CURRENT TRENDS IN SPECTRAL REFLECTANCE IMAGING TECHNIQUES: A QUALITATIVE APPROACH TO THE INVESTIGATION AND DOCUMENTATION OF BUILDING MATERIALS

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Introduction:

Preservationists utilize many techniques to evaluate sites and monuments, and continually strive for increasing levels of accuracy.[1] Today researchers are able to virtually reconstruct objects, buildings and entire sites through the use of digital-imaging technology, and many of these same techniques are being adapted to provide non-destructive documentation and material analysis.[2] Increasing portability and decreasing cost of digital-imaging equipment promises to yield myriad avenues for investigation and provide further opportunities for accurate documentation.[3]

In terms of architectural-conservation practice, three of the most promising areas for non-destructive or non-invasive documentation are laser scanning, photogrammetry and spectral imaging. Historically the domain of geologists and engineers, these techniques draw upon computer science and physics to remotely create highly accurate digital renderings of an object, surface, or area or land.[4] Laser scanning refers to the

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[1] Moropoulou, A., K. C. Labropoulos, E. T. Delegou, M. Karoglou, and A. Bakolas. 2013. "Non-destructive Techniques as a Tool for the Protection of Built Cultural Heritage". *Construction &Building Materials.* 48: 1222-1239. See also: Amat, Anna, Costanza Miliani, and Brunetto Giovanni Brunetti. 2012. "Non-invasive multi-technique investigation of artworks: A new tool for on-the-spot data documentation and analysis". *Journal of Cultural Heritage.* 14 (1): 23-30.

[2] Stal, Cornelis, Kim van Liefferinge, Jeroen de Reu, Roald Docter, Guy Dierkens, Philippe De Maeyer, Sophie Mortier, et al. 2014. "Integrating geomatics in archaeological research at the site of Thorikos (Greece)". *Journal of Archaeological Science.* 45: 112-125. See also: Bacci, M., R. Chiari, S. Porcinai, and B. Radicati. 1997. "Principal Component Analysis of Near-Infrared Spectra of Alteration Products in Calcareous Samples: An Application to Works of Art". *Chemometrics and Intelligent Laboratory Systems.* 39 (1): 115-121.

[3] Verhoeven, G. 2008. "Imaging the invisible using modified digital still cameras for straightforward and low-cost archaeological near-infrared photography". *Journal of Archaeological Science.* 35 (12): 3087-3100.

[4] Ch'ng, Eugene, Vincent L. Gaffney, and Henry Chapman. 2013. *Visual heritage in the digital age*. http://site.ebrary.com/id/10815805. See also: Johnson, Jeffrey R., William M. Grundy, and Michael K.

process of scanning an area or object with a laser to create a point cloud of data.[5] Similarly, photogrammetry refers to the capture of a point cloud of data via the integration of multiple images taken of an object using a digital camera.[6] As with laser scanning, specialized software creates digital meshes of a surface; this mesh is then refined further to create a volumetric 3D-orthographic rendering.[7] While laser scanning and photogrammetry compile information exclusively within the visible spectral range, spectroscopy and derivative forms of spectral imaging allow researchers to study data across a wider range of the electromagnetic spectrum. While the former give geometric, quantitative information, and three-dimensional visual information, spectroscopy provides data about material properties of an object. By altering the type and intensity of radiation permitted to fall upon an object, researchers are able to isolate, record, and ascertain the material composition based upon the spectral output.

Inspiration for this thesis research originated by way of a campaign to confirm the presence of particular pigments on architectural fragments at the Antonino Salinas Regional Archaeological Museum of Palermo.[8] This investigation utilized an imaging

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Shepard. 2004. "Visible/near-infrared Spectrogoniometric Observations and Modeling of Dust-Coated Rocks". *Icarus.*171 (2): 546-556.

[5] Henry Chapman, Eamonn Baldwin, Helen Moulden and Michael Lobb. "More Than Just a Sum of the Points: Re-Thinking the Value of Laser Scanning Data" 2013. *Visual heritage in the digital age*. 16."The potential of high-definition laser scanning survey has been demonstrated within the field of heritage for its ability to capture highly detailed and accurate information regarding surfaces of objects, structures, buildings and landscapes… At a terrestrial level, laser scanning has provided the opportunities to record built heritage at high accuracy and at dense resolution both on its own (e.g. Rüther et al. 2009) and in combination with other techniques (e.g. Al-kheder et al. 2009)."

[6] McCarthy, John. 2014. "Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement." *Journal of Archaeological Science.* 43 (89): 175-185.

[7] Agisoft PhotoScan User Manual: Professional Edition, Version 1.0.0 (2013) Agisoft LLC

[8] New York University, Institute of Fine Arts, Excavations at Selinunte, Italy field season May 26th through June 27th 2014. The work of the Selinunte Excavations is under the direction of Professor Clemente Marconi and in collaboration with the Soprintendenza BB.CC.AA of Trapani.

process known as multispectral imaging, or MSI, a technique which enables researchers to quickly and non-invasively establish characteristic properties across a surface, and to globally examine the behavior of materials when exposed to specific forms of radiation. Through the use of a digital camera, different radiation sources, and different filters, researchers capture images of spectral characteristics of the materials present on the surface. The process involves analyzing the manner in which radiation interacts with the surface material of an object and how that interaction is subsequently captured via a proscribed imaging process.[9] At present, only a handful of research teams incorporate such imaging techniques within large-scale architectural-documentation campaigns,[10] such as spectral imaging, terrestrial laser scanning, and the fluorescence-light detection and ranging (LIDAR) technique for remote scanning.[11]

While both (LIDAR) and laser scanning are viable options proven to non-invasively capture information on a large scale, — equipment costs, transport and ease of use present very real concerns.[12] As researchers Cecchi, Pantani, Raimondi, Tirelli and Chiari observe “Up to now, remote sensing applied to the study of historical buildings has mainly been limited to the monitoring of their structural features, while their

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[9] Joanne Dyer, Giovanni Verri, John Cupitt. Multispectral Imaging in Reflectance and Photo-induced Luminescence modes: A User Manual. Version1.0. British Museum, (October, 2013), 7.

[10] Armesto-González, Julia, Belén Riveiro-Rodríguez, Diego González-Aguilera, and M Teresa Rivas-Brea. 2010. "Terrestrial laser scanning intensity data applied to damage detection for historical buildings". *Journal of Archaeological Science.* 37 (12): 3037-3047.

[11] Raimondi, V., G. Cecchi, D. Lognoli, L. Palombi, R. Gronlund, A. Johansson, S. Svanberg, K. Barup, and J. Hallstrom. 2009. "The Fluorescence LIDAR Technique for the Remote Sensing of Photoautotrophic Biodeteriogens in the Outdoor Cultural Heritage: A Decade of in-situ Experiments". *International Biodeterioration & Biodegradation.* 63 (7): 823. “…the fluorescence lidar technique remotely detects the laser-induced fluorescence (LIF) emitted from a target when the latter is excited with laser radiation of a proper wavelength.”

[12] Raimondi, et al. 2009. 825.

chemical-physical characteristics are still investigated in the laboratory or *in-situ* measurements on a limited number of selected points with portable instrumentation."[13] Through the examination of non-invasive documentation techniques currently used in the conservation field, this study attempts to re-imagine a way of applying equipment used for the characterization of materials commonly associated with historic buildings and archaeological sites (e.g. construction and restoration).[14]

In consultation with imaging specialists and Columbia University faculty, a range of imaging techniques have been selected which represent potentially viable methods for non-destructive material analysis. Techniques of particular interest involve data collection within the visible and infrared regions of the electromagnetic spectrum, including thermographic-IR imaging, multispectral imaging, and hyperspectral imaging. By examining the materials associated with historic structures (e.g. stone, metal, brick, terra cotta, concrete and wood) and imaging technologies currently available, it is the goal of this research project to create a model for determining appropriate imaging techniques necessary to decipher construction materials. In this way, this paper attempts to qualitatively examine the feasibility of using spectral-imaging for *in-situ* exterior survey and assessment of building façades, where it can be important to quickly, remotely and non-destructively distinguish among original construction, biological growth, paint, and other colored building materials.

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[13] Cecchi, G., L. Pantani, V. Raimondi, D. Tirelli, and R. Chiari. 1996. "Fluorescence LIDAR Technique for the Remote Sensing of Stony Materials in Ancient Buildings [2960-19]".*Proceedings- SPIE the International Society for Optical Engineering.* (2960): 163.

[14] Lerma, J. L. 2005. "Automatic Plotting of Architectural Facades with Multispectral Images". *Journal of Surveying Engineering.* 131 (3): 73-77.

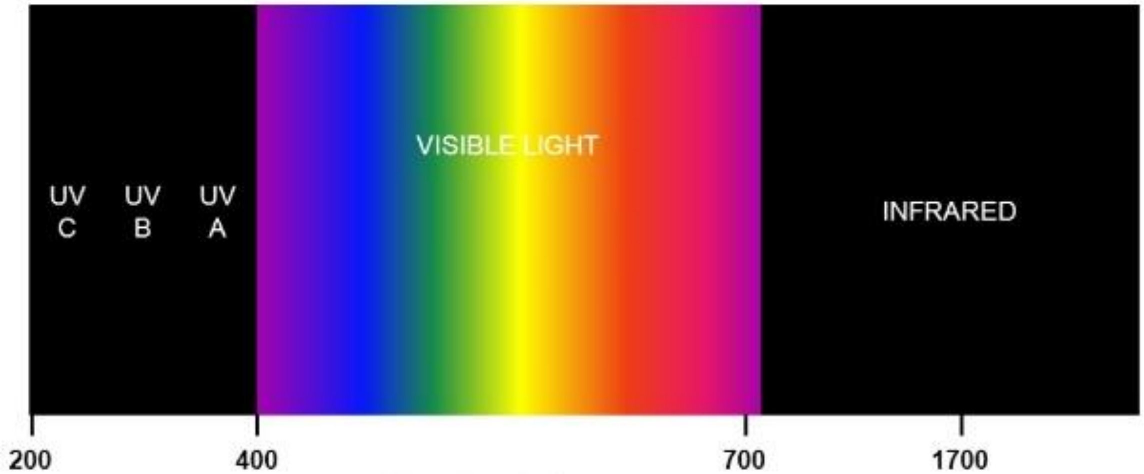

Figure 1: Wavelength ranges in the electromagnetic spectrum commonly used for multispectral imaging in cultural heritage applications.
(Image source: http://www.charismaproject.eu)[15]

Spectral imaging draws upon fundamental principles of spectroscopy, which is defined as the study of a material's interaction with light.[16] Light, as a form of radiation, is defined as a spectrum of energy known as the electromagnetic spectrum (EM). The spectrum is subdivided into groupings based on frequency.[17] These frequencies are defined in terms of patterns of photon movement collectively described as waves. Each wave incorporates not only the maximum wave height or amplitude (a), but also the distance between individual wave crests, known as wavelength (λ).[18] The isolated frequency (ʄ) of a wave describes the number of wave cycles or oscillations per unit length and is inversely proportional to wavelength; therefore, wavelength is inversely

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[15] Dyer, Verri and Cupitt. 2013. Multispectral Imaging in Reflectance and Photo-induced Luminescence modes: A User Manual. 1.

[16] Derrick, Michele R., Dusan Stulik, and James M. Landry. 1999. *Infrared spectroscopy in conservation science*. Los Angeles: Getty Conservation Institute. 4

[17] Derrick, Stulik and Landry. 1999. *Infrared spectroscopy in conservation science*. 5

[18] Ibid. "The amplitude is the height, or maximum size, of the wave, which corresponds to the intensity, or volume, of the signal. The frequency, v, is the number of oscillations, or waves, per unit time-that is, cycles per second. The wavelength, A, is the distance between two successive maxima or minima of a wave-that is, the length of one wave. The wavelength of the radiation is inversely proportional to frequency."

proportional to frequency and also to radiation energy.[19] Thus, velocity (v) = frequency (ʃ), multiplied by wavelength (λ); where v = 3 x 10^8 $_{m/s}$ (speed of light).

Graphic representations of the electromagnetic spectrum delineate predominant wavelength regions; the most familiar to readers being the ultraviolet (UV), the visible (VIS) and the infrared (IR) ranges. While all radiation (wavelength ranges) along the electromagnetic spectrum are present to varying degrees in sunlight, the filtering power of the earth's atmosphere controls the type and intensity of radiation permitted through (See Figure 2). Spectral imaging commonly utilizes radiation sources within the ultraviolet-, the visible- and the infrared-wavelength regions of the electromagnetic spectrum.

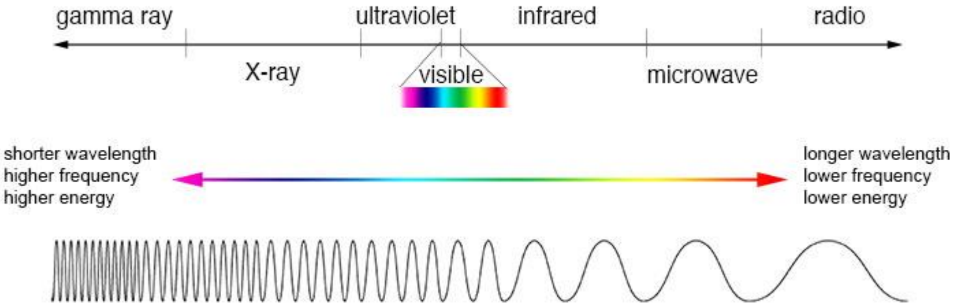

Figure 2: Comparison of wavelength, frequency and energy across the electromagnetic spectrum (Image credit: http://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html)

The visible region of the electromagnetic spectrum comprises wavelengths ranging from approximately 400 to 750 nanometers (nm),[20] and is subdivided into bands of color: red, orange, yellow, green, blue, indigo and violet (See Figure 3). Beyond the visible, the ultraviolet region extends from approximately 10-400 nm and is subdivided

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[19] Ibid.

