Beyond the Visible
Infrared Imaging for Museums

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This paper presents results of new approaches to imaging, specifically utilizing techniques developed by NASA for spacecraft missions to other solar system bodies. Results from a month long field project in Jerusalem in June-July 1994 demonstrate the usefulness of the new techniques on inscribed soft media and ostraca. The imaging approach is effective and useful on frescoes, mosaics, ink inscriptions on plaster, colored textiles and illuminated manuscripts. Most of the examples will be drawn from text material, as these are the objects we have had the most access to for this study, although we have examples from some of the other areas as well.

The techniques presented here are not generally suitable for imaging for cataloguing or archival purposes. They are meant for objects that are difficult to interpret or reassemble or conserve.

The Problem of Reading Ancient Documents

One of the major barriers inhibiting research into the historical, religious and cultural background of the Bible is the inability to retrieve data from ancient documents of the period. This is especially true of documents written on soft, perishable materials such as untreated animal skin, leather, vellum and papyrus. Such documents are particularly prone to deteriorate with a consequent degradation of data — more so than those written on hard media, such as clay tablets, stone and pottery sherds. Note, for example, the case of the most famous soft media texts of the Second Temple period, the Dead Sea Scrolls. Not only are such documents typically fragmentary, but the carbon-black inks in which they are written are often faded beyond recognition or indistinguishable from blackened or dark brown, aged writing surfaces. Thus a significant portion of the Dead Sea material is unreadable in visible light.

Imaging Spectrometry

Imaging spectrometry is a technique for image acquisition and analysis that relies upon the unique spectral signature of each target pixel (in the case of ancient scrolls, e.g., the ink versus the writing surface). When the respective spectral signatures of various parts of a given target vary, imaging spectrometry can be used to enhance this difference by means of computer imaging and analysis techniques. Even reflective differences as small as 1% can be successfully exploited to increase grayscale differentiation and, hence, legibility.

Imaging spectrometry is an accepted tool in such fields as geology, atmospheric studies, marine ecology and pollution control, and JPL has long been a leader in applying this technology. Imaging and analysis technologies have developed steadily over the last 20 years, and this is a mature technology with a considerable data base. Most research to date has been conducted by remote sensing aircraft or orbiting spacecraft. The LANDSAT Thematic Mapper, probably the most familiar to the public, registers images in six broad spectral channels in the visible and near infra red. The most advanced imaging spectrometer, Airborne Visible and Infra Red Imaging Spectrometer (AVIRIS), was designed and built by JPL, which continues to operate it along with a data analysis facility employing the most advanced image processing techniques.

How imaging spectrometry works

An imaging spectrometer acquires images of the same scene simultaneously in many contiguous spectral bands over a given spectral range (one might think of this as equivalent to a contiguous set of multi-color images). By adding wavelength to the image as a third dimension, the spectrum of any pixel in the scene can be calculated. Thus, imaging spectrometry allows the investigator to isolate any part of the target based upon its reflectance spectral signature. Once properly calibrated, these images can be used to obtain the reflectance spectrum for each image pixel, which can then be used to identify components in the target. For the geologist, imaging spectrometry yields compositional maps of geologic sites, showing *which* minerals are *where* [Kruse, 1990, Hook and Rast, 1990]. For the ecologist studying the rain forest, imaging spectrometry helps understand the large scale composition of the forest canopy [Johnson et. al., 1992]. For the biologist, imaging spectrometry yields functional maps, showing *which* biological molecules are *where* within a structure. For the text scholar, imaging spectrometry locates those image pixels that have ink, i.e., text, no matter how faint [Bearman et. al., 1993]. That powerful combination of imaging and spectroscopy, easily visualized with software, is what makes imaging spectrometry so useful.

