An Introduction to Hyperspectral Imaging Technology

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1.0 Introduction

This document is provided by Exelis to introduce hyperspectral imaging (HSI) technology. Some present-day applications of HSI technology are discussed.

Before getting into the HSI technology, we need to address some of its underlying concepts. In the next few sections, we will lead up to HSI by covering the following topics:

- Electromagnetic Radiation
- The Electromagnetic Spectrum
- Electromagnetic Radiation Interactions with Matter
- Spectroscopy
- Remote Sensing

After reading this primer you should understand fundamentally how HSI technology works.

2.0 Electromagnetic Radiation

Electromagnetic radiation (EMR) is energy in the form of electromagnetic waves. Electromagnetic waves get their name from a physical interaction between an electric field and a magnetic field that creates the wave.

The most familiar form of EMR is visible light. However, electromagnetic radiation consists of much more than just visible light. X-rays, gamma rays, microwaves, and radio waves are all EMR. The characteristic that distinguishes different electromagnetic waves is the wavelength.

Wavelength is just what it appears to be: the length of a wave. Electromagnetic waves oscillate in a pattern that continuously and exactly repeats itself, as shown in Figure 1. The wavelength is the distance traveled by the wave before its oscillation pattern repeats. This is also shown in the figure.

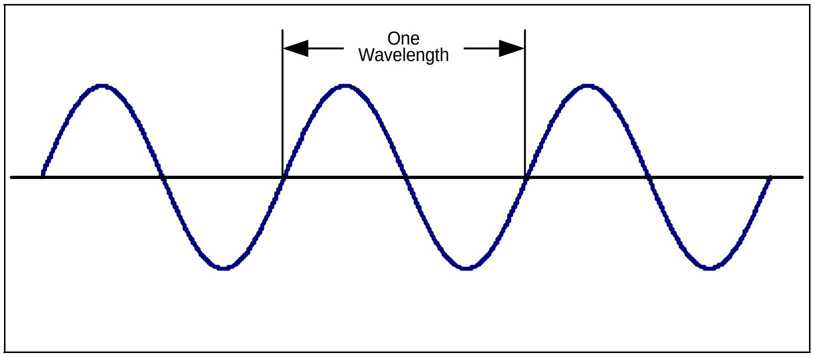

Figure 1. Electromagnetic Wave Form and Wavelength

The frequency of an electromagnetic wave is the number of times its oscillation pattern repeats each second. Frequency is stated in terms of cycles per second, where one cycle is one repetition of the up-and-down wave pattern. The unit of frequency is the hertz. One hertz is equal to one cycle per second. Hertz is abbreviated Hz, but often has an extra letter to indicate multipliers of 1000. For example, one thousand hertz is written "1,000 Hz" or as "1 kHz," where the letter k indicates 1000. Common prefixes are listed below in Table 1.

Table 1. Frequency Notation

Multiplier		Prefix	Frequency
1,000	(10^3)	k	kilohertz, kHz
1,000,000	(10^6)	M	megahertz, MHz
1,000,000,000	(10^9)	G	gigahertz, GHz

Since all electromagnetic waves travel at a constant speed—the speed of light[1]—longer electromagnetic waves oscillate slower than shorter electromagnetic waves. In fact, the product of frequency and wavelength is speed:

Frequency x Wavelength = Speed

From the equation above, it's easy to see that, since speed does not change, as the frequency increases the wavelength decreases, and vice versa. We will limit our discussions of electromagnetic radiation characteristics mostly to wavelengths.

[1] The speed of light in a vacuum is about 186,000 miles per second (about 300,000 km per second). Light slows a bit in air, but certainly not enough to concern us.

The unit of wavelength is the meter (m). Electromagnetic wavelengths also have common prefixes to denote multipliers of 1000. These are listed below in Table 2.