[20] In other source nomenclature 0.4-0.7 µm; the relationships between the different wavelength measurements is: 10,000 Å = 1,000 nm = 1 µm.

into the near UV (320-380 nm), middle UV (200-320 nm) and vacuum UV (10-200 nm).[21] At the opposite end of the spectrum, the infrared region is most frequently subdivided into three main categories: the far (FIR) from 20,000 to 500,000nm (20 to 500µm), the middle IR (MIR) 2,500 to 20,000nm (2.5 to 20µm), and the near IR (NIR) from approximately 700 to 2,500nm (0.7 to 2.5µm).[22] Other sources subdivide the infrared into five sections: the far IR (FIR) from 15 to 1,000µm; the long wavelength IR (LWIR) 6 to 15µm; the middle IR (MIR) 3 to 6µm; the shortwave IR (SWIR) from 1.4 to 3µm; and the near IR (NIR) from approximately 0.75 to 1.4µm.[23]

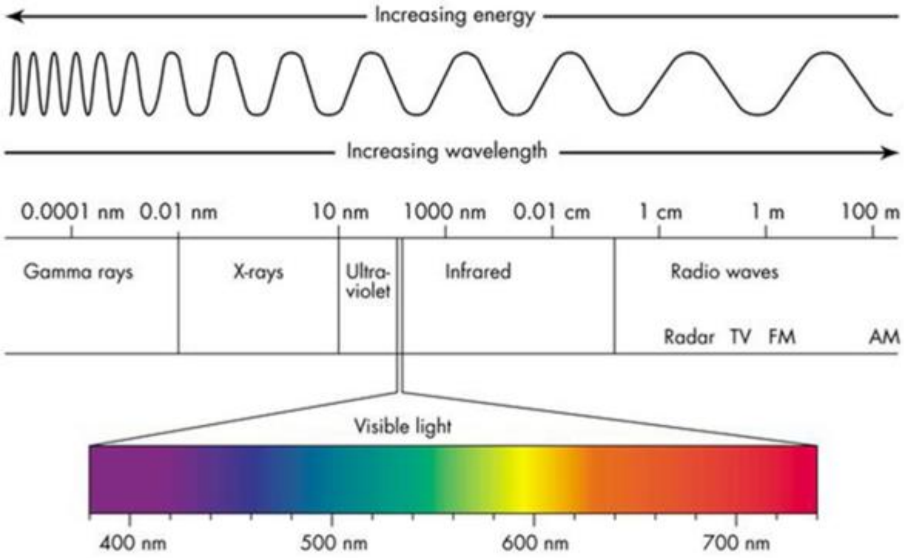

Figure 3: Detail of the electromagnetic scale illustrating major regions of radiation. (Image source: www.cyberphysics.co.uk)

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[21] Williams AR, and GF Williams. 1994. "The invisible image--a tutorial on photography with invisible radiation, Part 2: Fluorescence photography". *Journal of Biological Photography.* 62 (1): 3-19.

[22] Derrick, Stulik and Landry. 1999. 13. "The majority of analytical applications are found in the middle region, extending from 4000 to 500cm- 1 (2.5 to 20µm)."

[23] Verhoeven (2008), 3088.

When radiation strikes the surface of a material, it interacts with that material in three basic ways. The radiation is reflected; is partially absorbed and then emitted at a lower frequency; or is absorbed completely (See Figure 4).[24] Spectroscopy, unlike spectral imaging, is the quantitative measurement of the reflection, absorption, or partial absorption and re-admittance of radiation with a given material. This interaction between the radiation source and an object creates a spectral signature unique to each material.

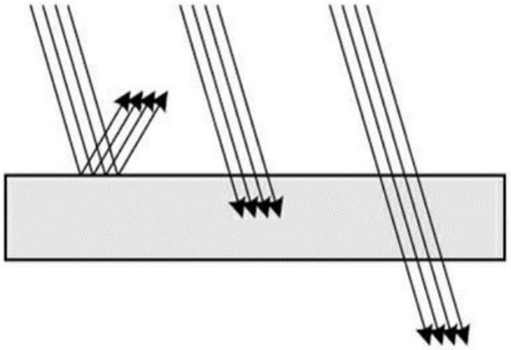

Figure 4: Illustrating the manner in which radiation reacts with matter via reflectance, absorption, or transmittance. (Image source: DOI: 10.7237/sjcea/102)[25]

Of the various useful imaging techniques, thermal imaging, or infrared thermography (passive IRT), is currently used as a non-destructive means to assess areas of water ingress, to identify previous conservation treatments, such as stone cleaning, stone consolidations, as well as provide evidence of biological growth and structural failure.[26]

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[24] Dyer, Verri and Cupitt, 2013. 3.

[25] Shaban, Alaa "Determination of Concrete Properties Using Hyperspectral Imaging Technology: A Review." *Science Journal of Civil Engineering & Architecture*, Volume 2013, Article ID sjcea-102.

[26] Meola, Carosena, Rosa Di Maio, Nicola Roberti, and Giovanni Maria Carlomagno. 2005. "Application of Infrared Thermography and Geophysical Methods for Defect Detection in Architectural Structures". *Engineering Failure Analysis.* 12 (6): 875-892.

Infrared thermography detects and maps variations of emitted infrared radiation by an object. A thermal camera captures the emitted radiation in the mid- and long-infrared regions, and renders a false color image corresponding to a temperature scale.[27] Studies have shown that thermal properties (such as conductivity, diffusivity, effusivity, and specific heat) directly correlate to spectral properties (such as emissivity, absorption, reflection, and transmission).[28] Therefore, infrared thermography provides additional spectral information within the IR range to enhance material characterizations and assist in categorization.

Unlike infrared thermography, which only collects data within the IR region of the electromagnetic spectrum, multispectral imaging can produce images illustrating the reflectance and/or emission of radiation across selected ultraviolet-, visible-, and infrared-wavelength ranges.[29] Images captured and produced by the camera using this technique fall into two categories: reflected-radiation images or emitted (photo-induced luminescence) images.[30] By combining these images, it is possible to characterize and map the surface of an object. [31,32]

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[27] Moropoulou, A., K. C. Labropoulos, E. T. Delegou, M. Karoglou, and A. Bakolas. 2013. "Non-destructive techniques as a tool for the protection of built cultural heritage". *Construction &Building Materials.* 48: 1223.

[28] Moropoulou, Labropoulos, Delegou, Karoglou, and Bakolas. 2013. 1224.

[29] Dyer, Verri, Cupitt (2013), 9.

[30] Ibid, *Figure 1-2*.

[31] Ibid, 10.

[32] Ibid, 4. For example, the CHARISMA Manual describes the process for creating an infrared-reflected false-color image by "…splitting the visible image into its red, green and blue (RGB) components and shifting the red and green components into the green and blue channels respectively. The infrared reflected (IRR) image is inserted into the red channel. The reflective properties of the object in the IR range are described by red colour on the R channel."

While multispectral images are based on broad wavelength segments, hyperspectral imaging is carried out incrementally, using discrete wavelengths over a continuous but narrow electromagnetic range. Each pixel of the hyperspectral image captures a continuous range of the electromagnetic spectrum for a given wavelength window. The resulting hyperspectral image provides a complete spectrum of the object in question. The choice of multispectral versus hyperspectral imaging depends entirely on the sample and type of questions one is trying to answer. By examining how these procedures relate to one another, this thesis seeks to address not only the potential for incorporating these techniques into a documentation campaign, but also to ascertain the breadth and level of accuracy of information obtained for each.

Questions this project will attempt to answer include:

- What type of information does each technique provide?
- Which situations are most appropriate for their use?
- What tools and approaches may be adapted from existing imaging protocols for use in *in-situ* documentation campaigns?
- What are the challenges to and opportunities for integrating this technology into cultural-resource survey and assessment?
- What additional or alternative tools and approaches may be developed or applied to improve the current documentation protocols?

Chapter 1: Tools and techniques

Modern conservation documentation uses analogue survey methods such as field sketching and standard photography as a non-destructive and non-invasive means of mapping sites and monuments. In addition to these traditional documentation techniques, digital imaging is increasingly used in order to augment the fidelity and reproducibility of conservation documentation and assessment projects.[33] Conservators typically rely on illustrative and analytical components to accurately document a site or structure; one a passive form of documentation and the other a physical, or chemical mode of testing. Examples of *in-situ* sample testing include microchemical spot testing and x-ray fluorescence spectroscopy (XRF). Microchemical spot testing is used mainly for the identification of pigments and involves the use of acids and reconstituting bases to quickly and with relative accuracy determine the elemental makeup of pigments through controlled chemical reactions. The XRF spectrometer measures the elemental readout of a sample by way of bombarding a sample with high energy x-rays to excite the sample nuclei and cause fluorescence—this emitted energy in the form of fluorescence is characteristic to each atom and therefore diagnostic.

While the accuracy of physical or chemical sample testing is decidedly high, there is increasingly a strong discouragement of sample testing[34] as contact may damage fragile

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[33] Cecchi, G., L. Pantani, V. Raimondi, D. Tirelli, and R. Chiari. 1996. "Fluorescence LIDAR Technique for the Remote Sensing of Stony Materials in Ancient Buildings [2960-19]" *Proceedings- SPIE the International Society for Optical Engineering.* (2960): 163.

[34] Janssens, Koen H. A., and R. van Grieken. 2004. *Non-destructive microanalysis of cultural heritage materials.* Amsterdam: Elsevier. 1-2. "According to Lahanier et al. [1], the ideal method for analyzing objects of artistic, historic or archaeological nature should be: non-destructive… fast … universal … versatile … sensitive … multi-elemental …"

cultural objects.[35] Several of the more recent documentation methods, including digital survey such as laser scanning, multispectral imaging, and hyperspectral imaging provide avenues for the non-destructive and non-invasive gathering of physical features including color, depth and volume.[36] Going forward, researchers anticipate that projects will incorporate aspects of data capture using several of these approaches and integrate the information into comprehensive platforms capable of showcasing individuated physical and chemical characteristics as "…the physical and chemical characteristics of different urban surfaces are represented in all parts of the visible (VIS), near infrared (NIR), shortwave infrared (SWIR) and thermal infrared (TIR) spectrum."[37] Furthermore, there is a growing demand amongst conservation professionals for cheaper, more portable equipment with widely accessible techniques and procedures.[38]

Each technique mentioned in this study provides different information and therefore, relates to specific questions regarding either the state of a building, or its materials. Documentation campaigns strive to answer fundamental questions such as: What types of materials are present? Are they stable or deteriorating? What is the material distribution across a surface? Does this indicate an original decorative program,

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[35] Chane, Simon, C., A. Mansouri, F.S. Marzani, and F. Boochs. 2013. "Integration of 3D and Multispectral Data for Cultural Heritage Applications: Survey and Perspectives". Image and Vision Computing. 31 (1): 91.

[36] Mohd Nasarudin, Nurul Ezaty, and Shafri, Helmi. 2011. "Development and Utilization of Urban Spectral Library for Remote Sensing of Urban Environment." *Journal of Urban and Environmental Engineering* (JUEE), v.5, n.1, 45. (Doi: 10.4090/juee.2011.v5n1.044056). http://periodicos.ufpb.br/ojs2/index.php/juee/article/view/10337.

[37] Herold, Martin, Dar A Roberts, Margaret E Gardner, and Philip E Dennison. 2004. "Spectrometry for Urban Area Remote Sensing—Development and Analysis of a Spectral Library from 350 to 2400 nm". *Remote Sensing of Environment.* 91 (3-4): 305.

[38] Arroyo-Bishop, Daniel. 1996. *Remote sensing for geography, geology, land planning, and cultural heritage: 23-26 September, 1996, Taormina, Italy*. Bellingham, Wash: Society of Photo-optical Instrumentation Engineers. 139.

or later intervention efforts? How are the materials interacting or affecting one another? Is one material preferentially degrading?

Drawing upon the principles of spectroscopy, spectral imaging is a visual representation of an object's interaction with radiation across the electromagnetic spectrum.[39] Examples such as NMR and IR spectroscopy are used to provide chemical information by breaking down constituent parts of a sample in order to provide feedback concerning its elemental or compositional makeup. Nuclear Magnetic Resonance (NMR) spectroscopy describes the presence and spatial orientation of the functional groups in a sample and in this way assists to confirm the identity of a substance. IR spectroscopy provides the absorbance spectra of functional groups within the IR wavelength region—thereby indicating which functional groups are present. For instance, carbonyl and hydroxyl groups both demonstrate very characteristic and therefore diagnostic absorption bands measuring between 5 to 6.5µm (2000 to 1500cm^{-1}) and 2.5 to 4µm (4000 to 2600cm^{-1}) respectively.

Analysis of spectral images created using radiation sources from across the electromagnetic spectrum provides researchers with even further information pertaining to a material's chemical composition and physical properties.[40] Initially developed for planetary and astronomical remote sensing, spectral imaging has gained popularity over

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[39] Janssens, Koen H. A., and R. van Grieken. 2004. 367.

[40] Ibid. 16. "For area examinations of works of art, five regions of the electromagnetic spectrum are of special interest: radiation in the visible range (400-780nm)…near or long-wave ultraviolet radiation (320-400nm)…near infrared radiation (780-3000nm)…radiation in the intermediate (3-6picometers) and far (6-15picometers) IR are used in IR-thermography… which is useful for conservation of historic buildings and multispectral aerial surveying."

the past few decades and spread to numerous tangential research fields.[41] Specifically, non-invasive imaging techniques will continue to play a key role in the examination and conservation of cultural sites and monuments.[42]

Able to distinguish amongst rock formations in geological survey and in mining operations, remote spectral imaging also provides information relating to a substrate's surface condition. For example, spectral analysis has determined the absorption ranges of salts with "…samples of gypsum crusts have diagnostic absorption features near 1023, 1225, 1457, 1757, 1800, and 2336 nm, whereas halite crusts have diagnostic absorption features near 1442, 1851, 1958, and 2226 nm."[43,44] The non-invasive mapping of materials across a surface also has applications for archaeological survey,[45] non-destructive art conservation practice,[46] and even within the construction industry.[47]

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[41] Liang, Haida. 2012. "Advances in Multispectral and Hyperspectral Imaging for Archaeology and Art Conservation". *Applied Physics A: Materials Science & Processing.*106 (2): 309.

[42] Papadakis, Vassilis, Afrodite Loukaiti, and Paraskevi Pouli. 2010. "A Spectral Imaging Methodology for Determining On-line the Optimum Cleaning Level of Stonework". *Journal of Cultural Heritage.* 11 (3): 325. "To date, research into FTIR (Fourier transform infrared micro-spectroscopy) presents an interesting avenue for investigating heterogeneous cultural materials—specifically, more ancient artifacts."