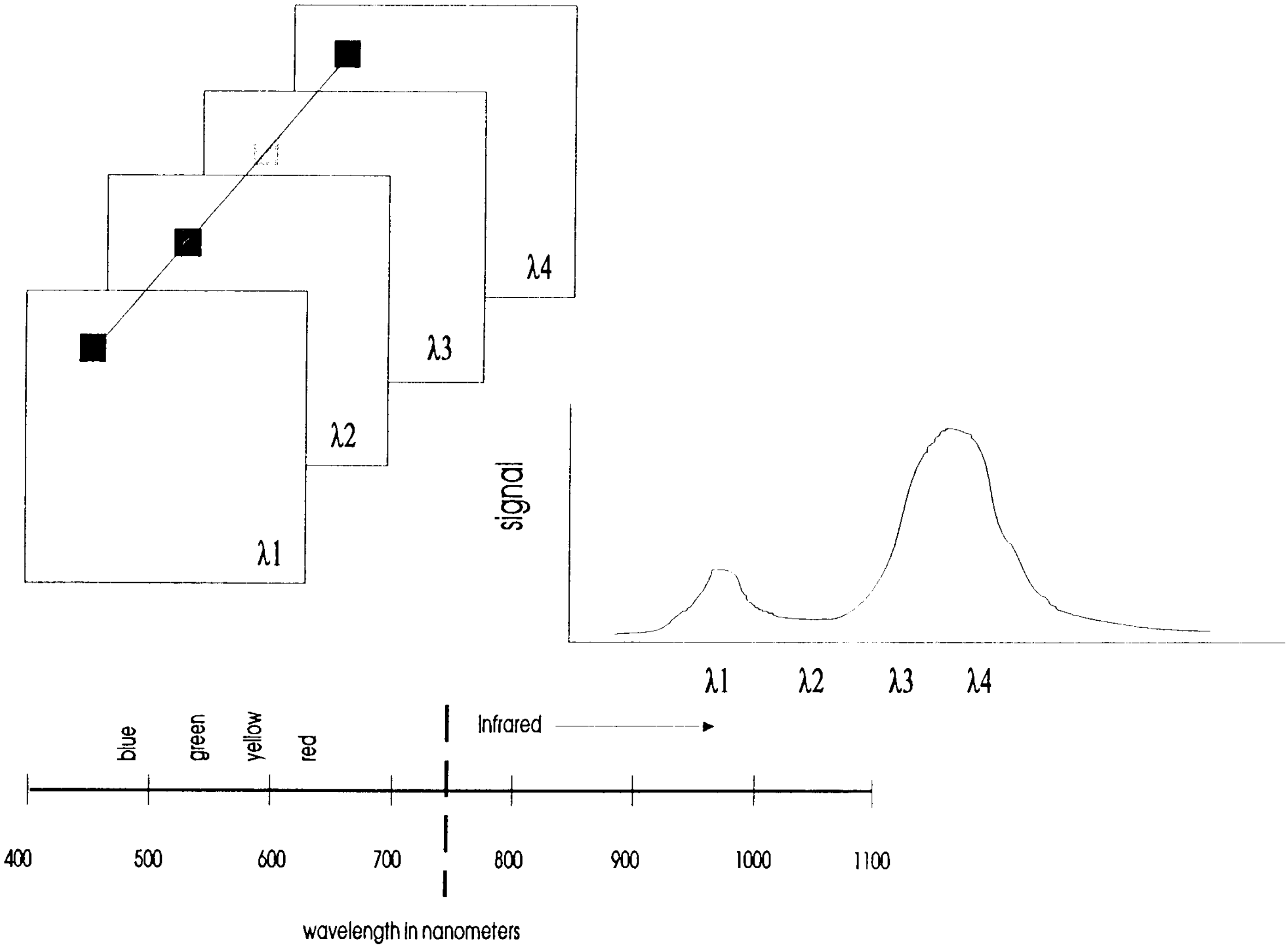

Figure 1 illustrates the approach to image acquisition and analysis, showing four image slices of the same scene, each at a different wavelength. (An actual instrument may take 100 such images over the visible to near IR, ~400 to ~1000 nm, or ~0.4 - 1.0 _m, the spectral range spanned in this work). The visible part of the spectrum is ~0.4-0.75 _m, while the region out to 1 _m is the infrared.

The images are then stacked in a computer, from the lowest wavelength to the highest, to create an "image cube." The spectrum of a selected pixel is obtained by skewering it in its third dimension, wavelength, as the inset in Figure 1 shows. Spectral analysis can then be performed in any of several ways. One is to identify the measured spectrum by comparing it with a library of known laboratory spectra. A variation is to conduct principal component analysis, i.e., model spectra from a variety of possible target components to obtain a spectrum that matches the one measured. In either case, spectral tagging is then applied: All pixels with one specific spectrum are located and visualized in a false color image.

The key to successful use of imaging spectrometry is to image in selected, narrow wavelength bands. Broad band imagery loses spectral selectivity as small spectral differences become mixed with those of neighboring wavelength and spectral features become lost in the background. This may be compared to trying to find a blue-green jellybean among a million blue ones. By taking two images, one in the blue and one in the blue-green, and subtracting the blue image from the blue-green one, one is left with an image showing only the blue-green jellybean. One needs *both* images; since blue-green contains some blue, the blue-green jelly bean would not stand out in a blue image. Continuing the analogy, a color photograph (broad-band imaging) would not be helpful.

