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Spectral signature databases and their application/misapplication to modeling and exploitation of multispectral/hyperspectral data

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1.0 ABSTRACT

Spectral signature databases abound in the field of remote sensing. Scientists use these databases to assist in their analysis everyday. Many decisions are made about hyperspectral data and the observations made with this data based on the assumption that these databases contain “ground truth” representations of the signatures for materials sensed. For the most part, this is true if the team collecting the signatures that populate these databases follow sound practices when collecting this data. The data does, however, represent a very specific picture of the “truth”. Signatures found in databases represent a specific collection configuration or geometry. The source of illumination, whether it is artificial or natural, is in a very specific location as is the sensor used to collect radiance for the derivation of the reflectance signatures. A signature found in the database is useful for only a very specific scenario, one that matches the geometry used during ground truth collection. There are other very significant factors regarding illumination field and scattering properties of the material and reference standards that influence the computed reflectance signature. This work will illustrate some of the dramatic variation that can exist in the reflectance signatures derived for the same material using different techniques. Difference upward of 30% may exist for the same material. These observations are presented so that scientists who look to these databases in the future will consider very carefully the metadata that is presented with the signatures that they use to make sure they are applicable to the phenomenology and collection scenario that they have under study. These observations should also point out that signatures presented without detailed metadata could be very hazardous to use if the outcome of the analysis being performed relies upon the absolute reflectance spectra being known.

Keywords: reflectance spectra, collection geometry, bidirectional reflectance, signatures database

2.0 INTRODUCTION

Spectral reflectance signature libraries are ubiquitous with ground truth data for remote sensing data. Many experimenters have legions of scientists, technicians, graduate and undergraduate students on the ground during an aircraft or satellite overpass to characterize either the reflectance of the target or to measure absolutely the ground leaving radiance. Many companies produce instrumentation that make this process easy to carry out, however, the ease of use of the instrumentation is often confused with the production of quality spectral reflectance or spectral radiance data.

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The incident energy falling upon a surface follows the laws of conservation of energy and is described by Lillesand and Kiefer (1999) by the relationship

$$E_i(\lambda) = E_r(\lambda) + E_a(\lambda) + E_t(\lambda) \quad (1)$$

where E_i denotes the incident energy, E_r the reflected energy, E_a the absorbed energy, and E_t the transmitted energy. For sensing systems working in what is generally referred to as the visible, near infrared, and shortwave infrared (V/NIR/SWIR) portion of the spectrum from 0.4 to 2.5 microns, the reflected energy is the parameter of primary importance. This reflected energy is found by rearrangement of Equation 1 as

$$E_r(\lambda) = E_i(\lambda) - \{E_a(\lambda) + E_t(\lambda)\} \quad (2)$$

stating that the reflected energy is the incident energy reduced by the total amount of energy absorbed and transmitted.

The structure of a reflecting surface is also an important consideration when trying to describe how the reflected energy is distributed upon leaving that surface. Specular reflection results when a material's surface is flat or mirror-like. In this case, all of the incident energy is reflected in a direction equal but opposite to the angle of incidence of the incoming beam with respect to the surface normal. A roughened surface, that is one that exhibits a uniform distribution of surface normals, exhibits what is referred to as diffuse reflection. In this case, the energy is reflected uniformly in all directions about the scattering point. Neither of these ideal reflectance descriptors exist in nature, where most materials fall somewhere between these extreme behaviors.

Equations 1 and 2 both indicate that the energy terms are a function of wavelength, denoted by the λ term in parentheses. The incident energy will result in varying amounts of reflected, absorbed, and transmitted energy depending upon the frequency of the incident radiation. This varying nature of the different terms leads to the capability to distinguish between material types based on the relative and/or absolute magnitudes of these separate energy terms.

In order to accomplish this segregation of material types based upon the varying amounts of energy that are reflected, absorbed, and transmitted, remote sensing practitioners will often remove the spectral effects of atmospheric transmission and path radiance as well as the spectral distribution of the source to arrive at an image derived product that represents material spectral reflectance. Elements of interest in this reflectance product derived from the image data can then be compared to a database of spectral reflectance data and the best-fit match across the bandpass of the sensor found and chosen as the material identity.

