provided additional protection for the Cave 1 scrolls over the 2000 years between their deposit and discovery. In fact, most of the scrolls were found scattered in the caves, completely exposed to the forces of nature, which led to extensive damage to these precious documents.

Despite surviving in the dry desert climate, the documents were extensively torn apart during this same window of time. The scrolls had broken apart into thousands of fragments, leading to a situation where scholars continue to work on piecing together this incredibly challenging puzzle. While this was initially done through manual study, more and more of this work has shifted to the digital worktable.

Establishment of the Israel Antiquities Authority

In 1991, with the establishment of the Israel Antiquities Authority, a unique laboratory was formed, dedicated to the preservation of these documents. Beyond the fragmentary nature of the collection of scrolls and documents, it became clear the fragments had undergone significant damage in the post-depositional and post-discovery processes that the Dead Sea Scrolls were subjected to. This created a situation where each fragment was examined macroscopically and characterized according to the conservation issues that it was suffering from. These issues included gelatinization caused by exposure to moisture, causing the leather to darken, delamination of the layers of the leather, cracking caused by the dryness of the material, flaking of the ink, ink corrosion resulting from the interaction of the leather or papyrus with the chemical composition of the ink and more. For some 15 years, the fragments underwent conservation processes which helped preserve the Dead Sea Scrolls, yet with no actual objective baseline for knowing whether or not the conservation procedures were helping or hurting the scrolls.

In order to create such a baseline, a unique multi-spectral imaging system and protocol was implemented, using a carefully chosen set of wavelengths and exposures in order to document the fragments. The wavelengths chosen spanned the near infrared and visible

spectra, avoiding the ultraviolet ranges, in order to avoid exposing the fragments to damaging light: 445 nm, 475 nm, 499 nm, 540 nm, 595 nm, 638 nm, 656 nm, 706 nm, 728 nm, 772 nm, 858 nm and 924 nm. The exposures used a set, never-changing positioning of camera, lens, lighting units and table on which the object was placed.

With Individual Multispectral Captures of 3.7 GB, Total Data for the Collection Now Exceeds 300 TB

All in all, 28 images are collected in each “click” of the camera, which are then unified to form a single true-color image of the fragment. Each fragment is documented on both sides, creating a situation where, for each fragment, 58 images are created. These images can be translated into objective mathematical values that reveal the chemical composition and state of the object. To date, the lion’s share of the collection has been documented at least once, with each fragment yielding 3.7 GB of data, and reaching over 300 TB of data for the entire collection. These data represent the baseline for which we can now continue the documentation, and using the same parameters determined at the onset of the project, monitor the state of preservation. This is done in numerous ways.

Control groups were determined at the onset of the project. These control groups were chosen as they exhibit damage patterns typical of the entire collection and are stored in the same conditions as the entire collection. The control groups are photographed periodically, under the same multispectral imaging system (MSI). In this manner, over the 15 years since the establishment of the MSI system, we have collected data representing every six months of storage of these fragments, which can be used to decisively determine whether any changes occurred to the state of the fragment and when exactly that change occurred. In this sense, we can cross-check this with any changes to the state of the general collection and follow whether a specific instance occurred (e.g., a change in the temperature and humidity patterns) which contributed to the damage or the improved conservation of the scrolls.

In addition to the imaging of the control groups, fragments are documented using the MSI system before and after an expected change is to occur. Such changes can be prior to and following a conservation procedure intended to improve the physical state of the fragment. In this sense, the comparison of the imagery can assist the conservator in determining whether the treatment was successful or not. This can then be used to reflect on the specific fragment as well as the procedure on a whole and its effectiveness in treating damage to the scrolls. Scrolls are also documented prior and subsequent to their exhibition.

Display Protocols for the Dead Sea Scrolls

Despite the many challenges in exhibiting the DSS, the IAA has adopted a policy of exhibiting scrolls to the public, as they are culturally important documents that should be shared with the general public. As such, the IAA has adopted a strict exhibition protocol, in terms of temperature ($20^{\circ} + 2^{\circ} \text{C}$), humidity (46–48% RH), light intensity (25 LUX) and extent of light exposure (15000 LUX hours). In order to examine whether the exhibition of scrolls is damaging under these conditions, each scroll is documented using the MSI system before and after its exhibition. Once again, by comparing the images, it can be determined whether the scroll was damaged during exhibition and whether the exhibition practices should be changed or ceased completely.

Where has all of this led us? To date, an enormous amount of data has been collected, which can greatly assist in monitoring the scrolls. Yet in order to actually monitor the state of preservation over long periods of time, this data must be compared with the original time-zero measurements. This can prove to be challenging when considering the scope of the data, which as noted above exceeds 300 TB of images that are translated into mathematical values.

The ever-expanding world of computer programming, including the implementation of AI-generated tools, is the next step in creating ways in which the data collected can be used to advance our knowledge. This is already occurring in Dead Sea Scroll research, where algorithms and artificial intelligence are using the data collected in the multispectral imaging system to try and group the fragments, reconstruct the missing pieces of the scrolls that have been lost forever, date the time of composition and even identify the different scribes using handwriting analysis. Yet our most important mission is the very long-term preservation of the scrolls, which was the starting point for establishing the multispectral imaging unit and protocols.

