

## Chapter 8

# A STUDY OF SPECTRAL IMAGING ACQUISITION AND PROCESSING FOR CULTURAL HERITAGE

SONY GEORGE, JON Y. HARDEBERG, JOÃO LINHARES,  
LINDSAY MACDONALD, CRISTINA MONTAGNER,  
SÉRGIO NASCIMENTO, MARCELLO PICOLLO,  
RUVEN PILLAY, TATIANA VITORINO, and E. KEATS WEBB

### ABSTRACT

Imaging spectroscopy, specifically multispectral (MSI) and hyperspectral (HSI) techniques, has been advanced as an effective non-contact analytical tool for cultural heritage (CH). The combination of digital imaging and spectroscopy results in the ability to map the spatial distribution of materials over an object, extract reflectance spectra for the identification of materials, enhance and reveal underdrawings, identify past conservation treatments, and measure colour. Development and increased application of these techniques to documentation of CH calls for the definition of best practices, to allow institutions to have reproducible and comparable data.

Focusing on spectral object documentation, the Working Group 1 (WG1) of the COST-Action TD 1201, Colour and Space in Cultural Heritage, had the task of identifying, characterising and testing spectral imaging techniques and devices in the 400-2500 nm range. To assess the various spectral imaging systems, WG1 performed a Round Robin Test (RRT). Five objects were recorded by nineteen institutions with various MSI and HSI systems and setups. This coordinated research effort aimed to gain a better understanding of the instrumentation, the elements of data acquisition, and the effects of the instruments and methodology on the accuracy and reliability of the data.

Summarising and visualising the received RRT data illustrated the challenges and complexity of the assessment and comparison of the different datasets. Understanding the variation in the resulting datasets helped to inform best practices for CH. The experience was a means of working towards optimised methodologies to lead to the application of non-contact, high-resolution techniques in the state-of-the-art documentation of CH.

---

**Keywords:** Imaging spectroscopy, polychrome surfaces, reflectance, spectral image quality, image colour accuracy, cultural heritage imaging, calibration workflow, multispectral, hyperspectral, COSCH

---

## Introduction

Imaging spectroscopy (IS) techniques, specifically multispectral imaging (MSI) and hyperspectral imaging (HSI), have presented promising advances in the field of non-contact analytical tools for cultural heritage (Fischer and Kakoulli 2006; Cucci et al. 2016). The combination of digital imaging with spectroscopy has expanded point-based, or one-dimensional (1D) spectroscopic techniques. IS provides the ability to distinguish and map the spatial distribution of materials over an entire object, extract reflectance spectra for the identification of materials, calculate colour, enhance and reveal underdrawings, detect changes in composition, and identify damage and past conservation treatments. The informative potential of applications and measurements is determined by the characteristics of the acquisition instrumentation. The increased application of IS techniques for the study and documentation of cultural heritage has resulted in the development of a range of spectral imaging systems. They are based, for example, on cameras with filtering systems or imaging devices with dispersive elements (MacDonald et al. 2013; Lapray et al. 2014). While the latter can offer better performance in terms of spectral resolution, they require sophisticated software and operator skills for the handling, processing, and interpretation of the large data sets acquired. Along with the variety of systems, procedures such as calibration, if not handled correctly, can make the comparison between the acquired data from different instruments impossible, as well as compromise the reliability of the data set. Related challenges include the lack of quality metadata collected in a standard way, the insufficiency of a shared common vocabulary, and the heterogeneity of file formats and software.

These challenges were acknowledged and addressed by Working Group 1 (WG1) of Colour and Space in Cultural Heritage (COSCH), which focused on spectral object documentation with the task of identifying, characterizing, and testing spectral imaging techniques and devices in the visible (Vis, 380–750 nm), near infrared (NIR, 750–1000 nm), and short wave infrared (SWIR, 1000–2500 nm) ranges. To assess the variety of systems and to work towards standardized methodologies and best practices for imaging cultural heritage objects through spectroscopic acquisition, WG1 carried out a Round Robin Test (RRT). Five objects were recorded by nineteen institutions (including museums, research organizations, universities, and IS equipment manufacturers) with various MSI and HSI systems and setups. The RRT was a coordinated effort to gain a better understanding of the instrumentation, the processes of data acquisition, and the effects of the devices and methodology on the reliability of the data. The challenges and issues that arose from bringing different data sets together and understanding the variability seen within them will help to improve protocols for the acquisition, handling, process-

ing, and sharing of spectral data sets. The goal was the practical application of non-invasive imaging techniques in the documentation of cultural heritage.

This chapter reports some of the most significant results and experiences of the working group. The aim is the standardization of methods and the promotion of best practices to allow cultural heritage professionals to achieve accurate, reproducible and comparable data.