[43] Howari FM, PC Goodell, and S Miyamoto. 2002. "Spectral Properties of Salt Crusts Formed on Saline Soils". *Journal of Environmental Quality.* 31 (5). 1453.

[44] Dei, Luigi, Marcello Mauro, and Giovanna Bitossi. 1998. "Characterisation of Salt Efflorescences in Cultural Heritage Conservation by Thermal Analysis". *Thermochimica Acta.* 317 (2): 133-140.

[45] Shillito, Lisa-Marie, Matthew J. Almond, James Nicholson, Manolis Pantos, and Wendy Matthews. 2009. "Rapid Characterisation of Archaeological Midden Components Using FT-IR Spectroscopy, SEM–EDX and Micro-XRD". *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy.* 73 (1): 133-139.

[46] Amat, Anna, Costanza Miliani, and Brunetto Giovanni Brunetti. 2012. "Non-invasive multi-technique investigation of artworks: A new tool for on-the-spot data documentation and analysis". *Journal of Cultural Heritage.* 14 (1): 23-30.

[47] Herold, Martin, Dar A Roberts, Margaret E Gardner, and Philip E Dennison. 2004. "Spectrometry for Urban Area Remote Sensing—Development and Analysis of a Spectral Library from 350 to 2400nm". *Remote Sensing of Environment.* 91 (3-4): 304-319

Recently, for example, spectral analysis has been implemented as a means for *in-situ* strength testing of concrete.[48]

Through research and information gathered during conversations with specialists such as Dr. John Delaney at the National Gallery in Washington, DC, this paper attempts to parse out the most salient techniques for documentation in an attempt to address concepts regarding the spectral imaging of building facades and materials *in-situ*. First, the individual techniques will be described in greater detail, followed by a discussion regarding how each technique applies to the materials under investigation. After establishing the procedural guidelines and data acquisition techniques, this investigation will then address limitations and constraints inherent with each proposed approach. While not exhaustive in scope, these procedures represent viable data collection tactics worthy of consideration. Although distinct in their approach, the various techniques discussed, such as thermal and spectral imaging are representative of the most portable and user-friendly versions for *in-situ* examination available today.[49]

1.1 Infrared thermography

Thermal imaging, known as infrared thermography, is the radiometric process of mapping emitted radiation within part of the infrared wavelength region as a function of

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[48] Brook, Anna. 2012. "Reflectance Spectroscopy as a Tool to Assess the Strength of High- Performance Concrete in-situ". *Journal of Civil Engineering and Construction Technology.* 3 (7). See also: Shaban, Alaa. 2013. “Determination of Concrete Properties Using Hyperspectral Imaging Technology: A Review.” Science Journal of Civil Engineering & Architecture, Volume 2013, Article ID sjcea-102, 11 Pages. DOI: 10.7237/sjcea/102

[49] MacDonald, L. W. 2006. *Digital heritage: applying digital imaging to cultural heritage*. Amsterdam: Elsevier. See pages 385-386 for detailed description of *in-situ* photo-capture process.

temperature.[50] Infrared thermography is the imaging process used for collecting spectral information from the longwave (LWIR) region, covering a wavelength range from approximately 7,500-15,000nm, though specialized thermal cameras such as the InGaAs and the InSb are able to measure beyond the 15,000nm wavelength range.

The relative power, or efficiency, of a material surface to emit thermal radiation is known as emissivity.[51] By evaluating emissivity levels "…differences in temperatures may lead to conclusions about the state of conservation of the materials and structures,[52] and consequently, assist experts to take suitable actions if necessary."[53] Since emissivity values differ based on unique physical and chemical properties, this enables researchers to distinguish among materials in a qualitative form of assessment known as passive thermography (See Figure 5).[54] According to the Forward Looking IR (FLIR) systems ThermaCAM P640 user manual "… materials and surface treatments exhibit emissivity ranging from approximately 0.1 to 0.95 … the emissivity of metals is low—only increasing with temperature. For non-metals, emissivity tends to be high, and decreases with temperature."[55]

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[50] FLIR Camera manual. Publ. No. 1558550 (January 16, 2007), 249-250. "…the near infrared (0.75-3µm), the middle infrared (3-6 µm), the far infrared (6-15 µm) and the extreme infrared (15-100 µm)..."

[51] FLIR Camera manual, 239. See also, Avdelidis, N.P., and A. Moropoulou. 2003. "Emissivity Considerations in Building Thermography". *Energy and Buildings.* 35 (7): 663-667.

[52] Tavukcuoglu, A, A Duzgunes, E Canersaltik, and S Demirci. 2005. "Use of IR thermography for the assessment of surface-water drainage problems in a historical building, Ağzıkarahan (Aksaray), Turkey". *NDT & E International.* 38 (5): 402-410.

[53] EuroMed and Marinos Ioannides. 2012. *Progress in cultural heritage preservation 4th International Conference, EuroMed 2012: Limassol, Cyprus, October 29-November 3, 2012: proceedings*. Heidelberg: Springer. http://site.ebrary.com/id/10640337.

[54] Avdelidis, N.P., and A. Moropoulou. 2003. "Emissivity Considerations in Building Thermography". *Energy and Buildings.* 35 (7): 663.

[55] FLIR Camera manual (2007), 239.

The FLIR ThermaCAM P640 camera, on loan from New York University's Institute of Fine Arts Conservation Center with a spectral range of 7.5 to 13µm (640 x 480 IR resolution), detects the infrared radiation emitted from an object, converts the radiation to a temperature, and displays the temperature distribution as a false color image. The radiation captured by the camera sensor is typically the sum of: emitted object radiation transmitted through the atmosphere, emitted atmospheric radiation, and the reflected radiation transmitted through the atmosphere.[56] Thermographic imaging is widely used in industrial applications to inspect electrical and mechanical equipment and also for various building applications such as examining insulation, moisture mapping,[57] surface discontinuities[58] such as cracks and abnormalities[59] and consolidation mapping.[60,61]

Taken from a distance without the need for touching or disturbing the object, the captured image is a thematic matrix of pixels, which corresponds to an adjoining false-color temperature scale in the camera view finder. These images relay information regarding physical characteristics of materials which may at first glance, appear identical. For example, figure 5 illustrates material differentiation between limestone urns

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[56] Ibid.

[57] Avdelidis, N. 2003. "Detection of Water Deposits and Movement in Porous Materials by Infrared Imaging". *Infrared Physics & Technology.* 44 (3): 183-190.

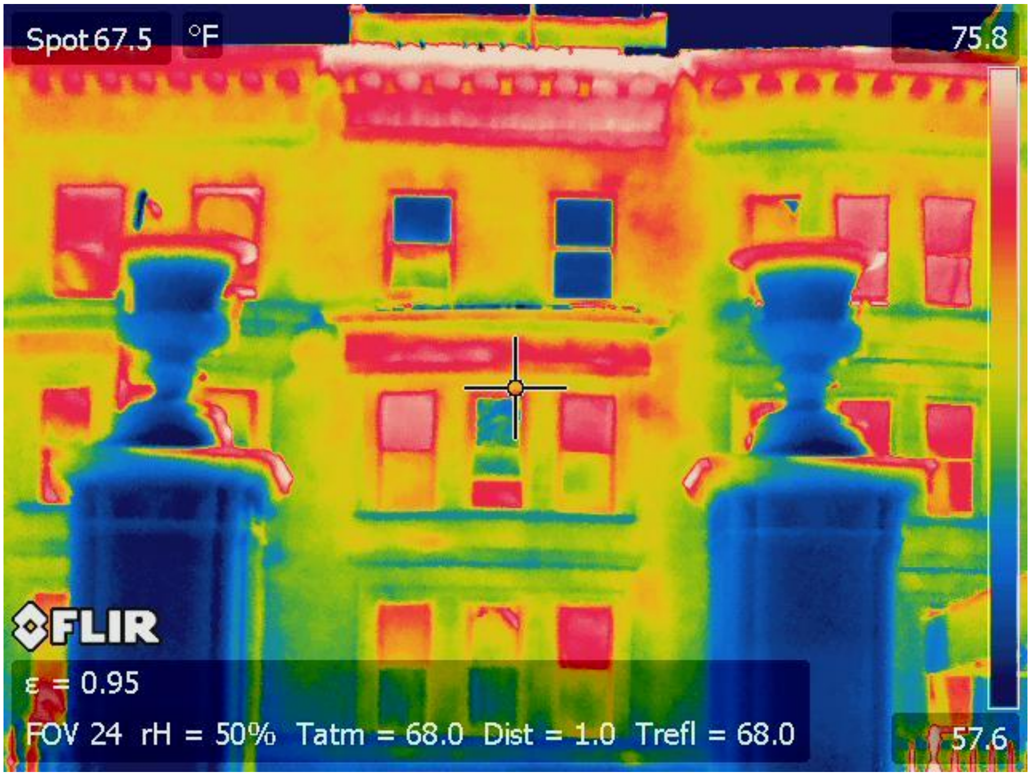
[58] Bisegna, F., D. Ambrosini, D. Paoletti, S. Sfarra, and F. Gugliermetti. 2014. "A qualitative method for combining thermal imprints to emerging weak points of ancient wall structures by passive infrared thermography - A case study". *Journal of Cultural Heritage.* 15 (2): 199-202.

[59] Paoletti, Domenica, Dario Ambrosini, Stefano Sfarra, and Fabio Bisegna. 2013. "Preventive thermographic diagnosis of historical buildings for consolidation". *Journal of Cultural Heritage.* 14 (2): 116-121.

[60] Avdelidis, N. 2004. "Applications of Infrared Thermography for the Investigation of Historic Structures". *Journal of Cultural Heritage.* 5 (1): 119-127.

[61] Grinzato, E., P.G. Bison, and S. Marinetti. 2002. "Monitoring of Ancient Buildings by the Thermal Method". *Journal of Cultural Heritage.* 3 (1): 21-29.

decorating the south entrance gates of Columbia University in the foreground and a brick building façade located on 114th St. in the background. The different emissivity values represented in the false color image (Fig. 5) readily distinguish the blue limestone urns from the yellowish green brick, and also from the red metal cornice of the building façade. This is because the various materials shown each emit infrared radiation at different frequencies based upon their physical and chemical makeup at different temperatures. As one may expect, the metal cornice of the building clearly stands out against the remaining brick façade. What is not shown is the limestone urns are actually imaged predominately in shadow, while the materials corresponding with the building across the street are still bathed in afternoon sunlight.



Figures 5: FLIR ThermaCam P640 image demonstrating emissivity differentiation between limestone urns located at the south entrance gates of Columbia University in the foreground and brick building façade on 114th St. in the background.

1.2 Multispectral imaging

While infrared thermography focuses on one particular wavelength region, multispectral imaging using modified DSLR digital cameras is a method of observing the response of materials to selected wavelengths via specific radiation sources. Wavelength regions are isolated by filters, which allow for some features not readily apparent to be made visible and distinguished.

> Multispectral and hyperspectral imaging collect images of an object in a series of spectral windows… It was first applied for qualitative band to band comparison in order to identify areas of different material composition natural degradation of material, past conservation intervention, preparatory sketches, and quantitatively for improved precision in colour measurement…As a non-invasive imaging technique, it has the advantage over invasive techniques in that investigations can be carried out on any object (even on intact and fragile ones where samples cannot be taken) and anywhere on an object.[62]

This method of spectral data capture is particularly useful for qualitatively assessing and characterizing applied surface coatings such as paintings, frescoed halls, or decorated monuments.[63] For example, the MSI process is considered to be more or less diagnostic in cases testing for the presence of Egyptian Blue pigment using Visible Induced Luminescence (VIL). While this technique is useful for field capture, external *in-situ* shooting conditions vary based on the environment and incoming radiation levels therefore, careful advanced planning is required.[64]

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[62] Liang, Haida. 2012. 309.

[63] Blazek, J.; Soukup, J.; Zitova, B.; Flusser, J.; Tichy, T.; Hradilova, J. 2013. “Low-cost Mobile System for Multispectral Cultural Heritage Data Acquisition”. *Digital Heritage International Congress* (Digital Heritage), (Volume: 1): 73. (Doi: 10.1109/DigitalHeritage.2013.6743715).

[64] Rogerio-Candelera, M.A., V. Jurado, L. Laiz, and C. Saiz-Jimenez. 2011. "Laboratory and *in-situ* assays of digital image analysis based protocols for biodeteriorated rock and mural paintings recording". *Journal of Archaeological Science.* 38 (10): 2571.

Using a modified DSLR camera and sunlight as a radiation source, one may utilize the MSI approach to characterize surface coatings on buildings. It is best to start with the 1,000nm filter and proceed incrementally to narrower ranges using, for example 830nm, 750nm, 720nm, and 680nm filters. Imaging in regions of the IR beyond the capabilities of a modified digital camera (e.g. wavelengths over 1,000nm), requires the use of either a specialized IR camera, such as an InGaAs or InSb camera. For examples of equipment and wavelength ranges commonly used for MSI investigation, see Table 1 below.