Table 2. Wavelength Notation

Multiplier		Prefix	Wavelength
0.001	(10^{-3})	m	millimeter, mm
0.000 001	(10^{-6})	µ	micrometer, µm
0.000 000 001	(10^{-9})	n	nanometer, nm

The wavelengths we are concerned with are all in the nanometer (nm) range. One nanometer is one billionth of a meter. To help put this in perspective, there are 25.4 *million* nanometers in an inch.

2.1 The Electromagnetic Spectrum

Electromagnetic wavelengths vary from very, very short (gamma rays) to very, very long (radio waves). Gamma ray wavelengths are so short that physicists refer to their energy instead of their wavelength. For example, the wavelength of a high-energy gamma ray is a few ten-thousandths of a nanometer (about one hundred trillionths of an inch). On the other hand, long radio waves have wavelengths of tens of kilometers! The corresponding frequencies are about one million million gigahertz (10^{21} Hz) for the high-energy gamma ray down to about 100 kilohertz (10^{5} Hz) for the long radio wave. That's quite a difference!

The entire family of electromagnetic radiation, with all its different wavelengths, is called the *electromagnetic spectrum*. The electromagnetic spectrum is broken down into named ranges. You've probably heard some or all the names already, but you may not have known where they fit in the electromagnetic spectrum. The electromagnetic spectrum is illustrated below in Figure 2. Keep in mind that the spectrum does not end at 10^{-14} meters or at 10^{4} meters. However, unless you are a particle physicist or an astrophysicist, these values represent reasonable end points for most purposes.

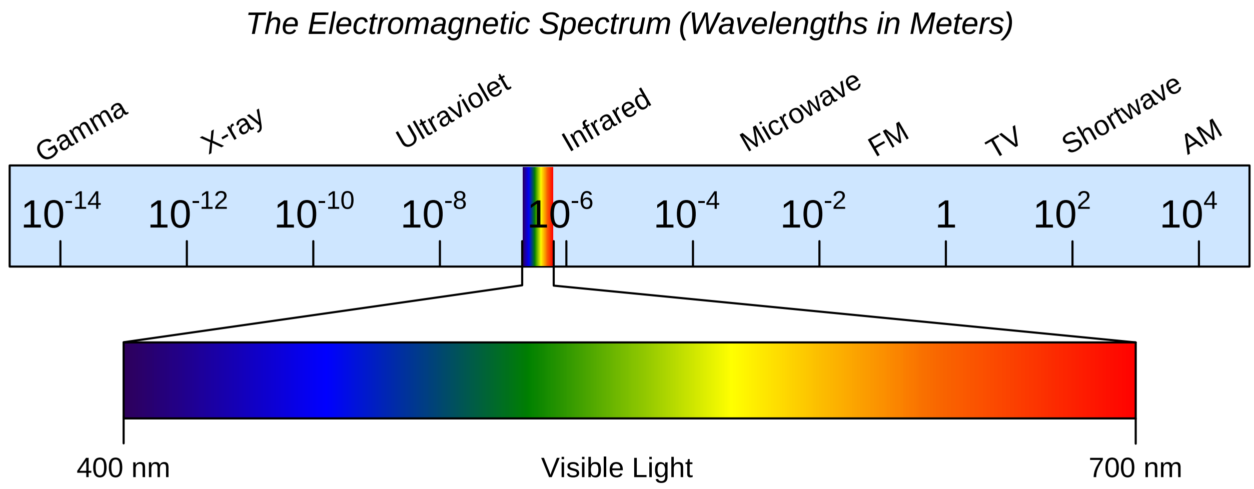

Figure 2. The Electromagnetic Spectrum

The visible portion of the electromagnetic spectrum extends from 400 nm to 700 nm. It is only a very small part of the overall range of wavelengths in the spectrum. And, all the other wavelength ranges, from gamma rays to AM radio waves, span a wider range of wavelengths than does visible light. For example, the infrared range includes a broad range of wavelengths. It begins just above the longest waves in the visible portion (red) and extends up to the wavelength range that is used for communication. Infrared wavelengths range from about 700 nm up to 1 millimeter. The part of the range closest to the visible spectrum is called near infrared and the longer wavelength part is called far infrared.