While this process sounds easy enough in principle, the behavior of these surfaces are anything but ideal as described previously. Spectra that are measured and placed into databases typically represent data collected under very specific conditions of illumination and collection. For materials that are neither perfectly diffuse nor specular, the position of the source and the position of the sensor used to make these reflectance measurements will result in a spectral reflectance factor of the form

$$\rho(\lambda, \theta, \phi, \theta_s, \phi_s) = \frac{E_r(\lambda, \theta, \phi, \theta_s, \phi_s)}{E_i(\lambda, \theta, \phi, \theta_s, \phi_s)} \quad (3)$$

The newly introduced angular terms represent the zenith and azimuth angle of the sensor with respect to the material normal, θ and ϕ , and the same orientation angle for the source, θ_s and ϕ_s . This term is referred to as the bidirectional reflectance factor since it depends simultaneously on the direction of these two entities. The absorbed and transmitted terms are assumed to be negligible for the sake of this discussion indicating that the material is opaque in the bandpass of interest.

For many surfaces, these bidirectional reflectance factors result in significant variation of the magnitude of the factors depending on the relative position of the illuminating source and the collecting sensor. It should become clear that if

this is the case, then the data in many spectral databases are very specific to the manner in which they were collected and as a result may not represent the remote sensing scenario against which you might be applying them. This work will attempt to demonstrate this fact and expound on the necessity of complete and accurate metadata for a spectrum ingested into a database, and, equally as important, that the user of these database factors pay particular attention to and understand the conditions under which the data was collected before it is used.

3.0 BACKGROUND

As previously mentioned, the reflectance of a particular material is dependent on both the wavelength of interest and the surface roughness characteristics or microstructure. Using a spectroradiometer, such as the FieldSpec Pro® from Analytical Spectral Devices (ASD) (2002), one is able to capture radiance entering the aperture of this instrument. The radiance captured is a composite of the radiance leaving the surface, composed of reflected direct solar, scattered solar, and background illumination that attenuated by the intervening path transmission as well as augmented by the scattered path radiance. A simplified aperture entering radiance, L , is given by

$$L(\lambda, \theta, \phi, \theta_s, \phi_s) = \left\{ \frac{E_s(\lambda)}{\pi} \cos \theta_s + L_D(\lambda) + L_B(\lambda) \right\} \rho(\lambda, \theta, \phi, \theta_s, \phi_s) \tau(\lambda, \theta) + L_u(\lambda, \theta) \quad (4)$$

where E_s is the spectral exoatmospheric solar irradiance, L_D is the spectral downwelled sky radiance, L_B is radiance incident on the target from background objects, τ is the spectral transmission and L_u is the path radiance from the intervening path.

To back the reflectance factor out of this equation, several simplifying assumptions are made for short-range radiometric measurements. Since the path over which field spectral measurements are made is on the order of one meter, the transmission is assumed to be unity and the scattered path radiance term zero. Under these assumptions, Equation 4 can be re-written as

$$\rho(\lambda, \theta, \phi, \theta_s, \phi_s) = \frac{L(\lambda, \theta, \phi, \theta_s, \phi_s)}{\frac{E_s(\lambda)}{\pi} \cos \theta_s + L_D(\lambda) + L_B(\lambda)} \quad (5)$$

Since the quantities in the denominator are not easily measured explicitly, their effects are normalized by the use of a transfer reflectance standard that allows for calibration of the sensor and provides traceability back to a laboratory standard if desired. If a transfer standard such as Spectralon® is used in place of the material in Equation 5, the reflectance of the standard can be written as

$$\rho_{std}(\lambda, \theta, \phi, \theta_s, \phi_s) = \frac{L_{std}(\lambda, \theta, \phi, \theta_s, \phi_s)}{\frac{E_s(\lambda)}{\pi} \cos \theta_s + L_D(\lambda) + L_B(\lambda)} \quad (6)$$