The Imaging Spectrometer

An imaging spectrometer consists of a device for spectral selection, imaging optics, a sensor and a data acquisition system. The major criterion for this project was to utilize only technologies that could be reduced to a compact, simple, table-top instrument suitable for field campaigns or institutions such as museums. Figure 2 shows how the technology was implemented, and the components of the system are described below. Liquid crystal tunable filters (LCTF) were used for wavelength selection; standard photographic lenses for optics; and an astronomical slow-scan cooled silicon CCD camera with Macintosh based data system for image acquisition and storage.

A liquid crystal tunable filter (LCTF) is an electronic variable bandpass filter that is inserted into the optical path of the imaging system and provides spectral selection for each image slice of the image cube. Relatively new technology, an LCTF can be set to any wavelength over its tuning range (typically 300-400 nm) with commands from a computer. It is the LCTF that enabled the design and assembly of a portable imaging spectrometer.

Preliminary imaging with a video camera and frame grabber (an analog system) suggested that an all digital system would yield much better results. Video analog signals are noisy and yield only ~5- 6 bits after digitization with a frame grabber, resulting in a grayscale range of only 32-64. In addition to reducing contrast, this limits the processing that can be done after images are acquired. This can be solved by using a CCD camera that digitizes the data stream with a 12 or 16 bit digitizer immediately behind the signal electronics. This not only reduces noise but also increases the dynamic range and gray scale of the image to 4096 (12 bit) or 65,535 (16 bit). Further, a digital camera is not limited to the typical frame grabber video screen size of 540 x 480 pixels, allowing use of much larger image formats for better spatial resolution. A thermo-electrically cooled 16 bit digital camera with a mechanical shutter was used for the work reported here.

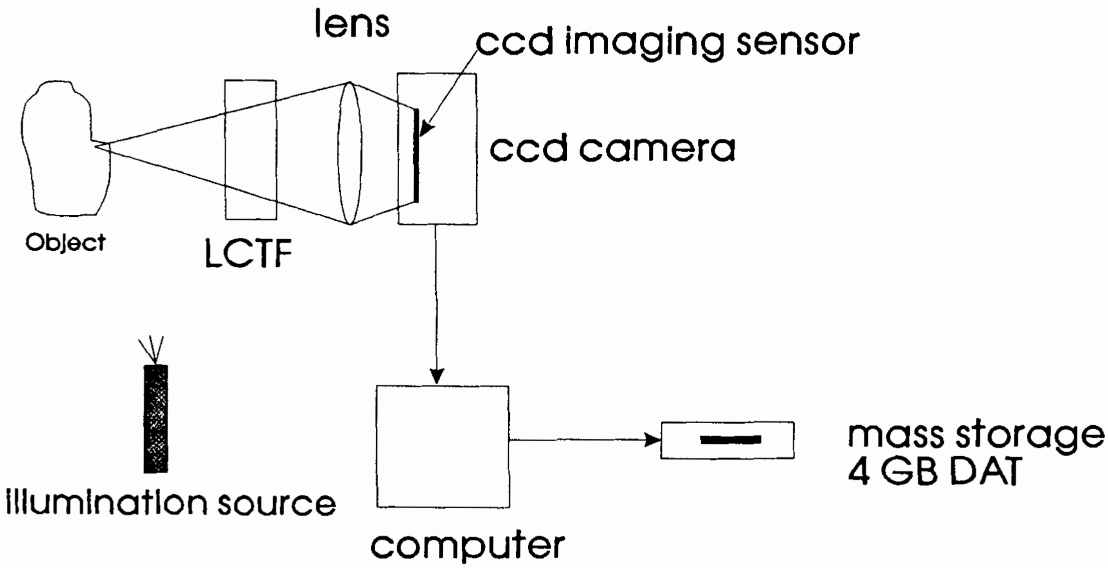

Figure 2. A schematic diagram of the portable imaging spectrometer.

Analysis of the image data shows that a 12 or 14 bit camera would also yield equivalent images. At the time when the system was designed, the camera choice was either 8 bit or 16 bits, with nothing in-between. There is no disadvantage to a 16 bit camera, except cost. Aside from the dynamic range, another reason to select one of the 12-14 bit cameras now available is to retain image shading. A coarser digitizing grid will lump together pixels that should actually be separate, reducing spatial details.

A Macintosh 840 operated a computerized data acquisition system. We wrote custom software for controlling and camera and LCTF with LABVIEW, a software product developed for generic instrument control. The user utilized a graphical control panel to take either single, fixed wavelength images or to set up and acquire image cubes. Preparation is required prior to acquisition of an image cube, in order to insure that acquired data is properly calibrated and suitable for analysis.