Table 1: Cameras and filters used for spectral imaging corresponding to particular wavelength coverage

Equipment	**Wavelength range**	**Use**
Nikon digital camera with IR-blocking filter removed	350 – 1100 nm	Permits greater control over imaging wavelength regions under investigation
UV/IR cut visible band-pass filter (e.g. IDAS_UIBAR)	Cuts out UV below 390nm and IR above 700nm	Visible-Reflected Imaging (VIS) Captures VIS range
680nm IR filter	Absorbs IR up to 680nm	Blocks IR light down to 680nm
720nm IR filter	Absorbs IR up to 720nm	Blocks IR light down to 720nm
750nm IR filter	Absorbs IR up to 750nm	Blocks IR light down to 750nm
830 IR filter (e.g. Schott RG830)	Absorbs IR up to 830nm	Blocks IR light down to 830nm
1,100 IR filter	Absorbs IR up to 1,100nm	Blocks IR light down to 1100nm
B&W 092 IR filter	Blocks VIS up to 650nm, permits 50% radiation from 650 to 700nm, and permits 90% radiation from 730 to 2,000nm IR	Used for IR photography
Fiber-optic reflection spectrometer (FORS)	350- 2500nm	Obtain baseline spectroscopy readings
Hyperspectral camera 1	400-950 nm	Captures Visible to NIR
Hyperspectral camera 2	960-1660nm	Captures NIR to SWIR
Hyperspectral camera 3	1,000-2500nm	Captures NIR to SWIR
ThermaCam P640 FLIR camera	750-1,300nm	Thermal imaging measuring NIR
FLIR SC6100 Indium Antimonide (InSb) camera	3,000-5,000nm or 1,500-5,000nm	Thermal imaging measuring SWIR & MIR
FLIR SC6700 Indium Antimonide (InSb) camera	(MWIR): 3,000-5,000nm or 1,000-5,000nm/ (LWIR): 7,500-9,500nm	Thermal imaging measuring NIR, SWIR, MWIR & LWIR
FLIR SC6800 Indium Antimonide (InSb) camera	3,000-5,000nm or 1,500-5,000nm	Thermal imaging measuring MWIR or SWIR

1.3 Hyperspectral imaging

Whereas multispectral imaging utilizes broader wavelength regions, hyperspectral imaging documents an object’s spectral fingerprint in ten or fewer, nanometer (nm) increments covering multiple spectral bands.[65] This approach enables researchers to construct a more detailed, and, therefore, diagnostic spectral readout of an object and its constituent physical and chemical components by generating spectral information for each pixel imaged by the hyperspectral camera. In this way, each pixel is a multidimensional vector and “Radiometric calibration of images acquired in numerous visible/infrared spectral bands can be used to produce quantitative results, thus *transforming* the imaging process into *imaging spectroscopy*, which can provide chemical information about materials.”[66]

At the National Gallery in Washington, DC, senior imaging specialist Dr. John Delaney and his team use a portable fiber-optic reflection spectrometer and modified hyperspectral cameras to quantitatively measure overlapping wavelength ranges in order to provide diffuse reflectance information of samples. The fiber-optic reflection spectrometer (FORS) is a portable remote sensing machine used to “…validate the spectra obtained from the hyperspectral cameras and referred to as “FORS reference spectra”.”[67] Fully portable, battery powered and of durable construction, the FORS device

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[65] Ricciardi, Paola, John K. Delaney. 2011. “Combining Visible and Infrared Imaging Spectroscopy with Site Specific, in-situ Techniques for Material Identification and Mapping”. *Revista de Historia da Arte*. Serie W (No 1): 257.

[66] Ibid, 254.

[67] Delaney JK, JG Zeibel, M Thoury, R Littleton, M Palmer, KM Morales, de la Rie ER, and A Hoenigswald. 2010. "Visible and Infrared Imaging Spectroscopy of Picasso's Harlequin Musician: Mapping and Identification of Artist Materials in-situ". Applied Spectroscopy. 64 (6):588. See also ibid, 587. “The spectrometer operates from 350 nm to 2500nm with a spectral sampling of 1.4 nm from 350 to

fits easily into a backpack and operates wirelessly or when tethered to a computer, thus enabling researchers to take readings in the field.[68, 69] Measuring a wavelength range from 350-2500nm, the fiber-optic reflection spectrometer creates apparent reflectance graphs by averaging 32 spectral cycles for each sample— this information is then used to identify specific chemical features characteristic of a particular material.[70]

The three modified hyperspectral cameras cover ranges 400 to 950nm, 960 to 1660nm, and 1000 to 2500nm respectively.[71] Since none of these hyperspectral cameras are portable, a specially designed easel supports and moves each sample piece for scanning according to coordinates programmed in by the operator (See Figure 6). This type of hyperspectral-imaging system is known as spatial scanning.

There are several types of imaging systems used in hyperspectral imaging: mosaic; multilayer; filter wheel; interferometer; and scanning. The mosaic format uses a common digital camera with a small filter covering the camera sensor; colors are not aligned and the operator must interpolate the RGB values for each processed pixel. The multilayer format uses two radiation detectors and an overlapping filter. The filter wheel

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1000 nm and 2 nm from 1000 to 2500 nm. The spectral resolution at 700 nm is 3 nm and at 1400 and 2100 nm is 10 nm."

[68] Swayze, Gregg A. 2004. *Preliminary report on using imaging spectroscopy to map ultramafic rocks, serpentinites, and tremolite-actinolite-bearing rocks in California*. [Reston, Va.]: U.S. Geological Survey. http://purl.access.gpo.gov/GPO/LPS54614. 7.

[69] "Technical Guide: Reflectance Materials and Coatings". Labsphere. www.labsphere.com: 6, 8. See also: "Standard Practice for Angle Resolved Optical Scatter Measurements on Specular Diffuse Surfaces," ASTM Standard: E1392-90.

[70] Ricciardi, Paola, John K. Delaney. 2011. 256. "…the 350-2500nm range, allowing access to the short-wave infrared region…yields important information for the identification of certain materials such as azurite (easily recognizable by two absorption bands at about 2285 and 2352 nm), lead white, and gypsum."

[71] Conversation with Dr. John Delaney at the National Gallery in Washington, DC on March 25, 2014.

system is a broad band sensor affixed to a rotating filter wheel with upwards of ten filters between the camera sensor and the source of incoming radiation. An interferometer system works by way of a moving mirror to determine wavelength. Finally the scanning, or ‘push broom’ system, spatially scans an object one line at a time.

Once the object is fully scanned, the spectral data is collated into a reflectance image cube.[72] These cubes are representative of the vertical slices of pixelated data generated by the cameras for each wavelength increment. Spectral resolution refers to those wavelengths to which a sensor is sensitive and describes the ability of a sensor to define minute wavelength intervals. There are two main components which are considered in spectral resolution: first, the number of wavelength bands or channels used and second, the width of each wavelength band. The larger number of wavelength bands used and the narrower increments measured for each wavelength band mean a higher image resolution and more comprehensive spectral data obtained for the object.

Figure 6: View of sample board on programmable easel and cameras at the National Gallery of Art, Washington, DC.

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[72] Delaney JK, JG Zeibel, M Thoury, R Littleton, M Palmer, KM Morales, de la Rie ER, and A Hoenigswald. 2010. "Visible and Infrared Imaging Spectroscopy of Picasso's Harlequin Musician: Mapping and Identification of Artist Materials in-situ". Applied Spectroscopy. 64 (6): 587.

Chapter 2: Spectral imaging and materials

In any *in-situ* documentation campaign, not only are the materials imaged important to understand, but environmental constraints also play a major role in determining the appropriate course of action. Important considerations include familiarization with topography, equipment requirements, as well as atmospheric conditions. Valid constraints associated with exterior spectral imaging campaigns are phenomena known as atmospheric windows, atmospheric scattering, and water absorption bands.

Atmospheric windows refer to specific wavelength regions, or holes in the atmosphere which permit radiation through onto the earth's surface. The ability of the atmosphere to allow radiation to pass through is known as transmissivity. In order to perform any type of radiometric or spectral imaging, researchers must stay within the boundaries of one or more of these transmissivity windows. There are four major windows: one region in the visible to the IR from 400 to 2,000nm; another in the IR around 3,000nm; a third, also in the IR at approximately 5,000nm; and the last broad region extending from 8,000 to 14,000nm.[73] While atmospheric windows permit desired radiation through, the radiation then comes into contact with the phenomenon known as atmospheric scattering. A form of particle interference, there are three main types of atmospheric scattering: Rayleigh, when radiation is scattered by smaller particles; Mie, when radiation is scattered by atmospheric particles of a similar size; and non-selective

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[73] Bertrand, Loïc, Laurianne Robinet, Mathieu Thoury, Koen Janssens, Serge X. Cohen, and Sebastian Schöder. 2012. "Cultural Heritage and Archaeology Materials Studied by Synchrotron Spectroscopy and Imaging". *Applied Physics A.* 106 (2): 377-396.

scattering, when the disrupting particles are larger than the in-coming radiation (i.e. water droplets).[74] Finally, there exist water absorption bands at approximately 1.4µm and 1.9µm which act in much the same way as atmospheric windows, forming veritable dead-zones prohibiting radiation to pass through and thus negating any spectral readings.[75]

Additionally, researchers must be cognizant that the reflectance data of any imaged materials may differ slightly from standard database values due to factors such as: moisture content, the angle of incidence, surface texture,[76] and distance between the camera and the object.[77] Inherent textural differences based upon rock formation and surface polish, must be taken into account when comparatively analyzing spectra as variations in surface conditions directly correlate to variations in emissivity readings.[78] As researchers Johnson, Grundy, and Shepard explain: “Laboratory spectroscopy of dust coatings demonstrate that thin (<100 µm) layers can effectively obscure the spectral signature of underlying materials in the visible and infrared…”[79] Finally, when analyzing spectral information, one must bear in mind that band frequency, shape, and intensity of

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[74] Savage, Stephen Howard, Thomas Evan Levy, and Ian W. Jones. 2012. "Prospects and problems in the use of hyperspectral imagery for archaeological remote sensing: a case study from the Faynan copper mining district, Jordan". *Journal of Archaeological Science.* 39 (2): 411-412.

[75] EuroMed 2012, and Marinos Ioannides. 2012. *Progress in cultural heritage preservation 4th International Conference, EuroMed 2012: Limassol, Cyprus, October 29-November 3, 2012: proceedings*. Heidelberg: Springer. http://site.ebrary.com/id/10640337.

[76] Osterloo, M.M., V.E. Hamilton, and F.S. Anderson. 2012. "A Laboratory Study of the Effects of Roughness on the Thermal Infrared Spectra of Rock Surfaces". *Icarus.* 220 (2): 404-426.

[77] Armesto-González, Julia, Belén Riveiro-Rodríguez, Diego González-Aguilera, and M Teresa Rivas-Brea. 2010. "Terrestrial laser scanning intensity data applied to damage detection for historical buildings". *Journal of Archaeological Science.* 37 (12): 3041.

[78] NDTMS (Symposium), and O. Buyukozturk. 2013. *Nondestructive testing of materials and structures proceedings of NDTMS-2011, Istanbul, Turkey*. Dordrecht: Springer. http://dx.doi.org/10.1007/978-94-007-0723-8. 92.

[79] Johnson, Jeffrey R., William M. Grundy, and Michael K. Shepard. 2004. "Visible/near-infrared Spectrogoniometric Observations and Modeling of Dust-Coated Rocks". *Icarus.*171 (2): 546-547.

curves are not always diagnostic for individual materials, but rather point to general characteristics and therefore must be utilized in conjunction with alternate forms of testing or analysis.

Using information gleaned from the NASA ASTER Spectral Library Version 2.0 website,[80] in conjunction with sample analysis run at the National Gallery, some conclusions may be drawn regarding the diagnostic spectral ranges of common building materials such as stone, metal, brick, terra cotta, and wood. This information will provide a baseline for comparison with future *in-situ* research projects.

2.1 Stone

Two common groupings of building stones are carbonates, such as limestone or marble, and silicates, such as sandstone and granite. Carbonates exhibit an absorbance region of 1,600 to 2,550nm and therefore are readily visible within the spectral range covered using the fiber optic reflection spectrometer (FORS) (see Figures 7 & 8).[81] This is corroborated by the spectral information taken from the ASTER database which covers a much wider wavelength region (1 to 14µm) and the fiber optic reflection spectrometer (FORS) used at the National Gallery measuring apparent reflectance from 350 to 2500nm. Thus, as demonstrated in the limestone sample graph shown in Figure 8, the FORS narrowly captures the diagnostic region for this material. A similar absorbance trend is noted for marble samples measured and compared with ASTER database spectra. Marble, another example of a carbonate rock, also demonstrates an absorbance range

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[80] Baldridge, A. M., S.J. Hook, C.I. Grove and G. Rivera, 2009. The ASTER Spectral Library Version 2.0. Remote Sensing of Environment, vol. 113, pp. 711-715. http://speclib.jpl.nasa.gov/

[81] Gaffey, Susan Jenks. 1984. *Spectral reflectance of carbonate minerals and rocks in the visible and near infrared (0.35 to 2.55[mu]m) and its applications in carbonate petrology*. [Washington, D.C.]: [National Aeronautics and Space Administration].

between 1,600 to 2,550nm (see Figures 9 and 10) again confirming the ability of the FORS system to confirm diagnostic absorbance regions for carbonate materials. This correlation works to greater or lesser degrees when comparing the spectral absorbance fingerprint regions of other building materials catalogued in ASTER to those spectra measured with the FORS.