In order to create traceability for the material measured, the sample reflectance measurement needs to be corrected for any errors in the instrument response. Using the spectral reflectance for the traceability standard measured above and the supplied spectral reflectance from the manufacturer, ρ_{NIST} , a spectral correction function can be computed using these terms as

$$c_{factor}(\lambda, \theta, \phi, \theta_s, \phi_s) = \frac{\rho_{NIST}(\lambda, \theta, \phi, \theta_s, \phi_s)}{\rho_{std}(\lambda, \theta, \phi, \theta_s, \phi_s)} \quad (7)$$

and, subsequently applied to the material spectral reflectance, ρ , to create a traceable material spectral reflectance as

$$\rho_{traceable}(\lambda, \theta, \phi, \theta_s, \phi_s) = \rho(\lambda, \theta, \phi, \theta_s, \phi_s) \frac{\rho_{NIST}(\lambda, \theta, \phi, \theta_s, \phi_s)}{\rho_{std}(\lambda, \theta, \phi, \theta_s, \phi_s)} \quad (8)$$

$$\rho_{traceable}(\lambda, \theta, \phi, \theta_s, \phi_s) = \frac{\rho(\lambda, \theta, \phi, \theta_s, \phi_s)}{\rho_{std}(\lambda, \theta, \phi, \theta_s, \phi_s)} \rho_{NIST}(\lambda, \theta, \phi, \theta_s, \phi_s) \quad (9)$$

Substituting in the measurable parameters in Equations 5 and 6 leaves

$$\rho_{traceable}(\lambda, \theta, \phi, \theta_s, \phi_s) = \frac{\frac{L(\lambda, \theta, \phi, \theta_s, \phi_s)}{\frac{E_s(\lambda)}{\pi} \cos \theta_s + L_D(\lambda) + L_B(\lambda)}}{L_{std}(\lambda, \theta, \phi, \theta_s, \phi_s)} \rho_{NIST}(\lambda, \theta, \phi, \theta_s, \phi_s) \quad (10)$$

$$\rho_{traceable}(\lambda, \theta, \phi, \theta_s, \phi_s) = \frac{L(\lambda, \theta, \phi, \theta_s, \phi_s)}{L_{std}(\lambda, \theta, \phi, \theta_s, \phi_s)} \rho_{NIST}(\lambda, \theta, \phi, \theta_s, \phi_s) \quad (11)$$

in which the environmental parameters cancel leaving a functional computation based solely upon the spectral radiance measurements made of the sample and standard.

While the form of the traceable spectral reflectance in Equation 11 is quite simple, the number of measurements required is infinite and the availability of the full bidirectional reflectance standard is non-existent. As such, simplifying assumptions need to be made in order to make this a tractable quantity. The first is that the measurements are made at some discrete number of sensor-source-target geometric configurations. The number and distribution depend upon the application and the behavior of the material being measured. The existence of a standard is a little more difficult to overcome and is often accomplished by using a pseudo-Lambertian material, such as Spectralon®, assuming the bidirectional nature of this material is negligible.

4.0 EXPERIMENTAL APPROACH

In order to demonstrate the affect the interaction of the reflectance standard, collection geometry, material geometry, and specific instrument design have on the derived spectrum for a particular material, an experiment was conducted in which pieces of standard blue tarpaulin, Baltic birch plywood, sandpaper, and asphalt were measured in numerous configurations.

As can be seen on a bright, sunny day, blue tarpaulins are not completely opaque. The blue tarpaulin referred to is the material that people use to protect equipment store outdoors. While this material affords this insight since it is transmissive in a bandpass where the human eye can see, there are many other materials that exhibit significant transmissivity in the near-infrared and/or shortwave infrared region. Transmissivity may be exhibited in these regions while the material appears opaque in the visible bandpass. This has led to countless numbers of spectra collected in which the backgrounds against which these materials are placed are integrally included in the final reflectance spectra. Caution needs to be taken to avoid this situation if the absolute spectral reflectance of the material is desired and can easily be accomplished with some simple comparative measurements. If the material's spectral reflectance signature differs when measured with a high reflectance background such as Spectralon® as a background and against a low reflectance background such as black Spectralon® or black packing foam, the material exhibits spectral transmissivity. While this may not be the case in the full spectrum scenario, notes should be recorded and distributed to indicate in which region(s) this material's spectrum may be suspect. In order to demonstrate the significance of this phenomenon,

the material's spectrum will be derived using a number of stacking configurations. Sandpaper presents similar transparent behavior to that of the blue tarpaulin but has a very different surface structure. The roughened surface of sandpaper causes it to exhibit more Lambertian-like reflectance characteristics. Baltic birch plywood and asphalt were chosen as they are opaque throughout the V/NIR/SWIR region of the spectrum and exhibit non-uniform surface structure with respect to composition, and ultimately, reflectivity.