2.2 Electromagnetic Interactions with Matter

When electromagnetic radiation strikes something—whether it is a solid, liquid, or gas—it undergoes one or more of three processes:

- Reflection – the EMR is turned back from the surface of the substance
- Absorption – the EMR is absorbed by the substance
- Transmission – the EMR passes through the substance

These three processes are illustrated in Figure 3.

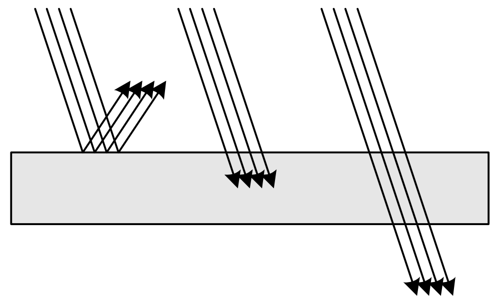

Figure 3. From Left to Right: Reflection, Absorption, and Transmission

All real substances undergo two or more of these processes. Most natural substances undergo all three of them. For example, consider light striking the water in a swimming pool.

- Some of the light is reflected. This is why you can see your reflection in still water, and why you need sunglasses around water on a sunny day.
- Some of the light is absorbed. This does two things: It warms the water, and it reduces the intensity of the light as it travels through the water. Think about how it is more difficult to see the bottom of the pool at the deep end than at the shallow end.
- Some of the light is transmitted. The transmitted light goes through the water, enabling us to see the bottom of the swimming pool.

Think about the swimming pool example described above. *Some* of the light is reflected. *Some* of the light is absorbed. *Some* of the light is transmitted. What determines *how much* light is absorbed, reflected, and transmitted?

The answer is: physical characteristics of the substance, and the wavelengths of the incident light.

Substances interact with EMR in different ways. They absorb, reflect, or transmit various wavelengths of EMR differently. Here are some common examples:

- An apple skin absorbs most of the visible light, but reflects many of the red wavelengths. Since many red wavelengths are reflected, the apple appears red. Likewise, tree leaves absorb most visible light, but reflect many green wavelengths. Since many green wavelengths are reflected, the leaves appear green.
- Clear plate glass transmits most visible light, but reflects some of it. This is why you can see through a window yet also see a slight reflection of yourself at the same time.

- Your skin absorbs infrared wavelengths. This is the reason you can feel the heat from some distance away from a red-hot stove burner or a fire. It is also the reason you feel warm in sunshine.
- Sunscreen lotion absorbs the ultraviolet wavelengths that cause sunburn. Since the ultraviolet light is not transmitted to your skin, your skin is protected from sunburn. The lotion transmits the entire visible spectrum, which is the reason your skin does not change color when the lotion is applied.
- The walls of your home:
  - Absorb some visible wavelengths and reflect others. The EMR wavelengths that are reflected are what give the walls their characteristic color. (If the walls are white, then they reflect all the visible wavelengths. Conversely, if they are black, then they absorb all the visible wavelengths.)
  - Absorb infrared wavelengths from sunlight. This is the reason they are warmer than the surrounding air on a sunny day, even in the winter time.
  - Transmit radio wavelengths. This is why radio antennae work inside your home.
- Water is a weak absorber and weak reflector of visible wavelengths. The wavelengths that are not absorbed or reflected are, of course, transmitted. Because water absorbs blue and green wavelengths less than other colors, objects that are underwater tend to have a blue-green tint. Water also tends to reflect blue and green wavelengths more than others, which gives large bodies of water a blue or blue-green appearance.

When we look at an object, our eyes receive EMR that is reflected from the object. The light that is reflected is the light that has not been absorbed by the object. Thus, absorption and reflection are key properties that give objects their characteristic colors.