## Earlier Research

Previous efforts have attempted to address colorimetric and spectroscopic imaging methodologies applied to the field of art conservation and documentation. There still exists a significant gap, however, in standardizing the application of spectral imaging techniques in academic, research and conservation laboratories. Several projects have contributed to the development of spectral imaging technology for the cultural heritage sector and have succeeded in designing high-performance hardware and software solutions for accurate image acquisition and processing. These started in the early 1990s with the VASARI project at the National Gallery, London, which achieved accurate high-resolution colorimetric images of paintings using a filter-based, multispectral scanning system in the visible region (Saunders and Cupitt 1993; Martinez et al. 2002). The CRISATEL project later extended the work into the NIR and applied basic spectroscopy techniques to the results (Ribés et al. 2005). Advances in technology made HSI possible in the 2000s. The use of pushbroom imaging spectroscopy was pioneered by IFAC-CNR in Florence (Casini et al. 2005) and by the National Gallery of Art in Washington (Delaney et al. 2010).

Although spectral imaging has been widely accepted by the cultural heritage community (Martin et al. 1999; Kerekes and Hsu 2004; Ribés et al. 2005; MacDonald et al. 2013), there remains a need to define guidelines for accurate image capture and a standardized workflow for processing raw data. Spectral image quality is influenced by a number of factors (Shrestha et al. 2014) and understanding their role and how different devices are used in the digital documentation workflow can help to define efficient procedures for acquisition and processing. This has been addressed through the COSCH RRT exercise, as presented in the following sections.

## COSCH Round Robin Test: Description of Work

The RRT involved nineteen institutions acquiring MSI and/or HSI data from selected targets. These institutions included museums, research laboratories, universities, and hyperspectral equipment manufacturers. Five targets were used for the RRT (fig. 8.1): an X-Rite ColorChecker chart, together with its associated white card, a Russian icon, a wavelength standard, and a replica panel painting.

### Round Robin Test

The first RRT object was the traditional standard X-Rite ColorChecker (280 mm × 216 mm) with twenty-four coloured square patches, each measuring 40 mm × 40 mm arranged in a four-by-six array. Although the ColorChecker does not fully represent the range of artists' materials or colour range, it is, nevertheless, a widely used colour reference target within the cultural heritage field and was employed to assess and compare the colour rendering characteristics of the various imaging devices.

The second object was the X-Rite white target, actually light grey in colour, which has the same dimensions as the ColorChecker and is coated uniformly with a paint that has a completely flat spectrum, that is, the same reflectance factor at all wavelengths. This was used to correct for non-uniformity of illumination, and also vignetting by lenses in camera-based systems.

The third object was a nineteenth-century, mass-produced Russian icon (265 mm × 220 mm), printed by polychrome lithography, using eight different inks, onto a tinned steel plate and nailed onto a wooden panel. It has a glossy surface over the coloured areas and a high specular reflectance from the golden metallic surface. The icon was used to investigate the spatial imaging characteristics of IS devices as well as their behaviour with highly reflective surfaces.

The fourth object was a SphereOptics Zenith Polymer Wavelength Standard (90 mm diameter × 15 mm thickness). Wavelength standards are reflectance targets designed for precise wavelength calibration of spectrophotometers, reflectometers, and other spectral instruments. This one is chemically inert, with a diffuse lambertian reflectance, composed of polytetrafluoroethylene (PTFE) doped with the oxides of the rare earth elements Holmium, Erbium, and Dysprosium. This combination gives the object a stable spectrum of characteristic, well-defined, and narrow features over the ultraviolet (UV, 200–380 nm), Vis, NIR, and SWIR spectral ranges, making it particularly suitable for accurate spectral calibration. The wavelength standard is supplied with traceable, laboratory-certified reference reflectance measurements covering the 200–2500 nm range. It was used to assess and compare the spectral accuracy of the imaging devices.

The documentation and study of works of art, in particular paintings, was the objective of the spectral imaging carried out by the participating teams. The fifth target was therefore painted. It was made especially for the RRT, using the medieval Tuscan panel painting technique, based on egg-tempera paints, described by Cennino Cennini in his *Il Libro dell'Arte* believed to be written in the 1390s (Cennini 1954). The panel (290 mm × 220 mm) consists of a wooden support with a gypsum ground, a canvas layer, and a second gypsum ground layer. Five types of drawing materials—watercolour, charcoal, graphite, a lead and tin-based metal-



**Figure 8.1.**  
 (a) X-Rite ColorChecker with sampling areas for colorimetric and spectral analysis;  
 (b) SphereOptics Zenith Polymer Wavelength Standard;  
 (c) Russian icon with sampling areas for colorimetric and spectral analysis;  
 (d) replica panel painting with sampling areas for colorimetric and spectral analysis.