The Next Preservation Challenges

Therefore, our next challenge must be to use the data collected – and expand on it – according to the needs of the preservation of the collection. By implementing analytical tools that can analyze big data, we can hope to advance our conservation practices. Through such analysis, a protocol can be developed for which conservation tools are more successful.

We can create a grading system in order to help conservators determine which fragments are in most danger and need to be treated immediately, and which fragments can be left alone in storage.

Such analysis can also help determine whether a scroll should or should not be exhibited. And perhaps even use this data in order to find ways of foreseeing the future and determining which fragments may develop preservation problems, and to pretreat them to preempt any risk to the scrolls.

What is the path forward for imaging-based conservation, and what lessons can be drawn from large-scale efforts such as the Dead Sea Scrolls project?

A primary observation is that acquiring high-resolution, high-spectral-quality datasets across large collections is extremely demanding in terms of time, cost, and labor. As a result, this approach is realistically limited to flagship objects and major institutions. This raises a critical question: how can similar capabilities be extended to smaller collections?

Recent advances in imaging technologies and artificial intelligence suggest a clear direction. The combination of accessible imaging modalities with machine learning is likely to form the foundation of future conservation strategies, independent of the specific imaging technique employed. Since earlier projects such as the scroll initiative, both hardware and software capabilities have advanced significantly. Imaging systems now span a wide range—from a few spectral bands to full hyperspectral datasets—while 3D capture technologies, including structure-from-motion and modern scanning systems, enable high-quality geometric and morphological monitoring. These developments are largely driven by parallel advances in robotics and computer vision.

When combined, these multimodal datasets and AI-based tools significantly lower the barrier to monitoring change overtime. Conservators no longer need extensive coding expertise, specialized in-

frastructure, or access to high-cost systems. Instead, user-friendly tools are increasingly becoming available and are expected to proliferate, further reducing technical and financial barriers.

A persistent limitation, however, is the lack of high-quality historical datasets, which constrains retrospective analysis.

While reducing the cost and complexity of modern imaging enables institutions to establish a new baseline for conservation monitoring starting NOW, it does not fully address gaps in past data. One promising approach to bridging the gap between cost and performance is the use of multispectral imaging with a small number of additional bands beyond RGB. Studies have shown that adding as few as 1–5 extra spectral bands can significantly improve color accuracy, reducing ΔE_{76} error by up to a factor of four compared to RGB imaging alone.

This reduction in error lowers the noise floor for detecting change and mitigates the effects of metamerism, which can otherwise obscure meaningful differences in standard RGB imaging. These improvements are sufficient to enable reliable detection of changes relevant to conservation. Importantly, such enhancements can be implemented using relatively simple and accessible technologies, including LED-based illumination, optical filters to eliminate harmful LED excitation emission spikes in the short-wavelength blue region, and compact multispectral sensors integrated into mobile devices (e.g., systems developed by Spectricity and imec). This creates a practical pathway for broader adoption across institutions of varying sizes.

Required Levels of Color Accuracy (ΔE_{76})

The required level of color accuracy (ΔE_{76}) depends on both the expected rate of change in an object and the time interval between measurements. Longer intervals allow for larger detectable changes and thus lower accuracy requirements, while rapidly changing phenomena – such as biological growth – demand more frequent monitoring. Published studies reporting typical changes in CIE $L^*a^*b^*$ values across different materials (e.g., paintings, stone, and built heritage) can inform the design of monitoring strategies, including sensor selection and measurement frequency.

Even modest increases in spectral resolution improve measurement precision and facilitate calibration against reference targets, enabling consistent comparison with future datasets. In this way, practical multispectral approaches can support scalable, standardized, and forward-looking conservation monitoring programs.

Very Long-Term Preservation of Calibration Targets

The very long-term preservation of calibration targets used with a multispectral imaging system and the time-zero capture data associated with them is also essential. Specially designed calibration targets can be printed with pigment inkjet inks on inkjet papers. The “reach-in” glass door freezers found in grocery stores throughout the world are well-suited for this. The relatively inexpensive units can maintain a temperature of -18°C to -23°C (0°F to -10°F) and a relative humidity of 20–30% (or lower).

The freezer units must be equipped with high/low temperature and relative humidity sensors that will automatically shut off power if the limits are exceeded. Packages containing calibration targets and documentation should be placed in polyethylene bags to act as a buffer during defrost cycles. Under these conditions, the calibration targets and human-readable printed spectral documentation can be preserved for 10,000 years or longer with negligible changes.

Multiple sets of multispectral imaging calibration targets and printed (human-readable) documentation should be prepared and preserved in the freezers in dispersed and secure geographical locations to insure their survival in perpetuity.