Field spectroradiometers are intended to collect spectral radiance data reflected by materials in a natural setting. The design of these instruments are much more variable than that of laboratory instruments, in many ways by necessity, as these instruments must be portable and ergonomic. For this study an Analytical Spectral Devices (ASD) FieldSpec Pro® was used to make equivalent measurements using a variety of different collection / illumination geometries. The ASD FieldSpec Pro® can either be equipped with a foreoptic collection probe exhibiting either a 1°, 3°, or 8° field-of-view with natural illumination, a high intensity reflectance probe (HIRP) that contains its own illumination source, or a High Intensity Contact Probe (HICP) that contains its own higher-intensity illumination source. The designs for these collection geometries are shown in Figures 1 and 2.

Figure 1 Generalized collection/illumination geometry utilized by the ASD FieldSpec Pro® equipped with a foreoptic collector. Direct solar and diffuse skylight provide sample illumination and the collected radiance extends over either a 1°, 4° or 8° field of view.

Figure 2 Generalized collection/illumination geometry utilized by the ASD FieldSpec Pro® equipped with a HIRP or HICP. Illumination is provided by a divergent artificial beam and the collected radiance is gathered by a bare fiberoptic cable with a field of view of approximately 25°.

Each of these configurations has advantages and disadvantages that the operator must be aware of when making the measurement. In addition, the person using the spectral signature data for analysis must be aware of these geometries to exploit spectral image data properly.

The foreoptic configuration has the advantage of closely resembling a typical remote sensing collection geometry, a nadir looking sensor under natural outdoor illumination. It does, however, rely upon the environmental conditions being constant during the measurement period. Conditions must be clear and sunny in order to insure an adequate spectral illuminant power across the bandpass of this instrument. The HIRP or HICP configuration has the advantage of being an “all weather” solution with its artificial light source. The collection angle for the radiance measurement is approximately 25° off axis with a 25° field of view. This configuration is very different than many remote sensing systems.

This study looked at spectra collected of standard blue tarpaulin, Baltic birch plywood, sandpaper, and asphalt. These samples can be seen in Figure 3. The samples that were known to exhibit transparent behavior in any portion of the V/NIR/SWIR region of the spectrum, namely the blue tarpaulin and the sandpaper, were measured with multiple layers of material compressed together atop a background of Spectralon®. All samples were measured using each of the three collection configurations mentioned previously. In addition, the samples were measured in two (2) unique azimuthal orientations with respect to the collection probe to accentuate and variations due to bidirectional collection geometry.

Hemmer and Westphal (2000) described anomalies that result from the fiberoptic collector used with the ASD FieldSpec Pro®. The ASD FieldSpec Pro® contains three individual array spectrometers that when concatenated together allow one to achieve full spectral coverage from 0.4 to 2.5 microns. These anomalies result from the use of a weakly randomized fiber that delivers different physical locations on a sample to each of the three arrays in the spectroradiometer. If the material being measured is heterogeneous in its composition and hence in its spectral makeup, then significant discontinuities may occur at the transition points in the spectra defined by detector switch over. This occurs at approximately 1.0 and 1.7 microns where the detectors switch from Silicon (Si) to two different Indium Gallium Arsenide (InGaAs) compositions. These same findings were observed in this study and will be pointed out where significant.

Figure 3 Samples used in this study (a) standard blue tarpaulin, (b) Baltic birch plywood, (c) sandpaper, and (d) asphalt with exposed aggregate.

5.0 RESULTS/OBSERVATIONS

A blue tarpaulin was measured using the ASD 8° foreoptic configured on a camera copy stand with the lights positioned at $\pm 10^\circ$ off axis with respect to the sensor to target path. The tarpaulin was measured with a single layer as well as multiple layers. Figure 4 illustrates the derived reflectance spectra for the scenarios when 1, 4, and 8 layers of tarpaulin material were stacked atop a Spectralon® panel.