**Table 8.1. Specification of the imaging devices used in the RRT.**

	System attribute		
	Operative range (nm)	No. bands	Spatial sampling (pix/mm)
<b>MSI LCTF</b>	400–720	33	4.2
<b>MSI LCTF</b>	400–720	33	6.8
<b>HSI pushbroom</b>	400–900	400	9–11
	950–1650	332	
<b>HSI pushbroom</b>	400–1000	160	16

point, and a lead-based metalpoint—were used to create lines and line patterns that were then covered with paints applied with two different thicknesses. Seven pigments—carmine, vermilion, burnt umber, malachite, azurite, lead white, and ivory black—were mixed in an egg tempera binder and applied to the panel. They were chosen to have distinctive spectra in the Vis, NIR and SWIR spectral ranges allowing useful spectral analysis to be carried out in any spectral region.

### Methodologies

Imaging spectroscopy is normally classified as either multispectral (MSI) or hyperspectral (HSI) but the distinction between the two is rather blurred (Liang 2012). The number of bands, their width and continuity are the parameters by which the two techniques differ. MSI systems are designed to acquire images over a limited number of spectral bands, usually with a set of filters having bandwidths from tens to hundreds of nanometres. HSI systems acquire images in narrower and more numerous contiguous bands, typically 100 or more having bandwidths from 1 to 10 nm. The advantage of HSI systems is to provide almost continuous spectral measurement, and therefore they are more accurate than MSI in spectroscopic analysis and material identification (Cucci et al. 2016).

There are several methods of wavelength selection which determine the design of the illumination and the spatial and spectral scanning strategy. For MSI devices tunable light sources may be employed, such as LED-based or filter-based lighting systems, with a monochrome digital camera. Alternatively white light sources may be used with filtered cameras, in which a filter wheel or tunable spectral filters, such as Liquid Crystal Tunable Filters (LCTF) and Acousto-Optical Tunable Filters (AOTF), are placed in front of the sensor (Lapray et al. 2014).

Most of the available HSI systems are based on prism-grating-prism (PGP) line-spectrographs connected to high-sensitivity detectors and the data acquisition is made in pushbroom modality, in which a complete spectrum of each point

Spectral sampling (nm)	No. bits	Setup information		
		Complexity	Portability	Cost*
10	12	Medium	High	M
10	16	Medium	High	M
1.3 2.1	14	High	Low	E
3.5	14	High	None	E

\* Cost: C = cheap (<€30,000); M = medium (€30,000–€50,000), H = high (€50,000–€80,000) and E = expensive (>€80,000).

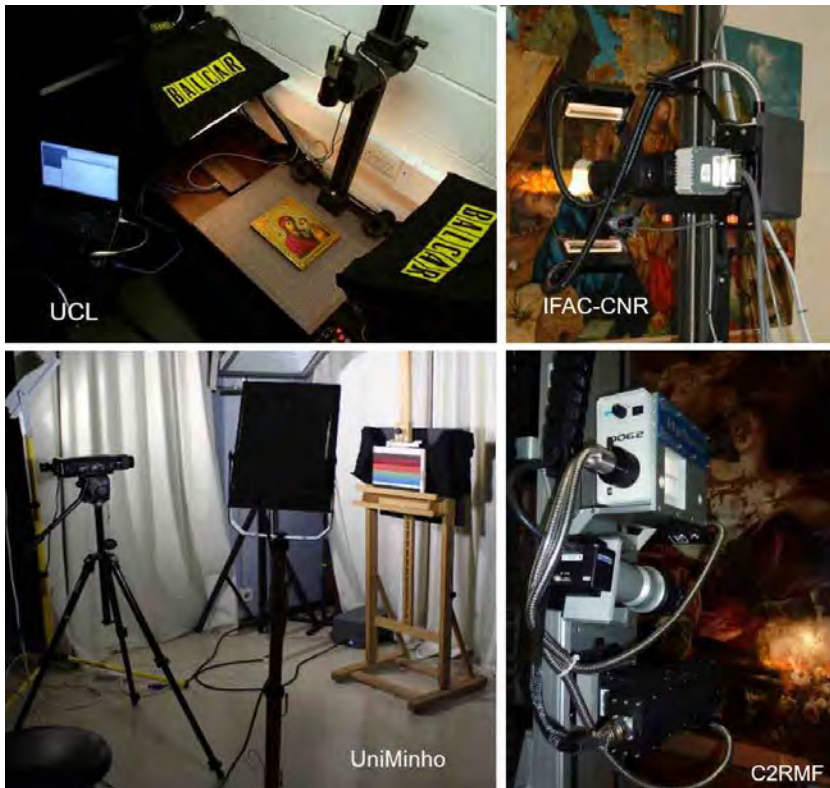


Figure 8.2. Different spectral imaging devices used within RRT. Left MSI; right HSI.

along a line is formed on one column of the 2D detector array and the area of interest has to be scanned one line at a time. A different HSI technology uses snapshot imaging spectrometers, which collect the entire data set (or data cube) in a single integration period without scanning (Hagen et al. 2012). Although the acquisition of a large number of contiguous narrow bands allows an accurate spectral acquisition, these systems are usually more complex, which decreases their portability and increases their cost. Some configurations of the MSI and HSI systems used in the RRT (fig. 8.2) are summarized in table 8.1.