As we have seen from the examples listed above, reflection, absorption, and transmission are not limited to visible wavelengths.

For simplicity, the remainder of this discussion will be limited to visible light and the near infrared band. A hyperspectral imaging system that operates among these wavelengths is often referred to as a VNIR (pronounced "VEE-ner") system. VNIR is an acronym for "*V*isible *N*ear *I*nfra*R*ed."

We will use the generic term "light" to refer to EMR in the visible and near infrared wavelengths.

3.0 Spectroscopy

Spectroscopy is the study of the wavelength composition of electromagnetic radiation. It is fundamental to how HSI technology works, as will be shown shortly.

3.1 Refraction and the Prism

Visible light is made up of many different wavelengths of EMR. In fact, white light is comprised of all the colors in the visible band, equally mixed. This can be seen by sending a beam of white light through a prism. When EMR passes from one substance to another, the waves change direction, or bend. This bending is called *refraction*. The angle at which a wave refracts depends on its wavelength. White light consists of many different wavelengths, and each different wavelength refracts at a different angle. Refraction causes the prism to spread the white light into its component colors. See Figure 4 for an illustration of the prism effect.

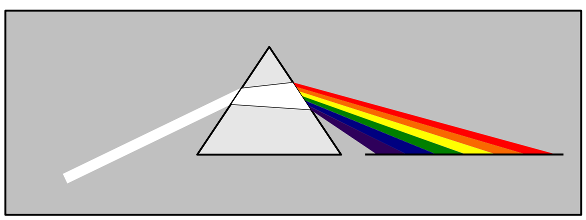

Figure 4. A Prism Disperses Light According to Wavelength

Figure 4 shows the color spectrum for white light, but what about colored light? For example, what would happen if green light was sent through the prism?

The answer is: It depends on the composition of the green light.

If the green light is *monochromatic*, that is, composed of a single wavelength, then only that pure, single-wavelength green light would exit the prism. Since the light consists of a single wavelength, all the waves will refract at the same angle and the prism will not disperse the beam. The refraction of monochromatic light is illustrated in Figure 5. Note how the beam exiting the prism is the same as the beam that enters the prism.

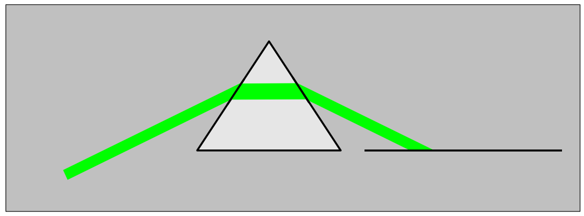

Figure 5. A Prism Does Not Disperse Monochromatic Light

Most natural light is actually a mixture of many wavelengths. If the green light entering the prism is actually a mixture of different wavelengths, then the prism will separate the light into its component colors. For example, the green light we see reflected from a tree leaf actually consists of several different wavelengths. There may be some blue, green, and yellow light in the green that we see. Sending this light through a prism will cause the different wavelengths to refract at different angles. The different refraction angles disperse the green light into its component colors, as shown in Figure 6.

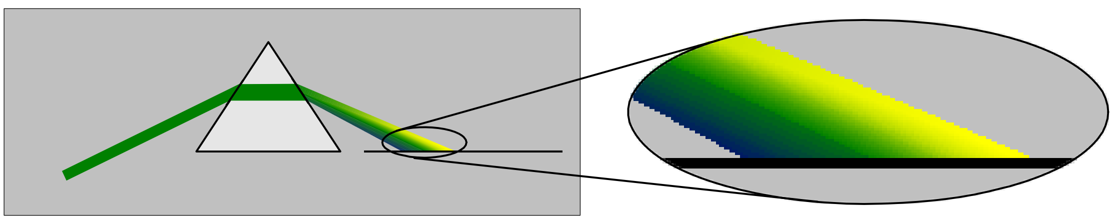

Figure 6. Light of Many Wavelengths is Always Dispersed by a Prism

Note that the green light entering the prism in Figure 6 actually contains various wavelengths of blue, green, and yellow light. In fact, almost all reflected light is *not* monochromatic—it contains a mixture of wavelengths that, when combined, give an object its characteristic color.