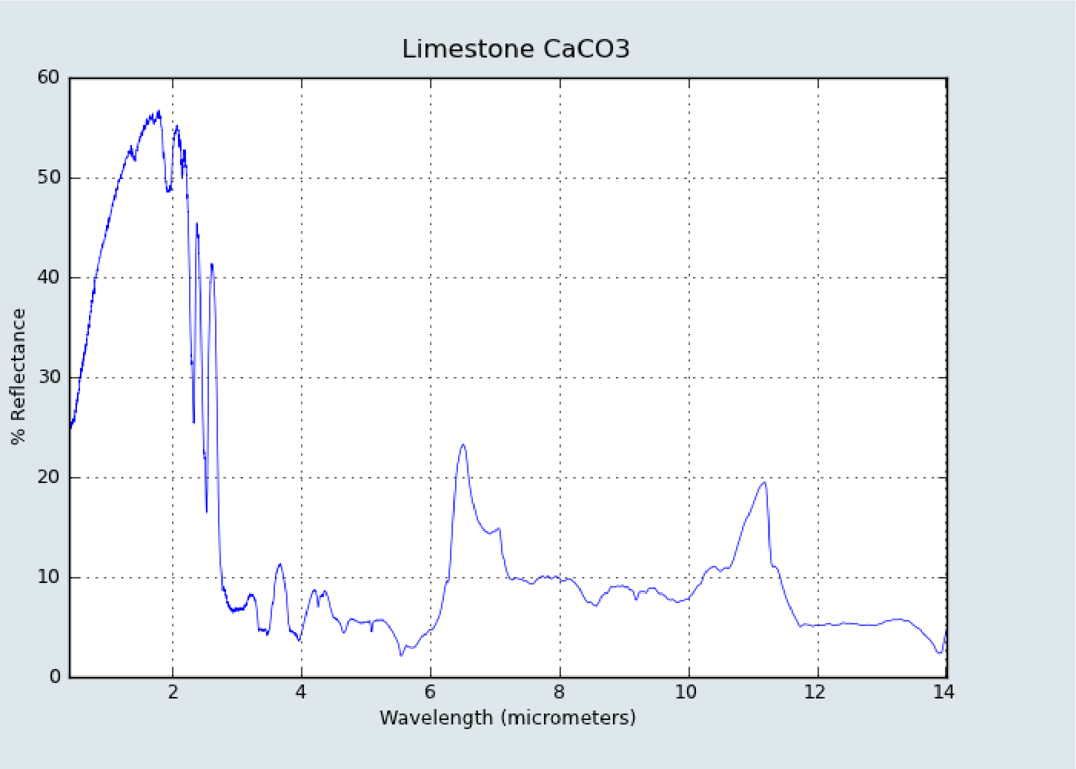

Figure 7: NASA ASTER database spectral reflectance curve for limestone.
(Image source: http://speclib.jpl.nasa.gov/search-1/resultsdisplay3)

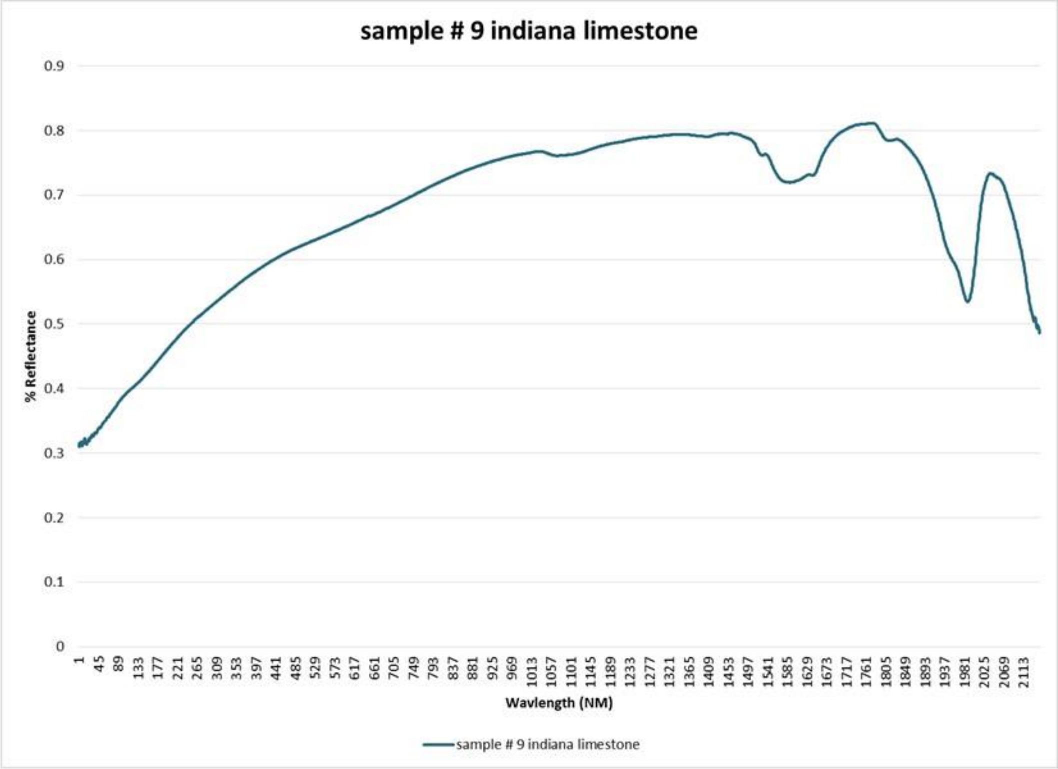

Figure 8: FORS spectrometer reading taken on March 25, 2015 at the National Gallery in Washington, DC for water saw cut Indiana limestone sample.

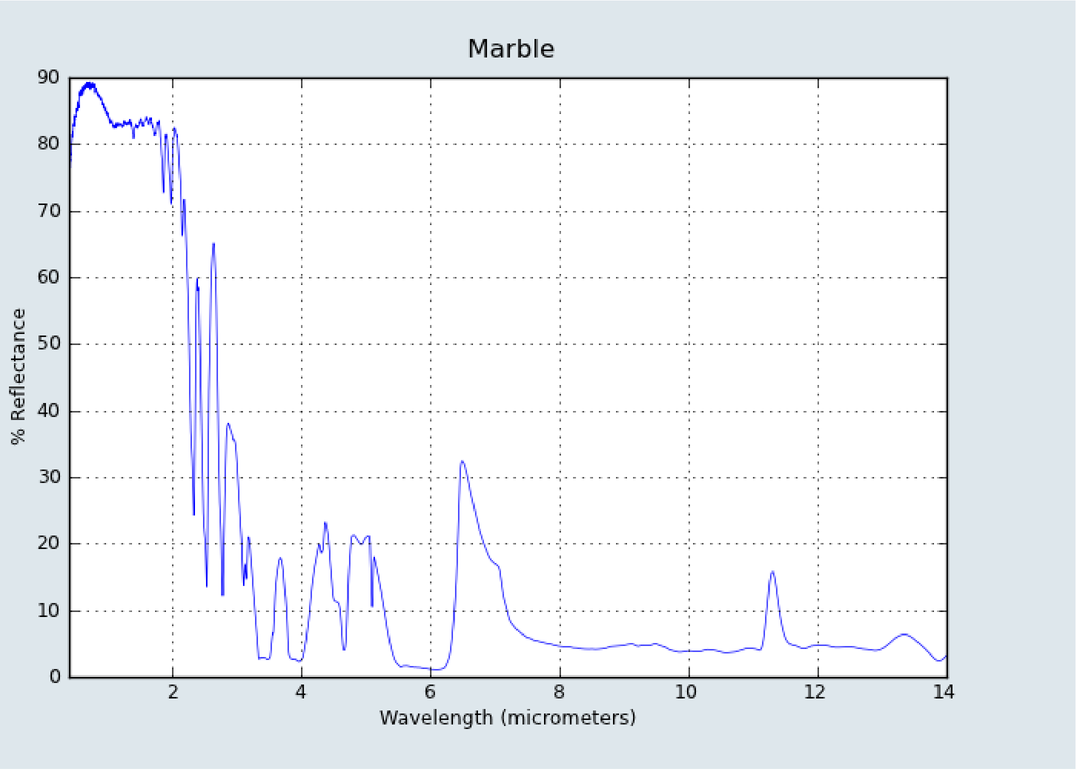

Figure 9: NASA ASTER database spectral reflectance curve for marble.
(Image source: http://speclib.jpl.nasa.gov/search-1/resultsdisplay3)

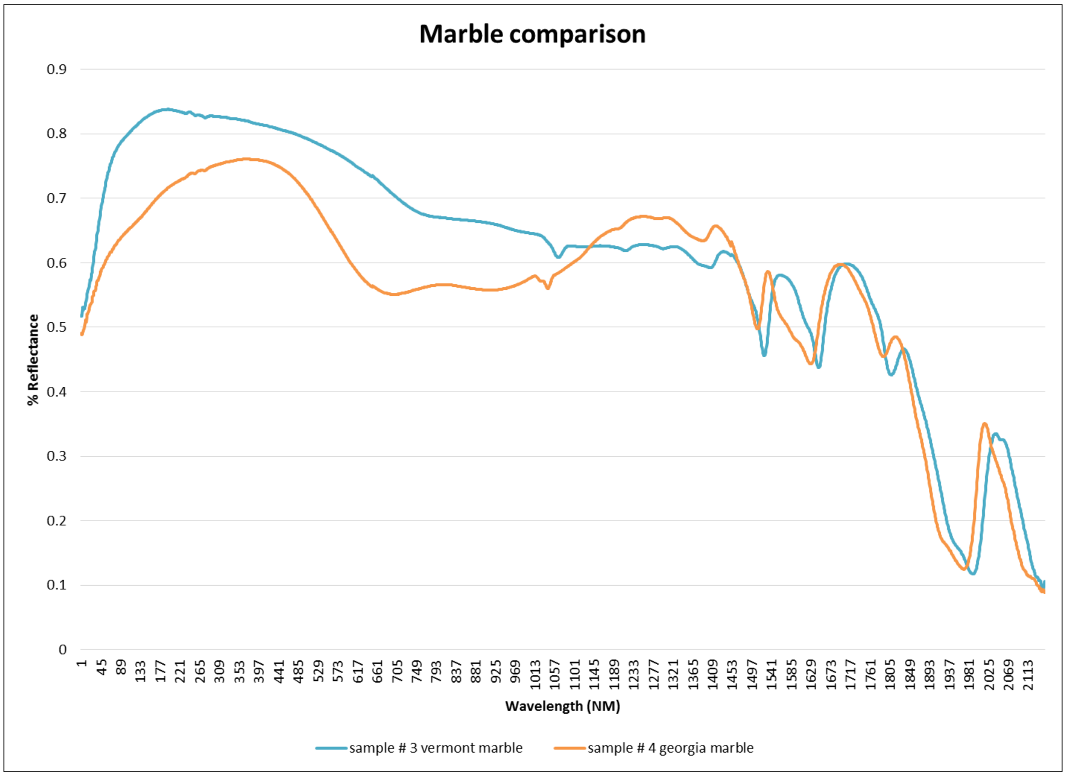

Figure 10: FORS spectrometer reading taken on March 25, 2015 at the National Gallery in Washington, DC spectral comparison of Georgia and Vermont marble samples.

Silicates make up the largest group of minerals and contain silicon and oxygen frequently in the form of SiO_4^{-4}—this group includes granites, terra cotta, and brick materials (See Figures 11, 12, and 13). In the case of silicates, the ASTER database indicates a fingerprint region corresponding to approximately 2500 to 3500nm, yet sample readings taken with the FORS only extend to 2113nm and thus, narrowly miss a crucial diagnostic region (See Figures 14, 15, and 16).

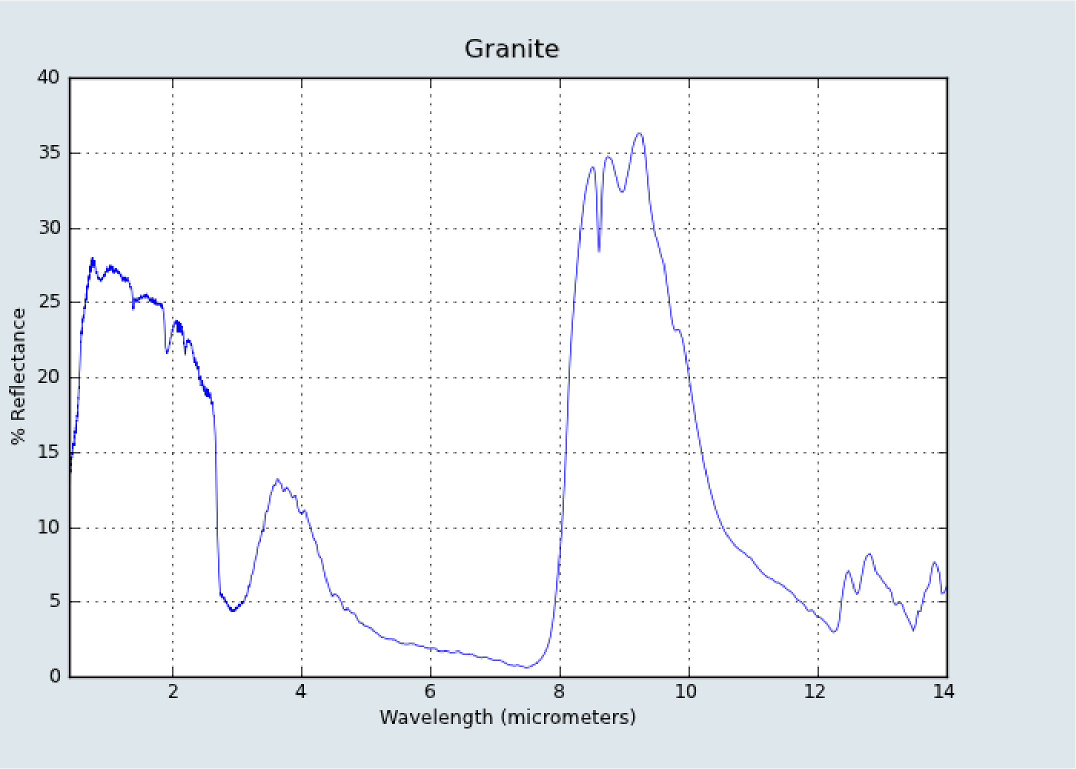

Figure 11: NASA ASTER database spectral reflectance curve for granite.
(Image source: http://speclib.jpl.nasa.gov/search-1/resultsdisplay3)

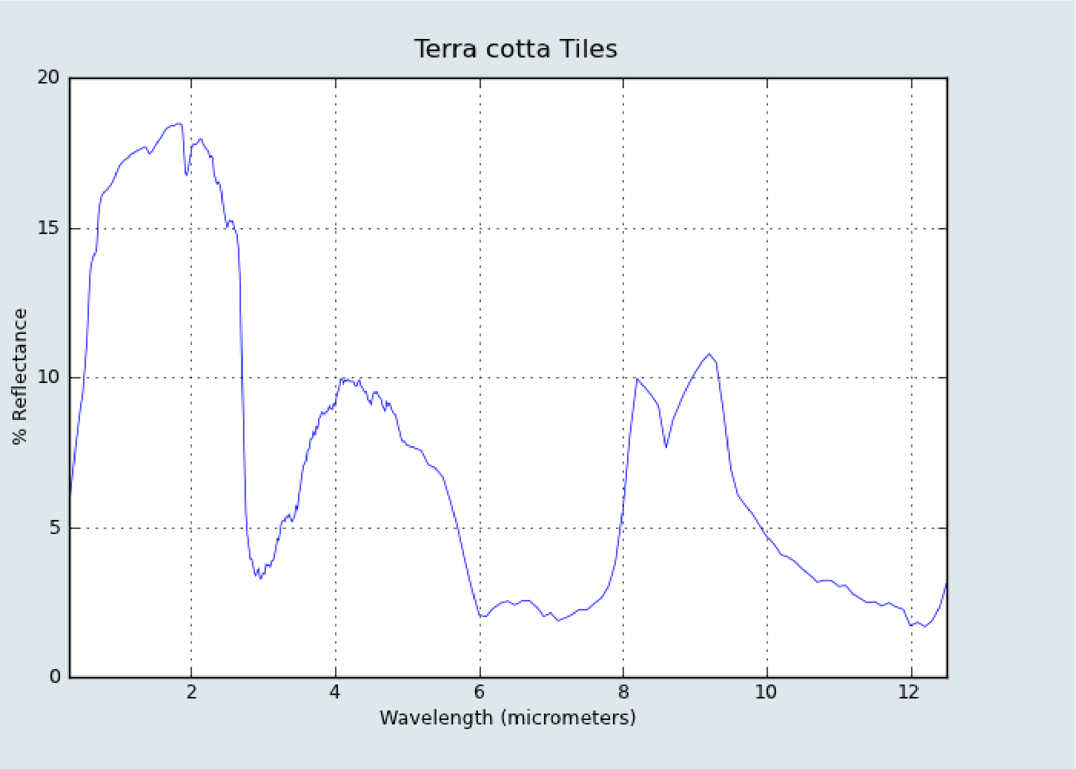

Figure 12: NASA ASTER database spectral reflectance curve for terra cotta.
(Image source: http://speclib.jpl.nasa.gov/search-1/resultsdisplay3)