The two most important characteristics of MSI and HSI systems are their spatial and spectral resolutions, which are linked to their spatial and spectral sampling characteristics. The former is a measure of a system's ability to resolve the desired details in the surface of an object of interest. There are different definitions for the factors related to spatial resolution, including pixel resolution (the number of pixels per linear mm) and optical resolution (the ability of an imaging system to resolve closely-spaced points). Pixel resolution influences the spatial resolution of an image, but is not the only criterion used to evaluate the resolving capabilities of a system. A higher pixel count may increase the image size, but does not guarantee a high spatial resolution, which depends on both optical and electronic components including the lens, aperture, detector, and signal processing (Cucci et al. 2016; MacDonald 2010). The spectral resolution, on the other hand, defines how well the system can resolve the spectral features by sampling wavelength, and is important for material identification (Cucci et al. 2016). Materials can be identified based on their characteristic spectral features, both absorption and reflectance, which can be observed with spectroscopic techniques including IS. Some materials have very narrow spectral features that can only be resolved by systems with a high spectral resolution, whereas other materials have broader features that can be resolved by systems with a lower spectral resolution.

## Comparison and Evaluation Procedures

### *Colorimetric and Spectral Analysis*

For data comparison a set of areas was selected on the X-Rite ColorChecker and in the Russian icon (figs. 8.1a and 8.1c). At each of these locations spectral reflectance data from the IS systems were averaged and compared with values obtained from a spectro-colorimeter (Minolta CM-2600d) with a  $d/8^\circ$  geometry (fig. 8.3). For non-uniform surfaces such as those of the icon, these measurements may express combinations of rather different spectra. It should also be noted that as the geometry of the spectro-colorimeter is different from that of the imaging systems direct comparison of the results must be made with caution. The CIE  $L^*a^*b^*$  coordinates were calculated using the CIELAB 1976 colour space with D65



**Figure 8.3.**  
Minolta CM-2600d  
measuring reflectance  
spectra on selected areas  
of the Russian icon.

illuminant and 2° standard observer. The CIEDE2000 formula was used to calculate the colour ( $\Delta E_{00}$ ) and chroma differences ( $\Delta C^*$ ) to compare the acquired and processed data (CIE 2004).

To compare the reflectance spectra extracted from the data acquired by each device with those acquired with the Minolta, two measures were used: the Root-Mean-Square Error (RMSE) and the Goodness-of-Fit Coefficient (GFC) (Valero et al. 2007). RMSE represents the standard deviation of the differences between two spectra, and GFC represents the cosine of the vector angle formed by those spectra. The two measures of performance differ since GFC is not affected by scale factors. The value range is from 0 to 100%, with a GFC  $\geq 99.5\%$  corresponding to acceptable recovery and GFC  $\geq 99.99\%$  to an almost exact fit.

### **Spatial Resolution Assessment**

Spatial resolution may be evaluated using diverse approaches (Holst 1998). Here three methods for assessing the spatial resolution are presented: visual comparison of resulting images, plotting of cross-sectional profiles, and calculation of the sampling density. The most straightforward way of assessing the spatial resolution of a system is to look at how well the resulting images resolve the details of the documented object. The second way is to plot the intensity profiles of a sequence of high-low reflective materials to determine the contrast between lines and spaces, such as line patterns on the replica panel painting (fig. 8.1d). For this object, for instance, as the resolution decreases, the ability to discriminate lines and spaces and the distance between peaks and valleys in the profile plots decreases. The third way is to calculate the sampling density, by dividing the number of pixels between two points by the corresponding physical distance, expressed as pixels/mm.

### Spectral Alignment Accuracy

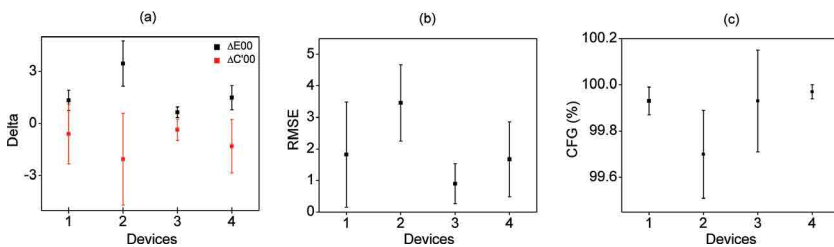
Spectral alignment accuracy can be obtained by using “spectrally well-known light sources” such as fluorescent lights, xenon or mercury lamps that exhibit distinct and stable spectral features (Polder et al. 2003). An alternative approach is through the use of reflective targets impregnated with rare earth oxides (such as holmium oxide, erbium oxide, and dysprosium oxide) that present discrete narrow and strong absorption bands (Burger 2006). In the RRT a SphereOptics Zenith Polymer Wavelength Standard was used (fig. 8.1b).