A *diffraction grating* is another tool that is used to disperse light into its spectrum. A diffraction grating is typically a material with a reflective surface onto which thousands of very fine, parallel grooves have been etched. The grooves are etched at specific angles, and high-precision gratings can have over a thousand grooves per millimeter on their surface. The grooves reflect incident light into its spectrum. Diffraction gratings provide more accurate and more consistent spectral dispersion than prisms. The wavelengths that are dispersed by the grating can be controlled by the angle, width, and spacing of the grooves.

3.2 Measuring the Spectrum

Just as there are an infinite number of wavelengths in the visible portion of the electromagnetic spectrum, there are an infinite number of colors. Each unique color contains different intensities of different wavelengths of light. We humans have a limited ability to discern between similar colors. But, using refraction, we can disperse light of any color into its unique spectrum, as is shown with a beam of green light in Figure 6. Once the spectrum is dispersed, we can look for similarities and differences in the composition of the light.

After a color spectrum is dispersed, we can divide the spectrum into separate bands. See Figure 7 below. In this figure, we have arbitrarily divided the green spectrum of Figure 6 into twelve adjacent bands.

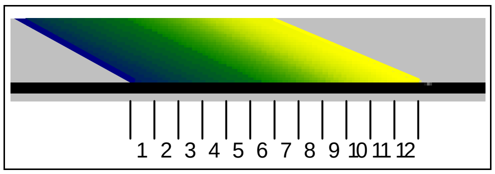

Figure 7. Dividing a Color Spectrum into Discrete Bands

After dividing the spectrum into discrete bands, we measure the intensity of the light in each band. After measuring the intensity, we assign it a value. Thus, we end up with a set of twelve intensity values for our green light—one intensity value per band. Let's assign twelve arbitrary intensity values between 1 and 10 to each of the twelve bands in our example. The assigned values are shown below in Table 3.

Table 3. Spectrum Band Intensity Values

Band	Intensity Value	Band	Intensity Value
1	2	7	7
2	3	8	8
3	3	9	6
4	5	10	6
5	5	11	5
6	7	12	5

Now, let's take the spectrum band intensity values and plot them on a graph. The result is shown below in Figure 8.

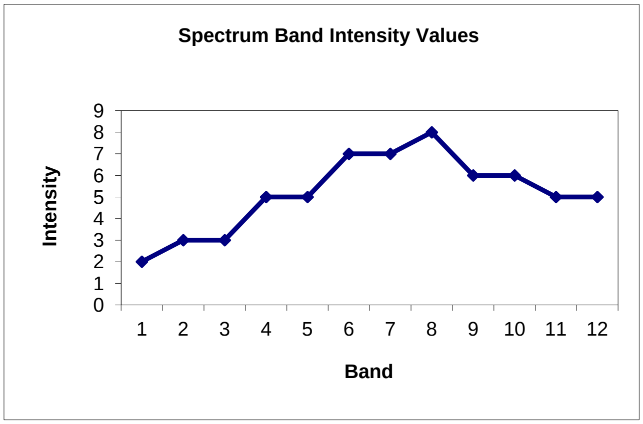

Figure 8. Spectrum Band Intensity Graph

The graph in Figure 8 is unique for the light that was measured in Figure 7 and split into twelve bands. If the light changes, even slightly, then the intensities of one or more bands will change and the graph will change.

By spreading the light into its spectrum and then measuring the intensity of its different wavelengths, we can discriminate between different light samples that appear the same to human eyes. This method of measuring the intensity of wavelengths in a sample of light represents a means to detect a specific combination of wavelengths.