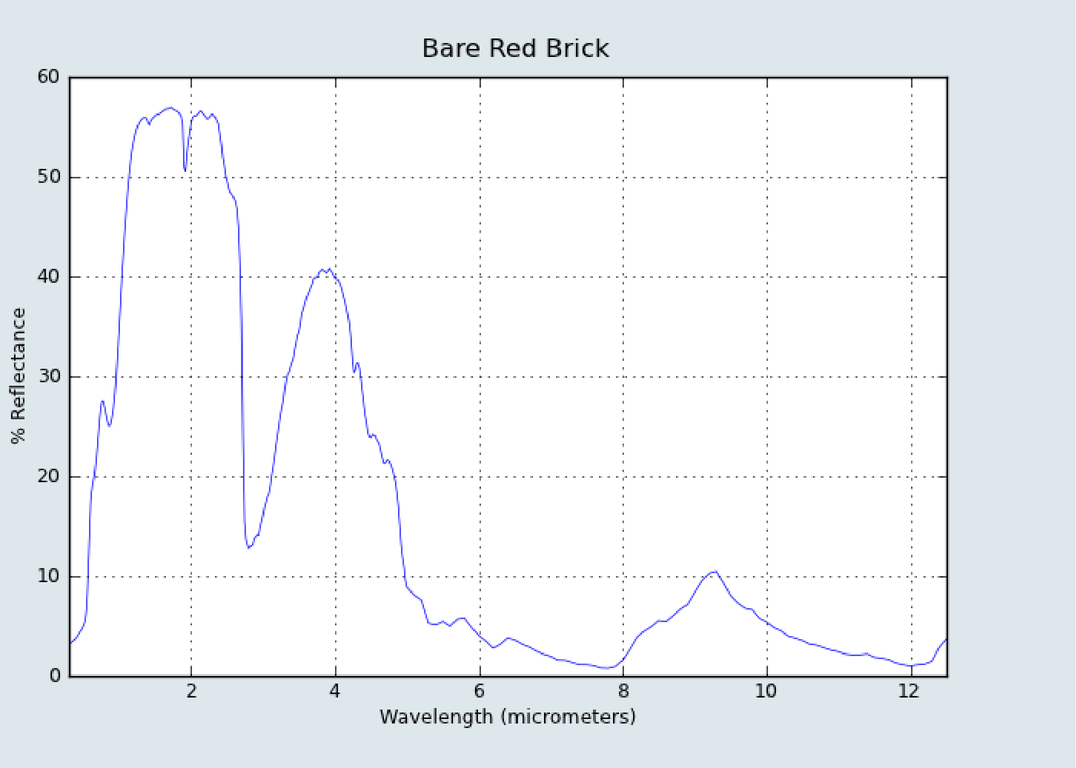

Figure 13: NASA ASTER database spectral reflectance curve for brick.
(Image source: http://speclib.jpl.nasa.gov/search-1/resultsdisplay3)

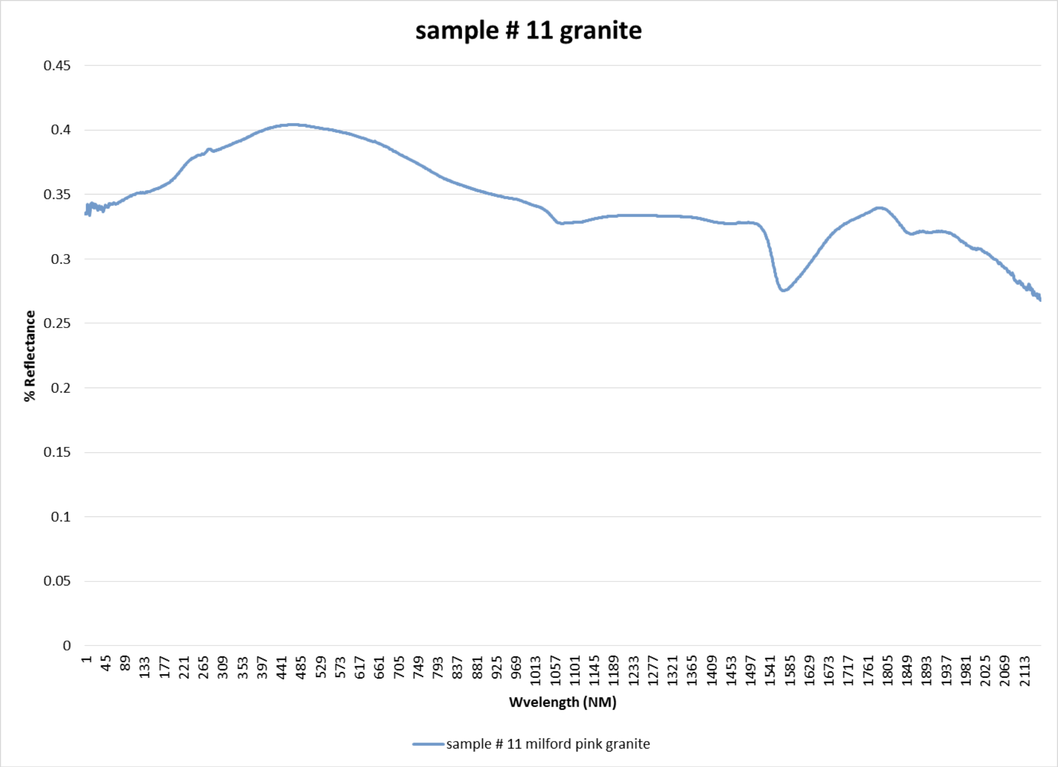

Figure 14: FORS spectrometer reading taken on March 25, 2015 at the National Gallery in Washington, DC spectral comparison of granite.

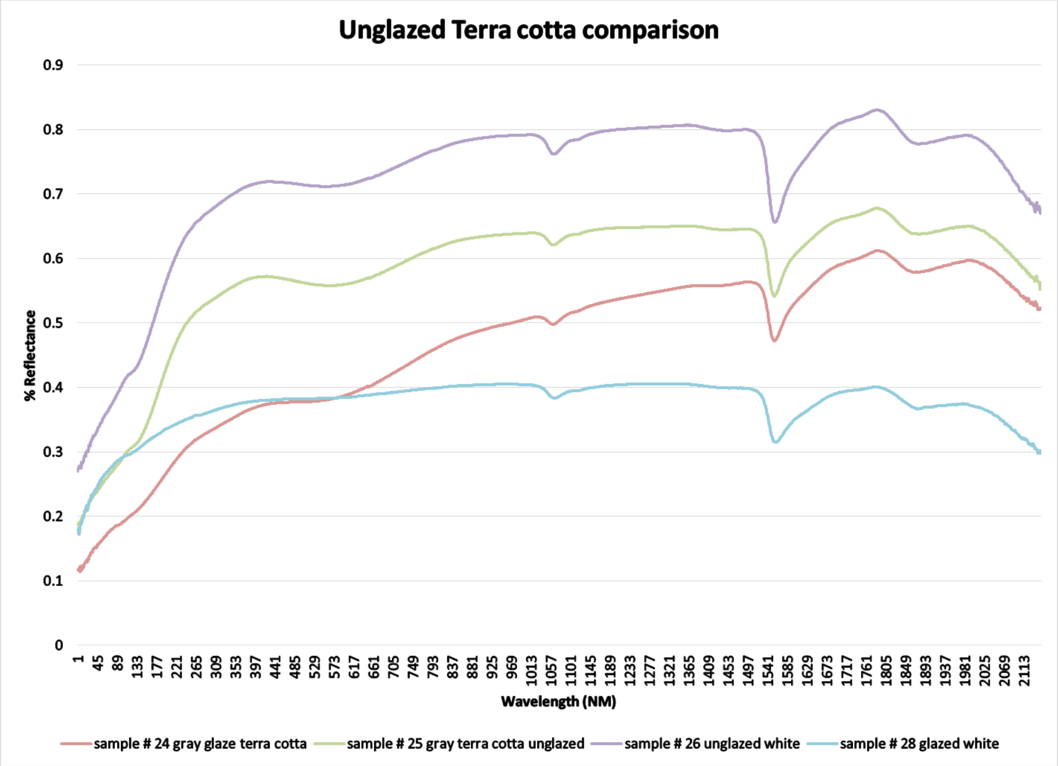

Figure 15: FORS spectrometer reading taken on March 25, 2015 at the National Gallery in Washington, DC spectral reflectance curve comparing unglazed terra cotta.

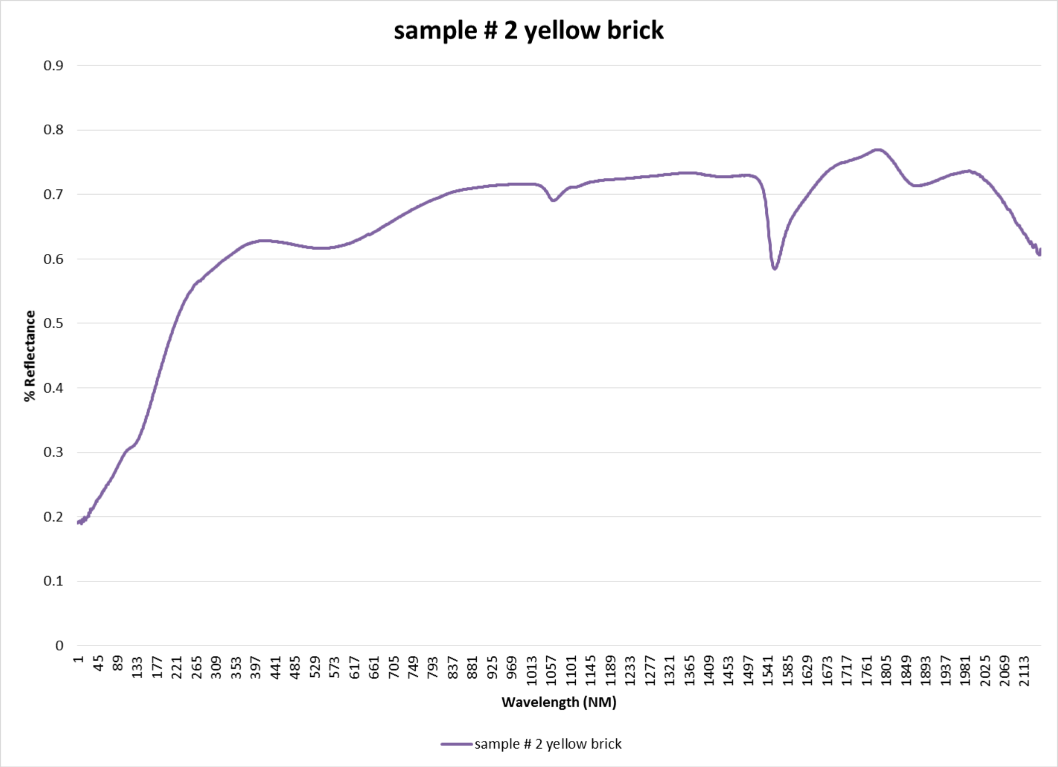

Figure 16: FORS spectrometer reading taken on March 25, 2015 at the National Gallery in Washington, DC spectral reflectance curve of yellow brick.

2.2 Metal

Metals present an interesting challenge in terms of defining broad characterization regions. As seen in thermal imaging examples, metals are highly responsive to fluctuations in temperature (see Figures 17, 18 & 19), yet vary greatly amongst one another with regard to diagnostic spectral absorbance ranges.

Samples, such as galvanized steel (Figure 20) exhibit a diagnostic spectral region from approximately 875 to 910nm, indicating the possibility for documentation using a standard MSI formatted digital camera and band-pass filters. It should be noted that iron metals exhibit a tell-tale absorbance spike around 780nm.[82] However, metals, such as aluminum, offer no such discernible fingerprint region (Figure 21), and fingerprint regions for copper samples range anywhere from 2100 to 2600nm (see Figure 22). It is for this reason that further cross reference with art-conservation multispectral-imaging protocols may prove useful to establish parameters for industrial metal analysis.

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[82] Conversation with Dr. John Delaney at the National Gallery in Washington, DC on March 25, 2014.