## Results for Each Object

### X-Rite ColorChecker

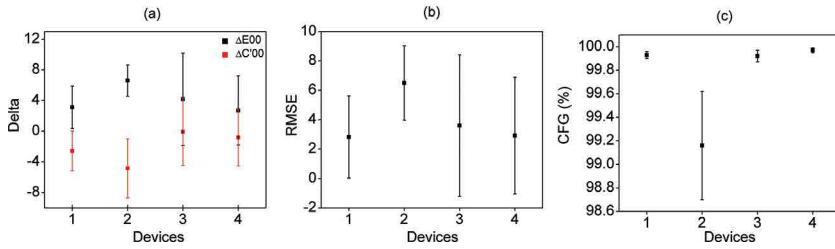
The ColorChecker was used to evaluate the colour and spectral accuracy of the different devices (fig. 8.1a). Colour differences and other colorimetric parameters calculated from the data acquired by four participating institutions are presented. Specifically, the discussion of those results is centred on: (i) the accuracy of colour and spectral reproduction of the ColorChecker; (ii) the problems related to non-homogeneity of the colour surface; and (iii) the definition of the most problematic areas (hues) for accurate colour and spectral recording.

Colour accuracy was verified by comparing the colorimetric values calculated from the MSI and HSI data with those obtained from direct measurement with the spectro-colorimeter. Figure 8.4a shows the average  $\Delta E_{00}$  (black symbols) and  $\Delta C^*$  (red symbols). Colour difference values are in general low and in all cases below four units. As expected, systems with a larger number of spectral bands approximate better (fig. 8.4a devices 3–4) to the spectrophotometer measurements than those with a small number of bands (fig. 8.4a devices 1–2). Comparison of the RMSE and GFC (figs. 8.4b and 8.4c, respectively) suggests that when scale factor is eliminated the performances of both types of systems are very similar.



**Figure 8.4. ColorChecker, comparison between the four imaging devices (MSI = 1, 2; HSI = 3, 4) and the spectro-colorimeter measurements: (a)  $\Delta E_{00}$  and  $\Delta C^*$ , (b) RMSE, and (c) GFC data.**





**Figure 8.6. Russian icon, comparison between the four imaging devices (MSI = 1, 2; HSI = 3, 4) and the spectro-colorimeter measurements: (a)  $\Delta E_{00}$  and  $\Delta C'$ , (b) RMSE, and (c) GFC data.**

The capability to resolve the fine spatial details of the icon also provides an indication of the spatial resolution of each system. An example of such detail extracted from three of the systems is presented in figure 8.7.

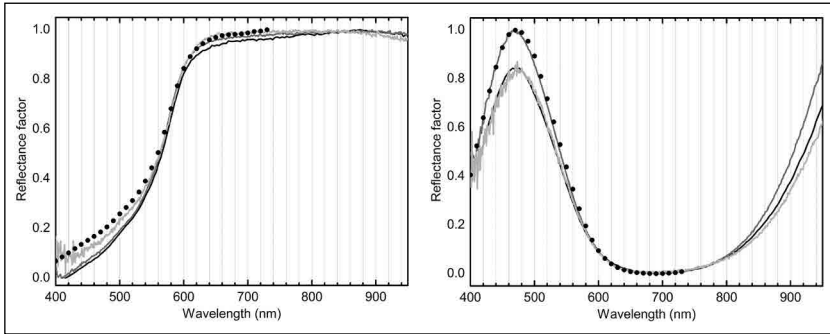
The ability of the four IS devices considered here in extracting spectroscopic data from the icon is shown in figure 8.8. It is evident that there is a sufficiently good accordance among those imaging systems in the obtained spectral shape of the spectra. However, those reflectance spectra cannot be perfectly superimposed due to differences in their reflectance values across the recorded spectral range. The blue vest and the skin were probably obtained by mixing a white pigment with Prussian blue and a red dye, most likely an anthraquinone-based dye, respectively.