We have already learned that different objects absorb and reflect light differently. If we capture the light that is reflected by an object and subject it to the method described above, then we can use the resulting information to detect the object by its reflected light. For example, assume we measure the light that is reflected from alfalfa plants by diffracting it into its spectrum and then measuring the intensity of the different wavelengths. If, at some later time, we measure the light from an unknown source and find that the spectrum and intensities match the spectrum and intensities for alfalfa, then we know the light was reflected by alfalfa. Fundamentally, this is the foundation of spectral imaging. *We use the spectrum of light reflected by an object to detect the object.*

3.3 Reflectance and Spectral Signatures

The light that is reflected by an object depends on two things:

- The light that *illuminates* the object
- The *reflectance* of the object

Reflectance is a physical property of the object surface. It is the percentage of incident EMR of each wavelength that is reflected by the object. Because it is a physical property, it is not affected by the light that illuminates the object.

Figure 9 shows the reflectance for four different things: a Cessna airplane wing, a Cessna airplane cowling, a yellow taxi roof, and dry grass. Each object's reflectance is plotted on the chart as a function of wavelength; such a chart is known as a *spectral signature*.

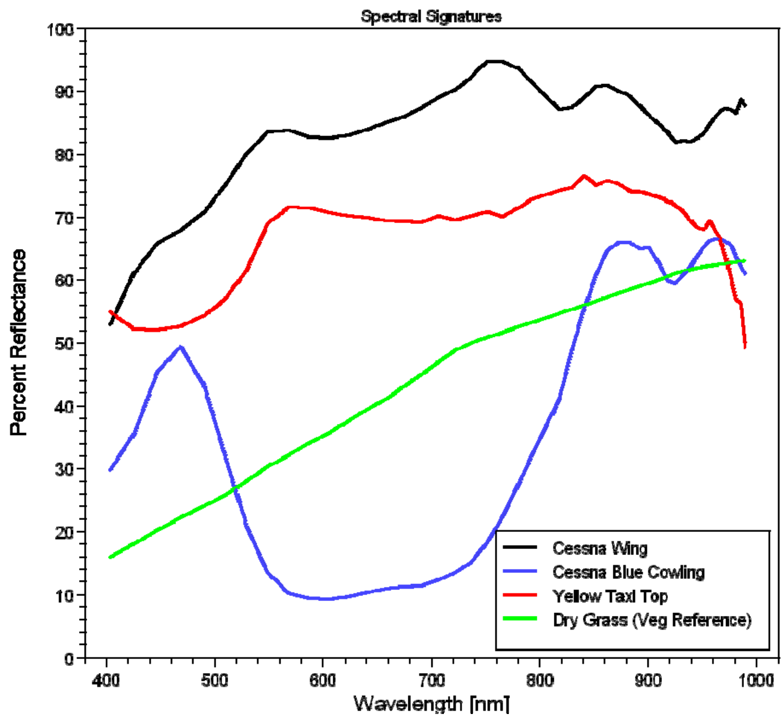

Figure 9. Examples of Spectral Signatures

A spectral signature is a unique characteristic of an object. You can think of it as an EMR "fingerprint." One of the ways a hyperspectral system can detect objects is by comparing reflected light with a library of spectral signatures. When a match is found, the object is automatically selected and highlighted for further inspection.

Note that the wavelengths of the spectral signatures in the figure range from 400 nm to 1000 nm (one micrometer). This is a typical operating range for a VNIR HSI system. Recall that the wavelengths for visible light range from 400 nm to 700 nm. Thus, a VNIR HSI system can sense wavelengths in the near infrared region that our eyes cannot see, and can use the extra spectral information to help detect objects. As you can see, the visible spectrum is only one-half of the total wavelength range that is sensed and measured.