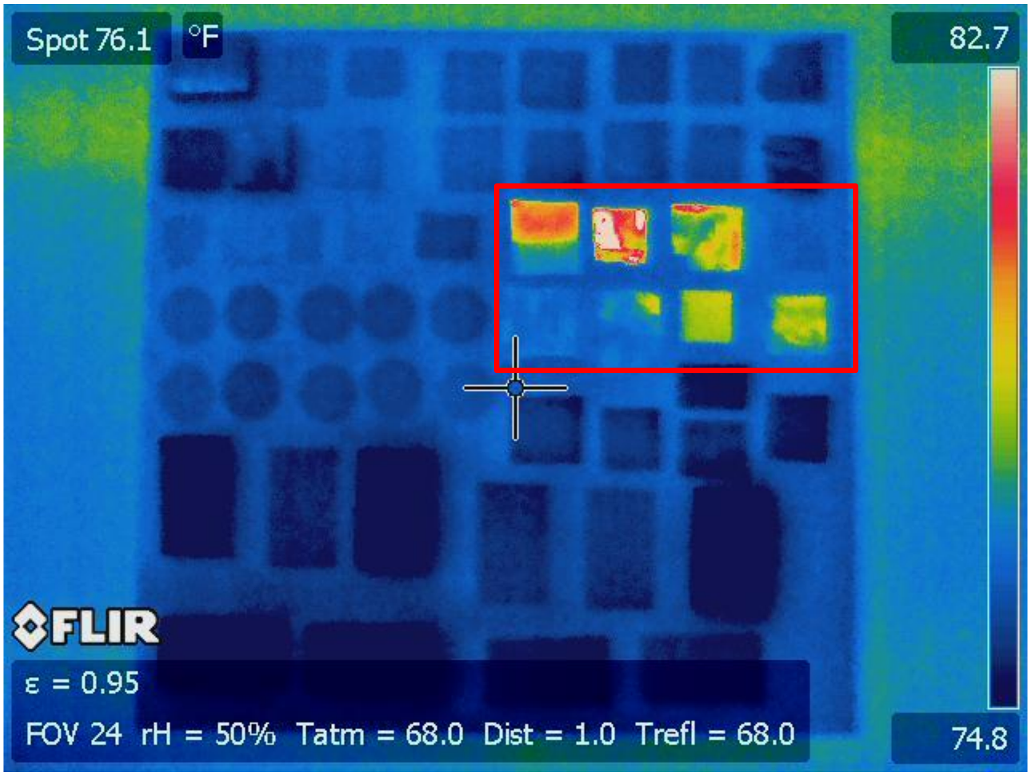

Figure 17: FLIR image demonstrating the variable range of metals shown in red square at ambient temperature.

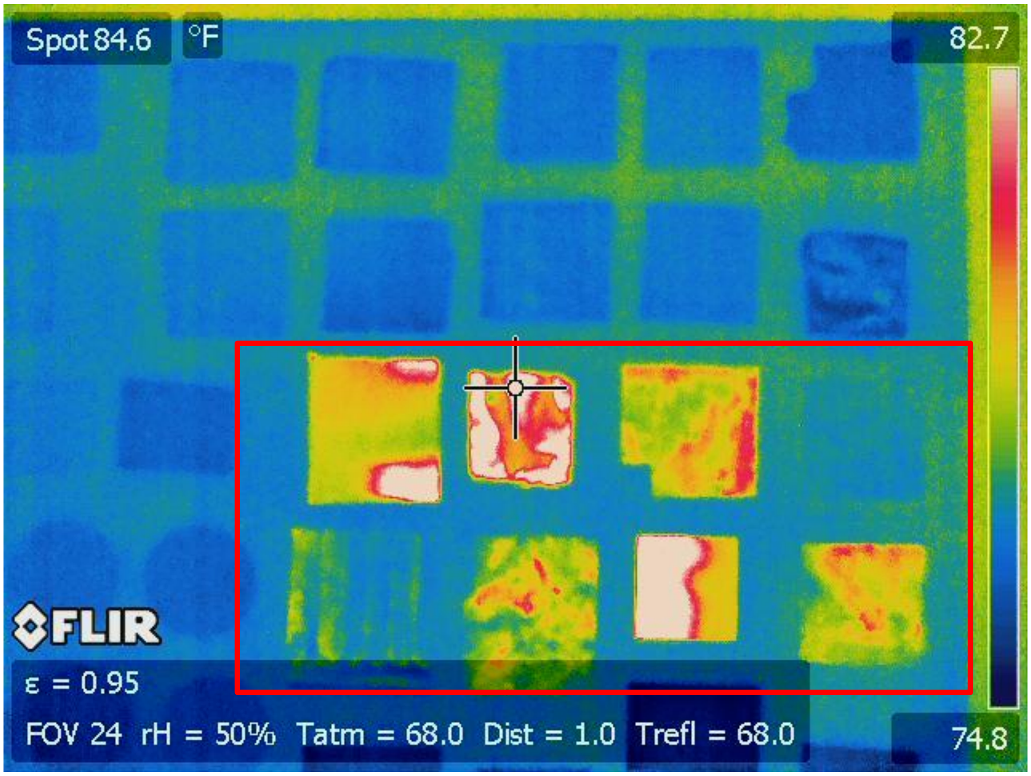

Figure 18: FLIR image (detail) demonstrating variable range of metals at heated temperature

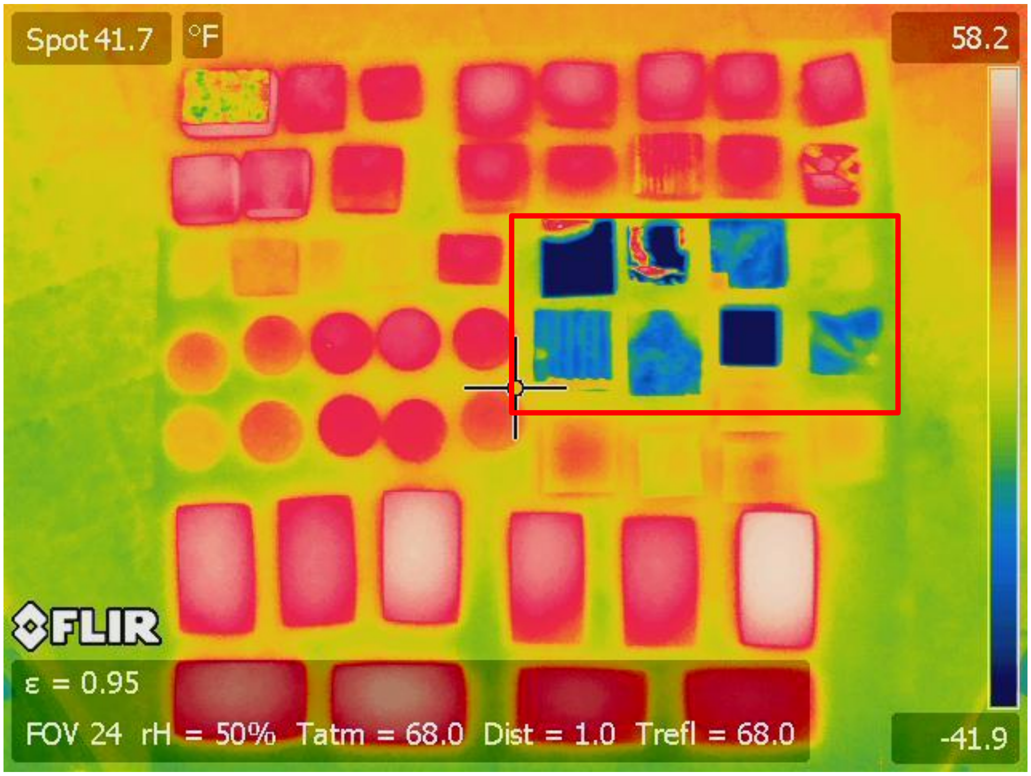

Figure 19: FLIR image demonstrating the variable range of metals shown in blue at cold temperature.

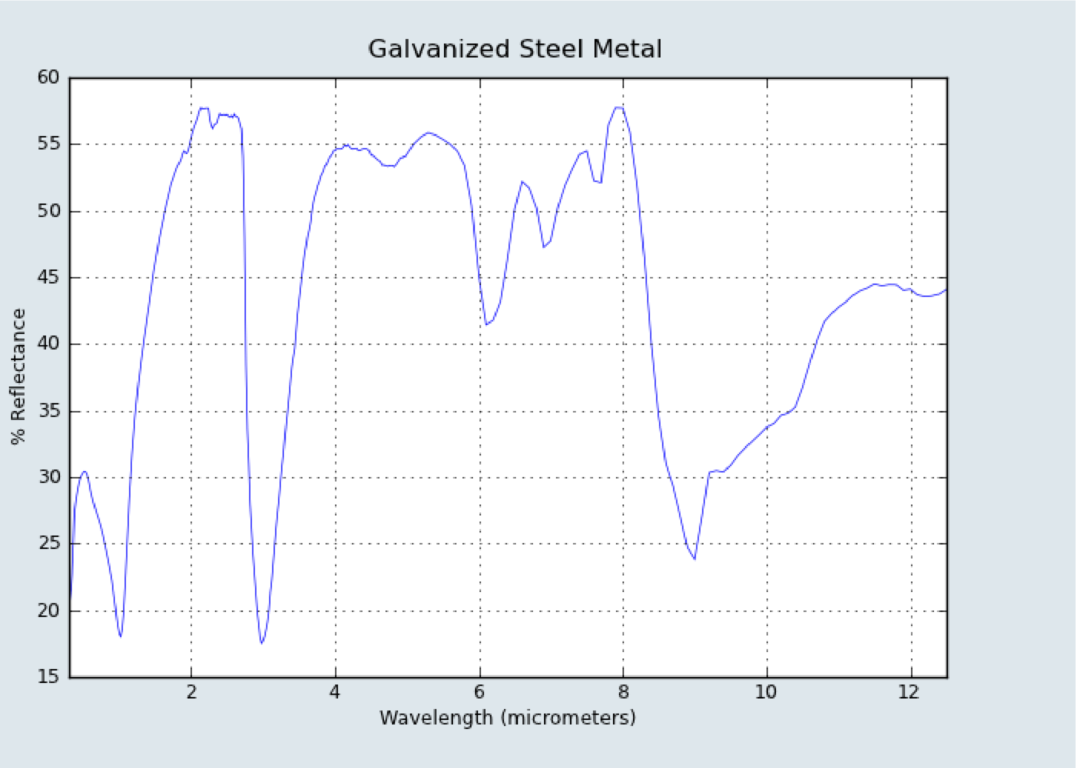

Figure 20: NASA ASTER spectral database reflectance curve for galvanized steel.
(Image source: http://speclib.jpl.nasa.gov/search-1/viewplot)

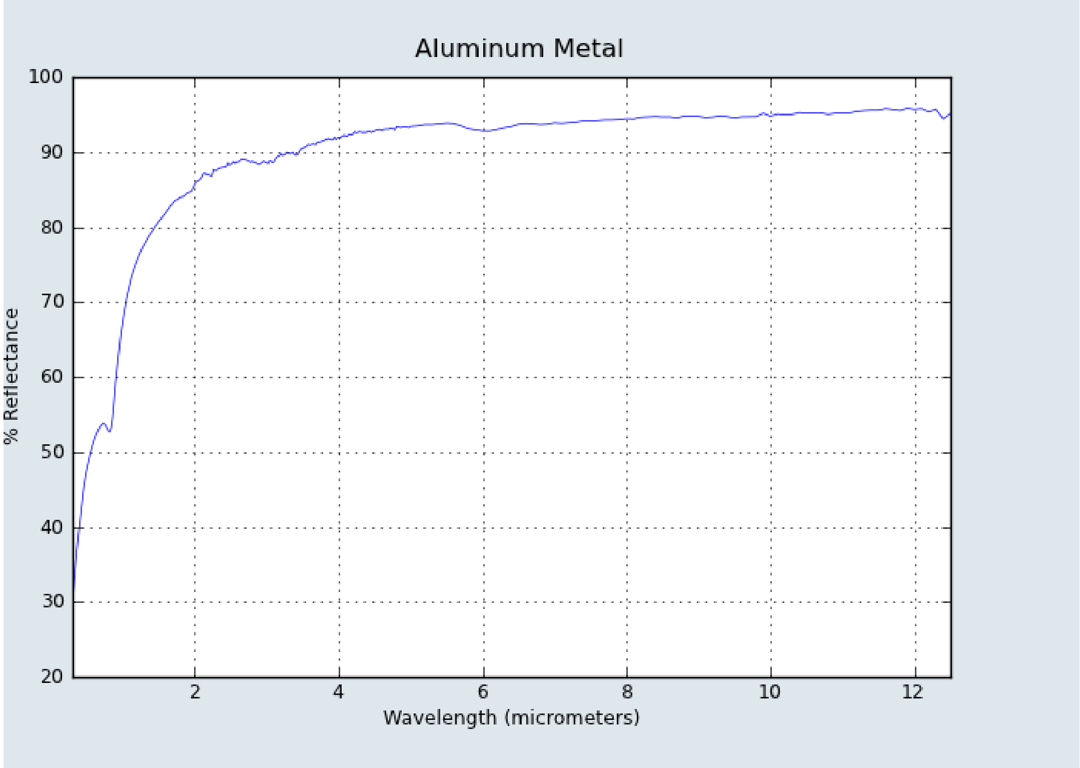

Figure 21: NASA ASTER database spectral reflectance curve for aluminum.
(Image source: http://speclib.jpl.nasa.gov/search-1/viewplot)

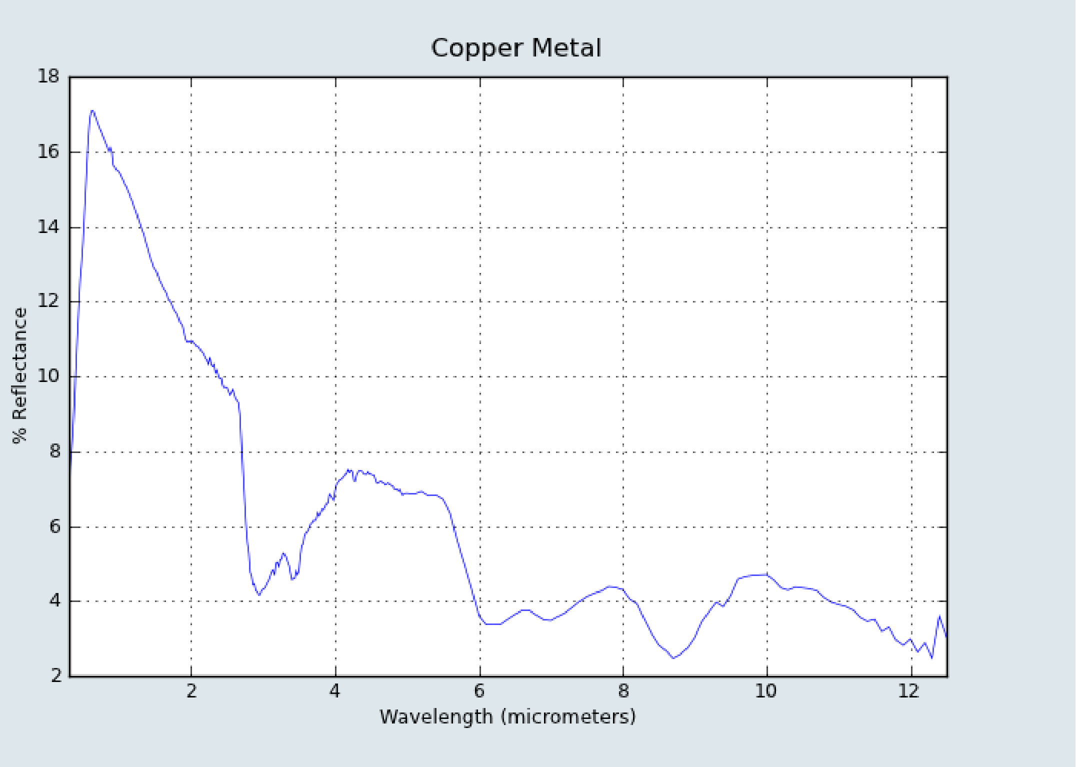

Figure 22: NASA ASTER database spectral reflectance curve for copper.
(Image source: http://speclib.jpl.nasa.gov/search-1/viewplot)

2.3 Wood

Materials, such as wood, are complex to interpret as their spectral-reflectance curves measured by FORS are relatively smooth and information available through online spectral databases provides little indication of diagnostic regions for a wide variety of species (see Figures 22 and 23). Analysis of spectral reflectance curves for vegetation is further complicated by the presence or absence of two contributing factors: chlorophyll and water absorption.[83] In the case of green vegetation, there are distinct differences in reflectance values across the visible, near-IR and mid-IR regions. In the VIS, there is a characteristic chlorophyll absorbance and low reflectance in the blue and red regions due to pigmentation of the leaves. In the NIR region, the internal structure of the plant controls reflectance values; whereas in the MIR region, the total moisture content of the plant controls reflectance values. There does appear to be a carryover absorption peak from tree spectra to the lumber samples (though less pronounced)—an absorption range approximately 1,600-1,800nm. For cases of wood identification, as in the case of silicates, use of a thermal imaging camera is required.