As mentioned previously, this material is transparent to the eye when it is held up to the sun. Figure 4 illustrates that transmission through the tarpaulin allows the Spectralon® panel to be visible to varying degrees dependent on the number of layers stacked. Variation in transmission by up to 30 reflectance units is visible in some wavelength regions. As the Spectralon® panel used in this experiment is spectrally flat, the shape and structure of the reflectance spectra remains constant between these measurements with only the magnitude of the signature changing. These same phenomena were observed with sandpaper stacked up to 16 layers.

One may also notice in these plots that the single layer reflectance spectrum exceeds 100% in magnitude. This will be discussed later when considering collection geometry.

Figure 4 Spectral reflectance signatures of multiple layers of blue tarpaulin atop a Spectralon® panel. These measurement were made using the 8° foreoptic mount on a camera copy stand with lights oriented $\pm 10^\circ$ of the sensor to target axis.

Figure 5 represents the spectral reflectance signatures for the four materials used in this study as a function of different collection configurations provided by Analytical Spectral Devices for their FieldSpec Pro® spectroradiometer. Of immediate concern is the fact that for materials that exhibit a specular reflection when viewed at an angle equal and opposite to the angle of direct illumination, namely the blue tarpaulin and the Baltic birch plywood, the different measurement configurations produce data, that when used to derive spectral reflectance, that generate signatures that

Figure 5 Spectral reflectance signature for (a) blue tarpaulin (32 layers atop Spectralon®), (b) Baltic birch plywood, (c) sandpaper (16 layers atop Spectralon®), and (d) open aggregate asphalt. All signatures represent the average of 30 individually collected spectra for each material. Spectra shown were collected with the high intensity reflectance probe (HIRP), the high intensity contact probe (HICP), and the 8° foreoptic (on a camera copy stand with illumination at $\pm 10^\circ$ off axis) provided by Analytical Spectral Devices for their FieldSpec Pro® spectroradiometer.

vary by upward of 40% at some wavelengths. The materials that exhibit more Lambertian-like behavior due to their surface structure, the sandpaper and the open aggregate asphalt, do not exhibit the variation in reflectance. The cause of such variation is obvious when looking at the collection geometry used. When illuminated and viewed from directly above, as in the case of the 8° foreoptic on the camera copy stand, there is a significant and broad width retro-reflection from the material surface to the collection optic. This retro-reflection is not present when performing a baseline standardization with the Spectralon® reflectance panel as it is more Lambertian in its scattering properties. As a result, the ratio used between the radiance collected for the two surfaces can easily exceed 100% in high reflectance regions of the spectrum.

An implicit assumption that needs to be made in the collection of radiance data for the derivation of reflectance is that the illumination field falling upon the surface being measured is uniform. The validity of this assumption is especially important if the surface being measured is heterogeneous in composition such as the asphalt sample measured in this study. If the illumination falling upon the surface is non-uniform, then the measurement of reflectance becomes a function of the positioning of that illumination field on the target. Similar to the finding of Hemmer and Westphal (2000), the result of measuring a heterogeneous surface can be unexpected in the sense that different portions of the sample may be presented to the various detectors that are used to obtain the complete spectra in the V/NIR/SWIR. A non-uniform illumination field will cause unexpected results when hot spots in the field fall on different constituents of the heterogeneous surface. Figure 6 shows the non-uniformity of the illumination fields produced by the HIRP and HICP. Current studies are underway in our laboratory to produce a similar device that would produce an extremely constant illumination field over the sample surface.

Figure 6 Illumination field incident on the target from (a) the ASD HIRP and (b) the ASD HICP. The illumination field is imaged as it falls on a piece of frosted glass in contact with the probe.

A significant observation that can be made by examining the results presented in this section is that the scattering nature of both the material and reference standard are critical factors in the determination of reflectance for that material. Implied in the derivation of reflectance given in Section 3 is that the scattering distribution for both the material and the reference standard are identical. The reference standard used throughout this study, Spectralon®, is assumed by most to be Lambertian in its scattering properties. If one places a source such as a flashlight on the surface of a Spectralon® panel, it immediately becomes evident that the material is translucent, allowing energy to enter into the material, scatter within the volume, and exit the surface. This behavior leads to a material that exhibits scattering distributions that approach a theoretical Lambertian reflector, however, no material is perfect in this respect. The materials used in this study span a wide gamut of scattering types. The sandpaper exhibits Lambertian-like behavior due to its multifaceted

roughened surface while the blue tarpaulin can, at many wavelengths, be very specular in nature. This leads to significant problems when trying to determine absolute reflectance.