3.4 Reflectance and Reflection

Because reflectance is a physical property, it does not depend on the light that illuminates an object. For example, consider the data for the Cessna blue cowling in Figure 9 (the blue line). Note the 50% peak at about 470 nm, which is blue light. This means that 50% of incident light at 470 nm will be reflected. About 10% to 12% of incident light at wavelengths from 550 nm to 700 nm is reflected, too. However, if light at any of these wavelengths is to be reflected, *it must be present in the light that illuminates the object*. If there is no 470 nm light in the illumination, then there is none to be reflected. But, *the absence of 470 nm light does not change the cowling's ability to reflect it*.

Here are some illustrative examples of reflectance and reflection:

- A white sheet of paper reflects all the visible wavelengths. However, if the paper is taken into a room that is illuminated only with red light, then the paper will appear red. This occurs because, even though the paper is capable of reflecting all visible wavelengths, only red wavelengths are present. Thus, only red wavelengths can be reflected, so the paper appears red.
- Likewise, if the white paper is taken into a room that is illuminated only with green light, then the paper will appear green. Since only green wavelengths are present, only green wavelengths can be reflected.
- For both cases, *the reflectance of the paper has not changed*—it is still *capable* of reflecting all the wavelengths of visible light.
- Figure 10 illustrates the effects of different wavelength illumination on the same sheet of white paper, where the reflection changes although the reflectance does not.

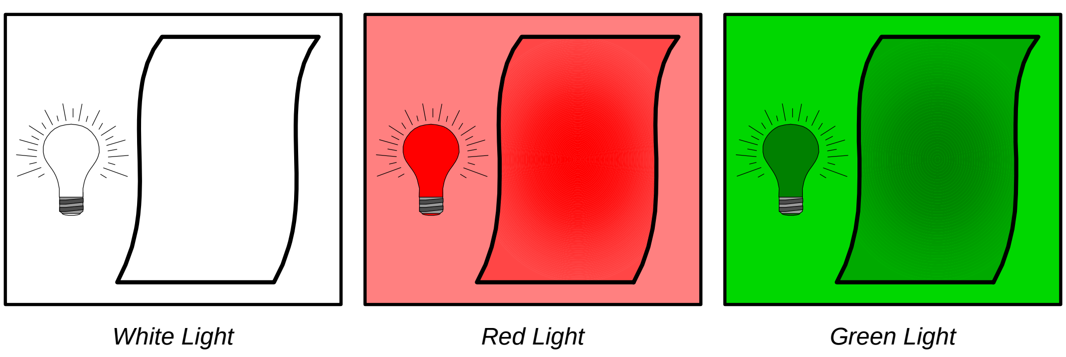

Figure 10. Effect of Illumination on Reflection with Constant Reflectance: Case 1

- A green piece of paper absorbs most visible light, but it reflects green wavelengths. Under white light illumination, the paper appears green. If it is taken into a room that is illuminated only with red light, then the green paper will appear black. This occurs because there is no green light to be reflected, so the paper reflects nothing, and therefore appears black. The fact that no green light illuminates the paper does not change its reflectance, which is its *capability* to reflect green light. As you would expect, if a green paper is illuminated with green light, it appears green–however, because the paper will appear brilliant relative to other nearby items, your brain may make you think it looks white!