Illumination was provided by a standard photoflood lamp, which has a color temperature ~3000 K, so the peak of the spectral output is ~1 _m. Since the spectral output is that of a blackbody, the intensity continuously decreases into the shorter, or visible part of the spectrum, but there is more than adequate light for imaging. Note that special "infrared" lamps are not necessary and, in fact, are useless in this context. Infrared lamps, designed to provide IR radiation in the ~8-14 _m region, generate almost no radiation in the region covered by the imaging spectrometer.

Additional images are required prior to acquisition of an image cube, in order to insure that the data is properly calibrated and suitable for analysis.

It is critical to know both illumination intensity as a function of wavelength and spatial variation of illumination intensity across the target. For example, the spectrum of the illumination source used for this work peaks at ~1 _m and continually falls in intensity towards the shorter (blue or visible) wavelengths. An image cube acquired with the same exposure time at each slice would seem to indicate that the reflectance spectrum declines at shorter wavelengths. However, that is an artifact due to the fact that there is also *less* light at those wavelengths. The correct reflectance spectrum is obtained by *dividing* the image spectrum by the illumination spectrum obtained from a reflectance target.

The calibration data needed to divide out the spectral illumination changes was obtained by acquiring an image cube of a reflectance target over the same spectral range as that of the text image cube. The target, made of a proprietary compressed plastic similar to Teflon (Spectralon), reflects all wavelength radiation *equally* over the visible and infrared range. Since the illumination light is reflected from the target equally for all wavelengths, the intensity of each image slice maps out the change in illumination with wavelength.

Spatial changes in intensity are similarly corrected with data from the Spectralon target. The documents were usually illuminated from the side and there was a distribution in intensity from one edge to the other. Dividing the text image by that of Spectralon target corrects this problem.

In anticipation of the results, presented later, it is important to note that a full image cube is not always necessary. In the case of texts, we discovered that single wavelength images at the appropriate wavelength can give excellent results. To be sure, there still is a need for at least one image cube, though, to locate that wavelength. Other objects require the full power of an image cube for analysis.

Image Analysis and Enhancement

Image analysis for imaging spectrometry is done in two stages. First the raw data is taken and the images calibrated by correcting for spectral and spatial illumination effects. As explained above, this step is required for meaningful comparison of the spectra of pixels at different locations in the image. The images are then interactively enhanced. Imaging spectrometry image cube data taken as described herein is called "band sequential," and several available software packages can handle the spectral nature of the data. For single image slices, any popular image software, such as Adobe Photoshop, will allow most image enhancement operations. However, these software packages in general do not allow for the image calibration steps. The imaging data system stores the images in a custom 16 bit file format, which would require preprocessing to make them available to such software packages.

The interactive nature of dealing with digital images is part of the power of this approach to imaging. Selected areas of the text can be enhanced or analyzed in different ways, depending upon the difficulty. Spectral tagging can be used to locate different parts of the image quickly; simply selecting a different pixel to tag as the target spectrum allows rapid changes in the analyzed image.

Images and Results

Dead Sea Scrolls

The subject fragments were viewed on-screen and briefly observed and evaluated as they were acquired. Software used for this purpose were Adobe Photoshop and NIH Image. The former is a popular image-processing software commercially available for both IBM and Mac platforms. The latter, freeware developed by the National Institutes of Health, is limited to use on a Mac. NIH Image lets one look at individual slices from an image cube in 16 bit format, although it neither uses 16 bits for image processing nor allows one to do pixel tagging and some of the calibration steps. Photoshop and similar image software all use 8 bit images, although new versions will be able to read 16 bit files.

Acquiring image cubes, as indicated above, was a lengthy procedure (up to 40 minutes) with the camera and software used during the 1994 field trip. During the project it was determined that the optimal wavelength for the ink and parchment of DSS fragments generally is found in the wavelengths of 970 nm to 1000 nm. Thus, in the interest of time and as no new knowledge was to be gained by taking image cubes of every fragment, image cubes were taken of only selected subjects. However, a new system under development at JPL with a new CCD camera and data acquisition software now will reduce the time required to obtain a full image cube to only a few minutes.

The real power of the approach becomes apparent when the images are loaded into an interactive image processor and magnified several times.

Figure 3 is a collage of image slices of the raw data from an infrared image cube of 4Q365 RP^c (ROC 800, Editors, Tov, White). Except for the last image, they have not been enhanced, demonstrating that the text contrast improves as the image wavelength moves further into the infrared. The last image is an enhanced version of the 970 nm image.