It has been shown that the reflectance computed using the three instrumental configurations examined in this study could produce differences up to 40% or more in particular portions of the spectrum. A primary contributor to the differences exhibited has roots in this difference in scattering properties. Figure 7 is a conceptual illustration of the difference in scattering distribution that might be observed between a material such as Spectralon® on the left and the blue tarpaulin on the right. There may exist a very strong retro-reflection in the nadir direction for such a material. The impact of this retro-reflection is two-fold. First, the retro-reflection off of the material surface can be directed right back into the reflector on the artificial light source in the case of the HIRP or HICP probes. This reflected radiance would be redirected back onto the surface, hence increasing the amount of incident radiation onto the material being measured. This retro-reflected energy, in the case of a material such as the blue tarpaulin, is much greater than in the case of Spectralon®. As a result, a reflectance measurement made in this configuration can produce a final reflectance spectrum that is much greater in magnitude than for that same material measured using a configuration that does not allow this retro-reflection to occur. Second, this retro-reflected energy can be captured directly by the sensor itself, depending on the magnitude of the solid angle over which the energy is scattered on its path to the sensor. This capture of excess energy is especially evident in those measurements made with the 8° foreoptic positioned on the camera copy stand with the lights positioned 10° to each side of the sensor. If this situation occurs, the computed radiance can again be much greater in magnitude than when this is not the case, *e.g.* with a more Lambertian-like scattering surface.

Figure 7 Conceptual illustration of (a) a near Lambertian reflector and (b) a reflector exhibiting strong retro-reflection in the nadir direction

These situations do not mean that the reflectance values computed under these configurations are wrong or exhibit significant error. In fact, they can be considered to be absolutely correct, for the configuration of the illumination source and the sensing detector. The bidirectional nature of reflectance becomes very evident in these situations and exemplifies the requirement for the collection team to record explicit descriptions of the configuration used for a particular measurement and, even more importantly, the user of these reflectance spectra need to examine the metadata to see if the spectra they have chosen to use for exploitation or analysis are derived from a geometry similar to that in which the remote sensing data that they are using was collected.

6.0 CONCLUSIONS

This study proved to be very enlightening and disconcerting in many ways to the authors. As providers of spectra that are ingested into many spectral databases, it is a major concern that the geometry under which these data are collected is such an influential factor to the overall magnitude of the reflectance. That being said, it is comforting to realize that because metadata has always been an important part of our product, the data that we have distributed and have been using is self-descriptive in the sense that the collection geometry is well defined. When data contained in these

databases are not accompanied by detailed metadata describing the collection geometry, the comfort level of users of this data should decrease drastically.

The transparent nature of materials being measured can greatly affect the quality of measured spectra, causing greater than a 40-point difference in reflectance magnitude in this study. While only a magnitude change was illustrated in this study, it should be noted by the reader that if these same measurements had been made atop a background that on its own exhibited a complex shaped spectral signature, this signature would be included as part of the materials spectra contained in the database. How many spectra that have been measured in such a manner are part of the numerous databases that are used every day?

The geometric configuration of the measurement has a marked effect on the magnitude of the spectra, with variations of over 30 reflectance units observed. The retro-reflection of energy directly into the collection optic or back onto the illuminating reflector can cause greater than expected amounts of energy to be recorded for a material exhibiting such scattering properties. These factors greatly support the need for reflectance measurements to be made under bidirectional conditions.

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8.0 REFERENCES

Analytical Spectral Devices, Incorporated (2002), *FieldSpec Pro® User's Guide*, Boulder, CO.

Hemmer, T.H., Westphal, T.L. (2000). *Lessons learned in the post-processing of field spectroradiometric data covering the 0.4 to 2.5 μ m wavelength region*, Proceedings of the SPIE, Image Exploitation and Target Recognition, Algorithms for Multispectral, Hyperspectral, and Ultraspectral Imagery VI, Vol. 4049, Orlando, FL.

Lillesand, T.M., Kiefer, R.W. (1999). *Remote Sensing and Image Interpretation, 4th Edition*. New York: John Wiley & Sons.