### SphereOptics Zenith Polymer Wavelength Standard

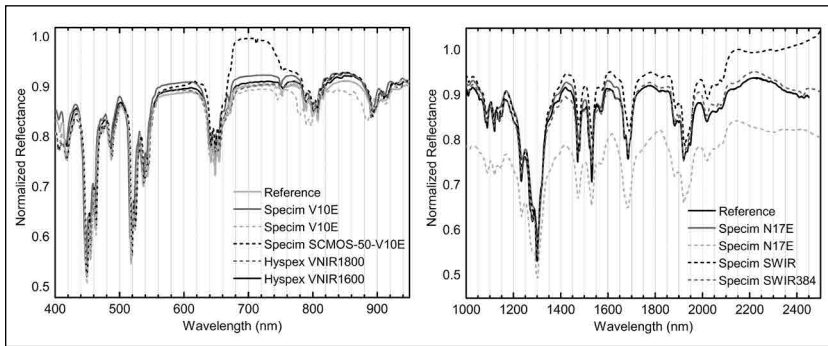
As wavelength standards are designed for use with spectral equipment with high spectral resolution, the analysis in this section is limited to the available data from HSI equipment only. The measured reflectance spectra of the wavelength standard for each HSI system were determined by taking an average over several thousand pixels, thereby significantly reducing noise. The spectral responses of the different systems for the wavelength standard are shown in figures 8.9 and 8.10, together



**Figure 8.7. Russian icon detail extracted from the different devices to show the spatial resolution quality from three IS systems.**



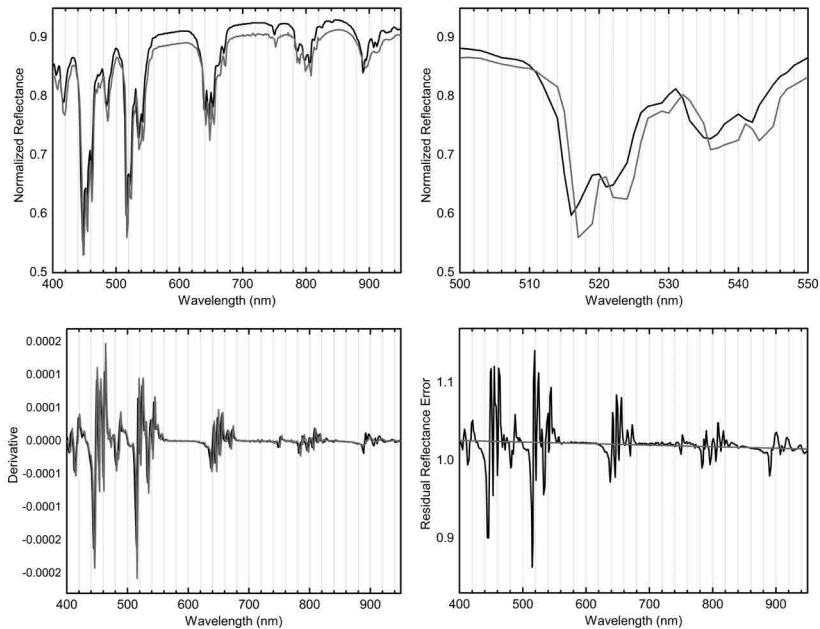
**Figure 8.8. Reflectance spectra from two different coloured regions (skin and blue vest, respectively) of the Russian icon reconstructed from the MSI and HSI data sets.**



**Figure 8.9. SphereOptics Zenith Polymer Wavelength Standard. Comparison of Vis-NIR (left) and SWIR (right) reflectance.**

with the certified reference values for the standard supplied by the manufacturer. The Vis-NIR and SWIR wavelength regions are shown separately. Although the spectra are broadly similar, there is a clear variability in amplitude, spectral shape, and also spectral misalignments between the reference spectra and the calibrated data from the various HSI systems.

The reference standard contains sharp narrow absorption bands and troughs, which in several cases are beyond the spectral resolution even of the HSI systems. Each system has slightly different wavelength ranges, different numbers of bands with different central wavelengths, and different bandwidths at each wavelength. Therefore, in order to make meaningful quantitative comparisons, it was first necessary to resample each of the acquired data to a common sampling basis and to convolve the reference spectra at the central wavelength for each band with a Gaussian distribution with the camera’s given full width half maximum (FWHM) in order to mimic the spectral and bandwidth characteristics of each HSI system.



**Figure 8.10.** Comparison of the reflectance spectra of wavelength standard for one of the Vis-NIR hyperspectral systems (top left), a zoom of a narrow range of wavelengths showing spectral misalignment (top right), the derivative of the spectra (bottom left), and the residual error with its linear regression (bottom right). Reference = grey line; Vis-NIR hyperspectral system = black line.

The residual error was calculated for each system from these resampled reference spectra (fig. 8.10). Although there are large errors at the sharp bands and troughs, the average errors are relatively small, ranging from 0.005–0.01 in the Vis-NIR region, but much higher in the SWIR region.

The spectral misalignment that can be seen in figures 8.9 and 8.10 can be better visualized by comparing the first derivatives of the two spectra. The zero-crossings correspond to the position of the absorption bands and bottoms of the troughs of the reflectance spectra. The results from a single HSI system are shown in figure 8.10, where a small spectral misalignment can be clearly seen in the zoomed view. In order to quantify this, phase correlation was used to measure a global offset between the resampled reference signal and the measured spectra. The results in table 8.2 show that this spectral misalignment ranged from 0.0 nm to 2.6 nm in the Vis-NIR region and from 0.0 nm to 2.0 nm in the SWIR region for the two different HSI systems.