Inexplicably, the Genesis Apocryphon (1QapGen) has suffered darkening and deterioration unprecedented among the DSS. Thus, the entire scroll was electronically imaged. In this case as well, merely imaging the scroll at 970 nm produced images that contain all the data of the infrared images of the early 1950s and also *reveal new text* [Greenfield and Qimron, private communication].

Similar results have been obtained with infrared imaging of papyri, not only by us [Bearman and Spiro, unpublished], but also by Androlini et. al.

Frescoes/Ostraca

We have applied this technique to some very colorful Roman frescoes. A calibrated image cube was taken from 400-710 nm and then analyzed. Those results clearly show how this technique can highlight and/or recover data that is not visible to the eye. Sample images will be shown during the presentation, but are not included in the paper as they are all in color.

Conclusions (and how to do it yourself)

Multi-spectral imaging is a useful tool for imaging 2-d objects that need enhanced imaging. It can improve contrast and legibility of ancient tests and ostraca and provide new approaches for other uses. Combined with powerful visualization software, the archaeologist (curator, conservator, text scholar) can use image cubes to analyze material for sorting, classifying and aiding reassembly, as well as image enhancement.

For some applications, a full image cube may not be necessary, especially after one has taken a full image cube and knows where in the spectrum to work. For example, as we have learned, many documents can be imaged in the 970-1000 nm region, at a single wavelength, for excellent results. Knowing that going in, a simplified system of a CCD camera and an appropriate filter would reduce costs. Using what is known as a cut-on, edge, or longpass filter, will increase the image signal so that a cooled CCD is not necessary. (A cut-on filter is one that rejects all wavelengths shorter (bluer) than its cut-on wavelength; e.g., a 900 nm cut-on transmits *only* radiation longer than 900 nm). Since CCDs are sensitive only to 1050 nm, a CCD camera combined with a 900 nm cut-on filter would image over a narrow spectral range of 900-1050 nm. This spectral range contains 10 times more illumination than when a 10 nm bandpass LCTF is used for spectral selection, so much shorter exposure times are possible. With shorter exposure times, an uncooled CCD camera, much less costly than a cooled one, can be used; further the cost of an LCTF is eliminated from the system.

In circumstances in which two or three or four wavelengths will yield the necessary information, a much simpler and less expensive system can be designed. Rather than using an LCTF that tunes the entire spectral range, the designer can split the image into three colors with dichroics-beamsplitters-and send a color image to separate detectors or use a filter wheel in front of a single detector. Another possibility is to use a three color LCTF, which is much less expensive. All of these possibilities will have large bandpass color images, increasing the signal considerably. As mentioned above, larger signal means uncooled and cheaper cameras. One could even use a camcorder for quick trials; for imaging above ~700 nm the infrared blocking filter should be removed.

At present, the spatial resolution or "spot size" of film images is superior to that of CCD cameras and high magnification images are best done with film. Within a year affordable CCD cameras should match film in this area. However, data from the field project indicates that *by and large this is not a concern for the DSS and other texts.* The physical scale of half-column images of the Genesis Apocryphon is 1 mm/7 pixels, or 142 µm/pixel. At that scale, the test is ~18 pixels tall and the letters range from ~12-17 pixels wide. As the figures show, the text is clearly legible at this spatial resolution.

Electronic imaging has several advantages over film that can be leveraged to advance scholarship, speed publication and improve the quality of the published data:

Electronic images are available immediately, in real-time, and the scholar can leave the session with images in digital form, ready for further work. There is no time delay for chemical processing or subsequent refocusing, Ideally, the editor can participate in imaging sessions to locate questioned areas and provide immediate feedback. If, for example, a close-up is needed, the imaging system can be adjusted on the spot to obtain the correct spatial detail. The editor can perform, or ask that the imaging technician perform, any number of image processing steps until the desired data is obtained. This precludes discovering problems after the shooting session has been completed, a disadvantage characteristic of film photography.

Digital imaging is suitable for routine production work. A considerable amount of text (or objects) can be imaged, enhanced and made available for scholars in a short time. Providing the highest quality images in a timely manner for scholars will enhance and speed the publication process.

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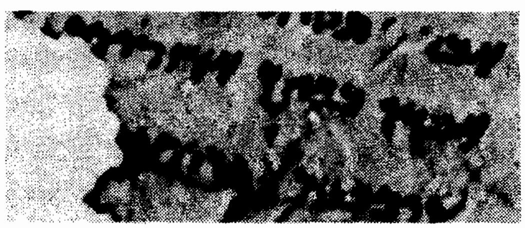
640 nm

680 nm

720 nm

970 nm



Enhanced image
unsharp mask + histogram adjust

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