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[83] Doneus, Michael, Geert Verhoeven, Clement Atzberger, Michael Wess, and Michal Rus. 2014. "New ways to extract archaeological information from hyperspectral pixels". *Journal of Archaeological Science*. 52 (18): 84-96.

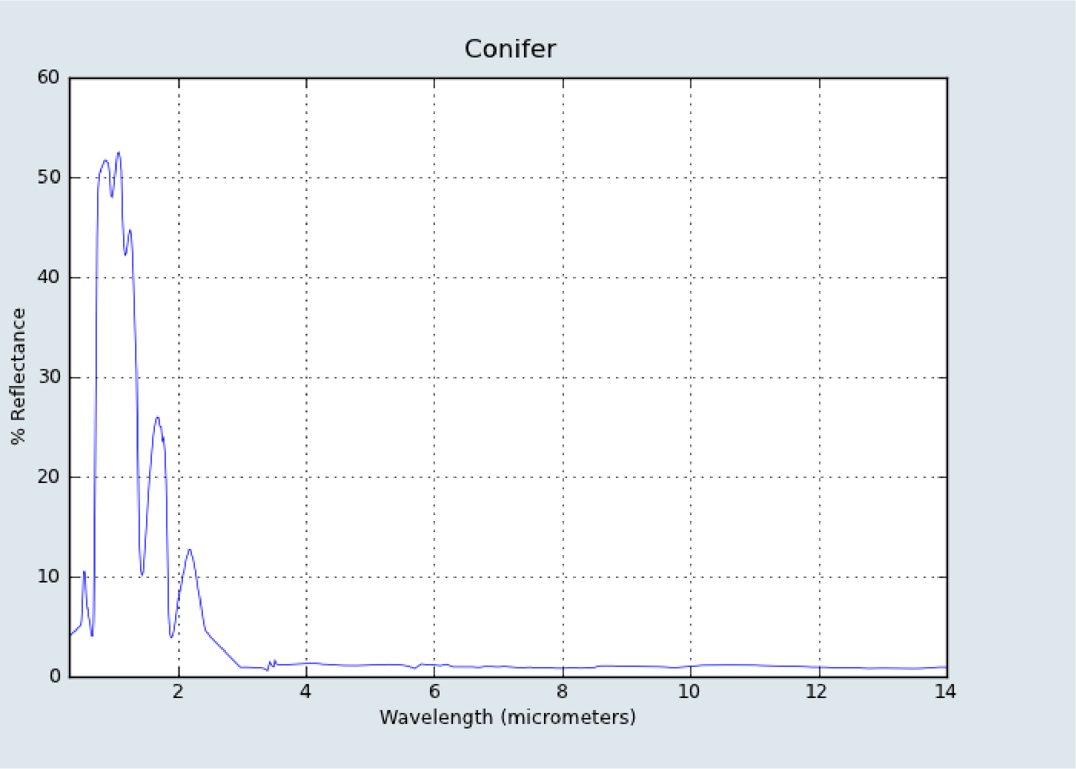

Figure 22: NASA ASTER database spectral reflectance curve for conifer tree.
(Image source: http://speclib.jpl.nasa.gov/search-1/viewplot)

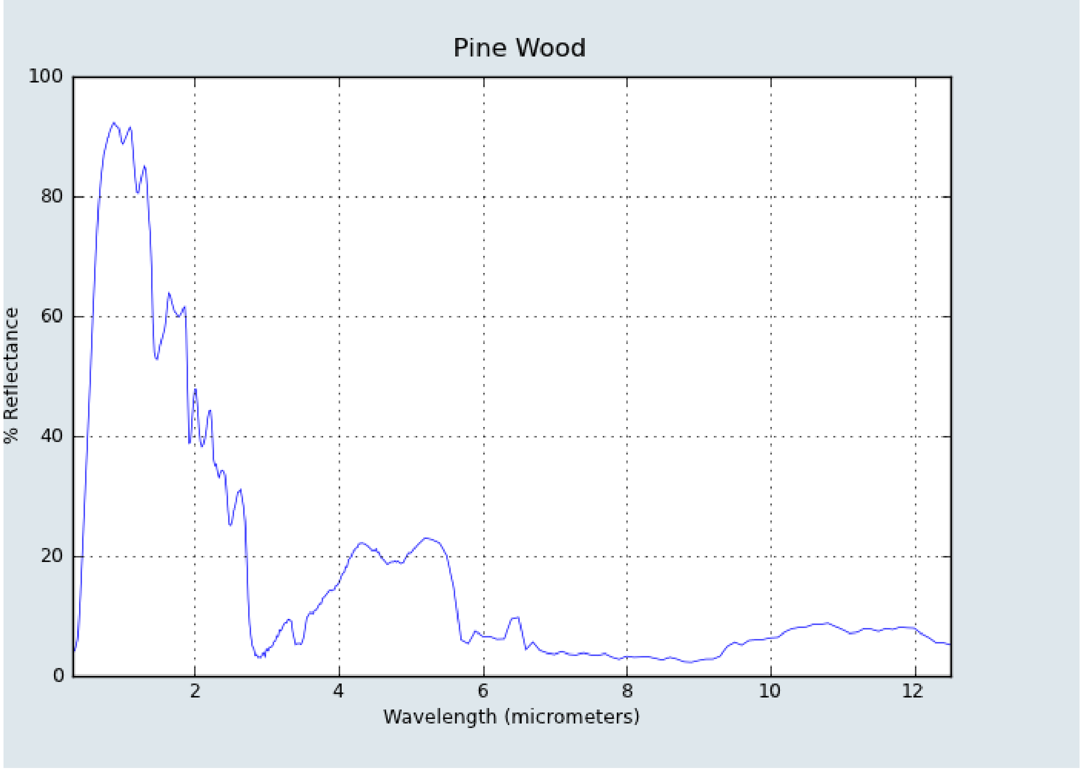

Figure 23: NASA ASTER database spectral reflectance curve for pine wood.
(Image source: http://speclib.jpl.nasa.gov/search-1/viewplot)

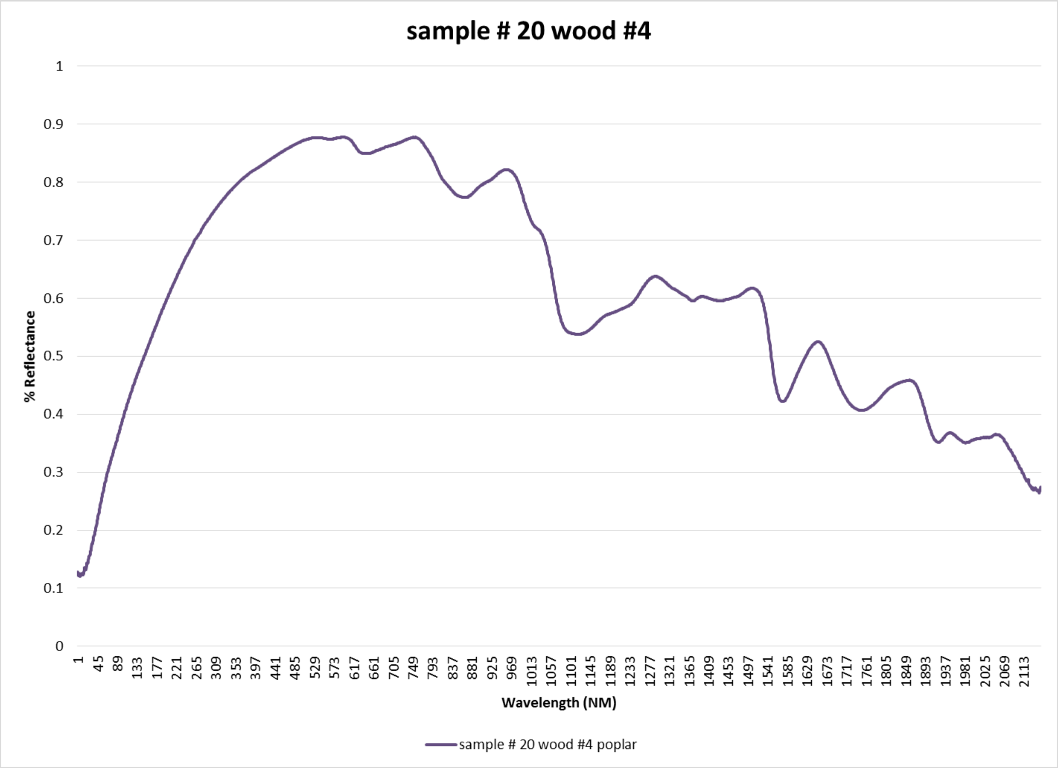

Figure 25: FORS spectrometer reading for wood sample #4 taken on March 25, 2015 at the National Gallery in Washington, DC.

Conclusion:

This project began as an investigation of non-invasive documentation and imaging techniques currently used in the conservation field with an eye towards reimagining a way of applying these techniques for the study of materials commonly associated with historic buildings and archaeological sites (e.g. construction and restoration). The intention to qualitatively examine the feasibility of using spectral imaging technology (taking a cue from MSI protocols) for *in-situ* exterior survey and non-destructive assessment of building façades and their materials has proven useful. It has been determined that using specific imaging cameras, in combination with band-pass filters and an FORS, represents a viable option for the initial surface investigations. For example, using a modified digital camera, such as a Nikon700, a B&W 092 IR band-pass filter, spectral imaging is able to broadly identify carbonates and therefore distinguish from silicate materials. This technique does not however, provide the necessary information required to distinguish amongst individual carbonates within a group. For the identification of silicates, a FOR spectrometer and thermal imaging camera, such as the FLIR P640, is most useful. And samples of metal and wood, while overlapping in several spectral regions, are easily distinguishable using a thermal imaging camera.

The challenges researchers will face integrating these techniques stems mainly from an availability of the requisite equipment and training. Today, many research facilities lack expensive thermal imaging cameras or ready access to modified DSLR cameras and filters to thoroughly explore the potential for these techniques. Going forward, as equipment costs fall and more individuals become aware of this technology, hopefully we will see greater numbers of researchers incorporate this technology into their cultural-resource survey and assessment.

Appendix 1: Glossary

Band-pass filter: a device used to accept or reject certain wavelength frequencies.

Electromagnetic spectrum: the range of all possible frequencies of electromagnetic radiation.

Emissivity: the relative power or efficiency of a material surface to emit thermal radiation in the infrared range.

Fluorescence: short term emission of radiation at a lower wavelength frequency following the absorption of radiation from a higher wavelength frequency.

Fluorescence Lidar: acronym of Light Detection and Ranging, is an active remote sensing instrument for the remote analysis of a target by means of a pulsed laser.

Frequency: the number of wavelengths passing a given point per unit of time.

Hyperspectral imaging: the documentation of an object's spectral fingerprint in ten or fewer, nanometer (nm) increments covering all twelve spectral bands.

Infrared reflectance images (IRR): reflected radiation in the IR (700-1100 nm) range.

Infrared reflected false-color (IRRFC): post-processing procedure of splitting red, green and blue channels whereby the red channel is processed (red channel is moved to green and the green channel is moved to blue).

Infrared spectral region: wavelength range covering 700-1100 nm; frequently subdivided into thermal, near, and shortwave regions.

Luminescence: when the incoming and outgoing (emitted) radiation are from different wavelength ranges.

Luminescence anisotropy: intensity of luminescence is a function of a specific orientation in relation to the crystallographic directions in the mineral.

Multispectral imaging: a method of observing an object using selected wavelengths (300-1100 nm) via specific radiation sources.

Photo-induced luminescence: optically stimulated luminescence.

Reflectance: when the incoming and outgoing (emitted) radiation are from the same wavelength range.

Reflected false color: a post processing technique of splitting red, green and blue channels whereby UV/IR information is combined with a VIS reflected image to aid in the characterization and differentiation of materials.

Spectral imaging: visual representation of a material's interaction with electromagnetic radiation.

Spectroscopy: study of the interaction of electromagnetic radiation with matter.

Thermal imaging: infrared radiation mapped as a function of temperature.

Thermoluminescence: luminescence stimulated by heat.

Ultraviolet spectral region: range of the electromagnetic spectrum from approximately 200-400 nm.

Visible reflectance images (VIS): standard photography where visible light is reflected back within the visible range.

Visible spectral region: range of the electromagnetic spectrum from approximately 400-700 nm.

Wavelength: the measured distance between two successive wave peaks.

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