The “Leon Levy Dead Sea Scrolls Digital Library,” Created by the Israel Antiquities Authority and the Arcadia Fund, with Assistance from Google

The “Leon Levy Dead Sea Scrolls Digital Library,” makes thousands of Scroll fragments accessible for free for everyone worldwide to read them in both Hebrew and English:

https://www.deadseascrolls.org.il/?locale=en_US

The Arcadia Fund, based in the UK and founded in 2001 by cultural heritage scholars Lisbet Rausing and Peter Baldwin, provided critical early financial support for the Dead Sea Scrolls multispectral imaging, digitization, and monitoring initiative, including funding the acquisition of the MegaVision multispectral imaging system, and Google built the digital image interface, translation into English and other language capabilities, and provides the worldwide internet free distribution of the library. The website offers five languages: English, Hebrew, Arabic, German, and Russian. Translations of the scrolls and scroll fragments are provided in Hebrew and English, with Aramaic and Greek text sources referenced).

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15 years old and obsolete in terms of CCD technology. It was disassembled in 2001 during the renovation of the Archives building. In principle we could have used the system to monitor photographs, but it would have been very challenging. The optical system was a unique design for the old Charters encasements. For example, when we switched filters we had to go through a laborious optical alignment procedure. In addition to the time required, this raised questions about the consistency of other variables which could limit the ability to detect small changes in photographs.” As of March 2026, the documents were not monitored for further fading, yellowing, cracking, ink flaking, or movement of fragments of the original inks. July 4, 2026 is the 250th anniversary of the Declaration of Independence. [12] David E. Sanger, “Once the Centerpiece of Celebration, a Faded Declaration Recedes – Sunlight and abuse have taken a toll on the document, encased in bulletproof glass,” *The New York Times*, July 3, 2026.

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Author’s Biographies

Dr. Joseph Uziel is a senior archaeologist at the Israel Antiquities Authority. Joe joined the IAA in 2011, where he is one of the leading archaeologists on Jerusalem, advancing scientific methods in the field-work of Jerusalem. Joseph served as the head of the Dead Sea Scrolls Unit for six years, overseeing the conservation, documentation, research and dissemination of knowledge on the Dead Sea Scrolls, during a time when digital tools influenced every aspect of their work.

Dr. Gregory Bearman is an optical physicist who developed spectral imaging technologies at the Jet Propulsion Laboratory in La Cañada Flintridge, California, near Pasadena (JPL is funded by NASA and is managed by the California Institute of Technology). Greg retired from JPL in 2007 and is currently head of ANE Image, Inc. in Pasadena. He was the first to apply modern digital and spectral technologies to ancient texts. He has been the imaging lead for the Leon Levy Dead Sea Scrolls Library since 2008, and he has focused on developing a calibrated spectral system along with software to monitor change over time. He has published in other areas of conservation, including monitoring of morphological change over time.

Shai Halevi received a B.A. in History and also an M.A. in Cultural Studies. He is a Musrara Art and Photography graduate and works as an archaeology and art photographer. He previously worked at the Bezalel Academy as its in-house photographer. Since 2010, Shai has been leading the Dead Sea Scrolls multispectral imaging project. As the Israel Antiquities Authority Documentation Manager for Jerusalem and Judea, he has developed advanced cartography methods. His techniques are derived from recent epigraphy research on identifying hidden elements. Additionally, he has photographed artworks and exhibitions for various museums and artists worldwide.

Ken Boydston is the chief engineer and color scientist at MegaVision, Inc., based in Ventura, California. Boydston led the development of the high-resolution MegaVision Multispectral Imaging and Analysis System, which was introduced in 2007. The system has been used to image and monitor with very large colorimetric data sets, and to conduct forensic analysis of the Dead Sea Scrolls in Israel, along with many other national and world cultural heritage treasures.

Henry Wilhelm is the director of research and publications at Wilhelm Imaging Research, Inc. in Grinnell, Iowa, USA. Wilhelm has authored or co-authored more than 35 technical papers that were presented at conferences sponsored by the Society for Imaging Science and Technology (IS&T), the Imaging Society of Japan (ISJ), the American Institute for Conservation (AIC), and the Florence, Italy Colour Photography and Film Preservation Conferences in the United States, Canada, Europe, Japan, and Asia.

In 1981, Wilhelm was the recipient of a Guggenheim Fellowship for what evolved into more than ten years of research on color print

fading under low-level incandescent tungsten illumination that simulated museum display conditions, utilizing glass filters, UV filters, and direct exposure.

With contributing author Carol Brower, he is the author of the 1993 book “The Permanence and Care of Color Photographs: Traditional and Digital Color Prints, Color Negatives, Slides, and Motion Pictures.” The complete 761-page book is available in PDF/A form at no cost from <www.wilhelm-research.com>. Since the book was posted online in 2003, more than one-half million copies have been downloaded worldwide.

In 2011, Henry received an honorary Doctor of Science degree from Grinnell College: “As a citizen of the town of Grinnell, and of the world, and for helping preserve society’s most important photographs as well as our own, Grinnell College is proud to recognize you today.”