**Table 8.2. Spectral misalignment errors of the different devices.**

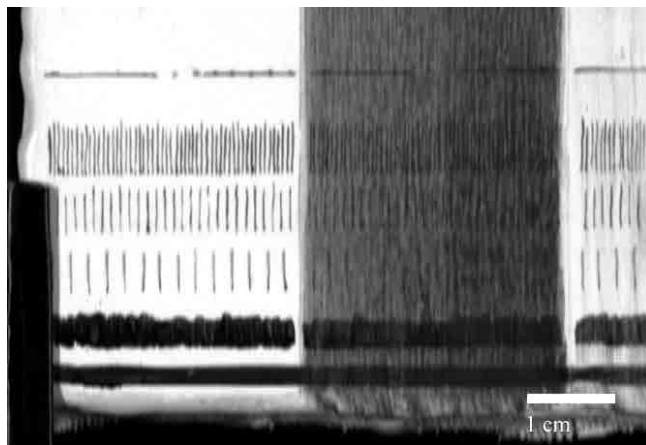
Vis-NIR		SWIR	
System	Misalign-ment (nm)	System	Misalign-ment (nm)
Hypspec VNIR1600	0.0	Specim N25E MCT	0.0
Hypspec VNIR1800	-0.1	Hypspec SWIR384 MCT	0.3
Specim V10E	1.0	Specim N25E MCT	0.8
Specim V10E	-1.3	Specim N25E InGaAs	2.0
Specim SCMOS-50-V10E	1.3	Specim N25E MCT	2.0
Specim V10E	2.6*		

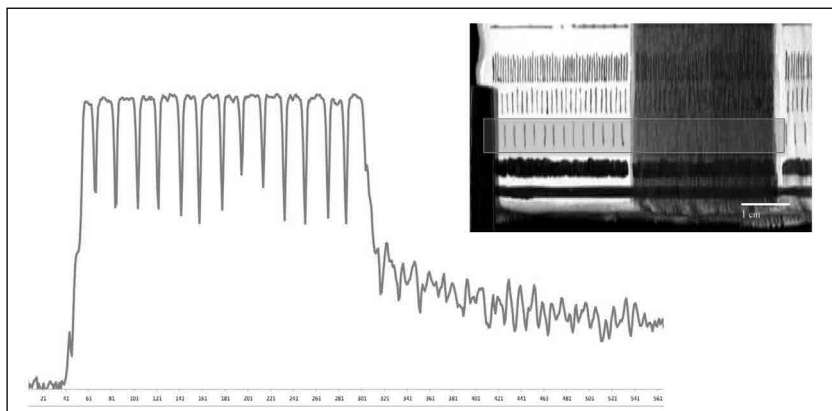
\* This system has very noticeable wavelength-dependent misalignment.

### Replica Panel Painting

The replica panel painting was employed to assess the ability of HSI systems to identify and characterize pictorial materials, and their spatial resolution in the NIR-SWIR region to unveil and study underdrawings. Visual comparison of images acquired from the two HSI systems provided an indication of the spatial resolution of the resulting data. As an example, a detail extracted from one of the HSI data sets (fig. 8.11) shows how the three sets of watercolour lines with spacing from 2 mm down to 0.5 mm were resolved. The true sensitivity in the spatial resolution of IS devices can be visualized by plotting the intensity profiles of the line patterns on the panel painting. The reported plot of the profiles of the watercolour

**Figure 8.11.** Detail of the replica panel painting extracted at approximately 1040 nm looking at the line patterns to assess the system's ability to resolve fine details.

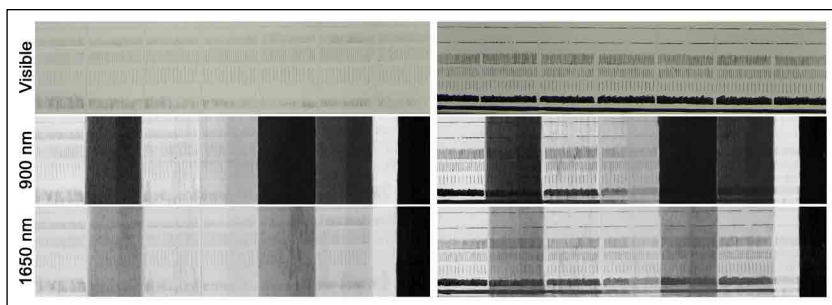




**Figure 8.12.** The vertical profile (left) from an HSI device data set looking at the exposed watercolour lines (right image) on the replica panel. The system is able to differentiate between the lines and spaces as seen with the well-defined peaks.

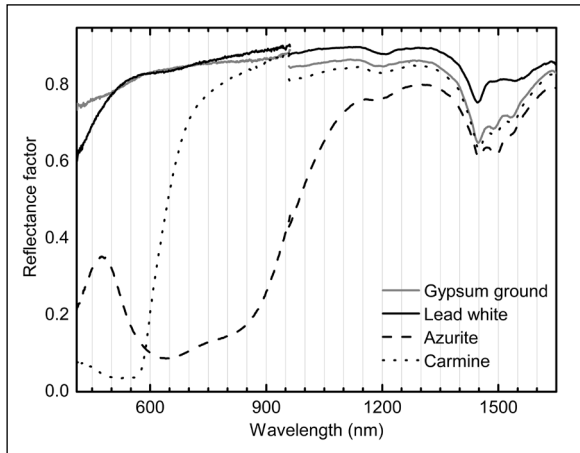
lines with 2 mm spacing shows a clear differentiation of the lines and spaces with greater distance in amplitudes between the peaks and valleys (fig. 8.12).

Concerning the NIR-SWIR region, even if it is possible to discriminate the areas presenting fine details, such as the lines with 1 mm pitch (fig. 8.13), the visualization of these underdrawings depends on the transparency of the paint layers. The ability to reconstruct images at different wavelengths from an HSI data set allows the user to penetrate deeper into the layers and obtain a higher degree of visualization. As an example, for the azurite layer, it was possible to observe the underdrawing clearly at  $\sim 1300$  nm, whereas for the malachite layer, the lines were only legible at  $\sim 1600$  nm. For both pigments, IS devices limited to a maximum wavelength of 1000 nm would not have been able to detect underdrawings behind such pigments.



**Figure 8.13.** Images extracted from the hyperspectral data cube at two different wavelengths for the visualization of underdrawing details made with lead- and tin-based metalpoint (left) and watercolour (right) techniques.

**Figure 8.14.**  
**Reflectance spectra**  
**from the painted areas**  
**made with carmine lake**  
**(dotted line), azurite**  
**(dashed line), lead**  
**white (solid line), and**  
**gypsum preparation**  
**(grey line) of the**  
**replica panel painting.**



Due to the high spatial and spectral sampling of some HSI devices, reflectance spectra from areas of 100 mm or less can be collected on fine polychrome objects. Vis-NIR-SWIR reflectance spectra extracted from the HSI data of the carmine-based red lake, azurite, lead white, and gypsum are reported in figure 8.14. In this spectral region gypsum can be identified by its three sub-bands in the 1447–1532 nm range; lead white can be identified by the presence of a spectral feature at 1450 nm; and azurite has its own distinctive absorption band at 1500 nm. Azurite also presents an intense characteristic absorption in the red-NIR region. Spectra of carmine red lake, on the other hand, in the case of paint layers that are less saturated, have a main absorption band in the Vis-NIR structured into two sub-bands at  $530\pm 5$  nm and  $567\pm 3$  nm. To identify those spectral bands precisely an IS device with high spectral resolution is usually required.

## Discussion and Conclusions

The RRT was a coordinated research effort to explore the instrumentation, the differing protocols of image acquisition, and the effects of the instruments and methodology on the accuracy and reliability of the data. It has provided an important insight into the reliability and comparability of IS systems and methodologies in use within the cultural heritage field.

In this chapter, the results of the assessment of a subset of the data sets, consisting of representative MSI and HSI systems has been presented. The devices and procedures from the RRT provide broadly consistent results with average colour differences at or below accepted thresholds and largely accurate spectral reproduction. There was, nevertheless, considerable variability in the data.

Sources of this variability included the equipment itself (MSI vs HSI, manufacturer, specifications), the users (museums, universities, research laboratories), and the methods of data processing (procedures and workflow), which resulted in varying levels of quality in the final spectral data.

In addition, there were several sources of error that affected the resulting data and measurements. These included errors in spectral alignment, noise, and distortions including amplitude as well as spatial distortions. Such errors can have important consequences for the use of spectral data in applications such as materials classification or pigment mapping, degradation monitoring, and colorimetry.

The results have highlighted the need to work towards standardized methodologies and the need to define best practices. It is important for cultural heritage users to understand the calibration (spectral, radiometric, and spatial calibration) workflow as well as understand the true accuracy, precision, and limits of the systems. Improved acquisition protocols and workflows can dramatically improve the accuracy and reliability of the measurements and the resulting data. In addition, the RRT made clear the importance of regular calibration, validation, and testing of the system.

Finally, it is important to stress the interdisciplinary nature of IS methodologies. Their application in the field of cultural heritage requires a blend of interdisciplinary expertise and collaboration, with specialized skill sets and knowledge that contribute to the outcomes of the research project. This aspect is crucial to obtain satisfactory and reliable results.