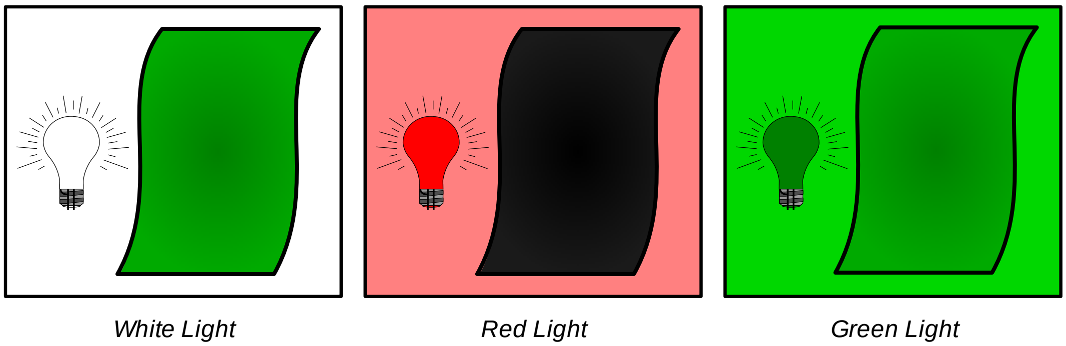

Figure 11. Effect of Illumination on Reflection with Constant Reflectance: Case 2

For both examples described above, keep in mind these two important points:

The reflectance *did not change*.

- The reflection *did* change but only because the composition of the illuminating light changed.

4.0 Remote Sensing

Simply stated, remote sensing is sensing something from a distance. HSI systems are remote sensing systems because they sense the light that is reflected from objects that are usually some distance away from the sensing system.

Many applications of HSI technology involve airborne and satellite-borne systems. These remote sensing systems sense the light that is reflected from the ground and from objects on the ground as the system passes overhead.

The light that is sensed by a remote sensing system is affected by the distance between the system and by the source of the light. An HSI system must account for these effects when comparing sensed spectra to spectral signatures.

4.1 Overview

The space between the ground and an airborne HSI system is, of course, filled with air. The air contains gases, water vapor, pollutants, and particulates. These atmospheric components affect the light that illuminates the ground. They also affect the light that is reflected from the ground. By the time light reaches an HSI sensor, it has undergone some significant changes from its original source. The following processes affect the light that is sensed by a remote sensing system:

1. Illumination – Light has to illuminate the ground and objects on the ground before they can reflect any light. In the typical remote sensing environment, which is outdoors, illumination comes from the sun. We call it solar illumination.
2. Atmospheric Absorption and Scattering of Illumination Light – As solar illumination travels through the atmosphere, some wavelengths are absorbed and some are scattered. Scattering is the change in direction of a light wave that occurs when it strikes a molecule or particle in the atmosphere.
3. Reflection – Some of the light that illuminates the ground and objects on the ground is reflected. The wavelengths that are reflected depend on the wavelength content of the illumination and on the object's reflectance. The area surrounding a reflecting object also reflects light, and some of this light is reflected into the remote sensor.
4. Atmospheric Absorption and Scattering of Reflected Light – As reflected light travels through the atmosphere to the remote sensor, some wavelengths are absorbed, some are scattered away from the sensor, and some are scattered into the sensor.

These four effects all change the light from when it leaves its source until it reaches the remote sensor. After the reflected light is captured by the remote sensor, the light is further affected by how the sensor converts the captured light into electrical signals. These effects that occur in the sensor are called *sensor effects.*

Each of these effects is described in more detail below.

4.2 Illumination and Atmospheric Scattering

During the daytime, an object on the ground is illuminated by several sources. Some of these sources are illustrated in Figure 12:

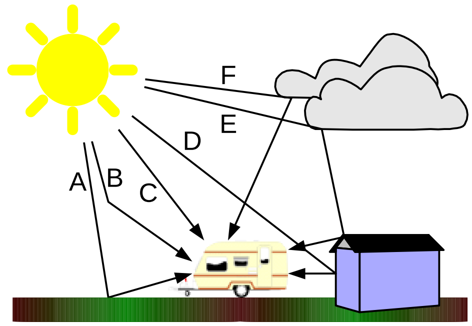

Figure 12. Varied Illumination Sources

In Figure 12, we see that an object (here a travel trailer) is illuminated by sunshine several ways. Some of them are as follows:

- A – Light from the sun is reflected by the ground and illuminates the travel trailer.
- B – Light from the sun is scattered by the atmosphere and illuminates the travel trailer.
- C – Light from the sun is neither scattered nor absorbed, and it directly illuminates the travel trailer.
- D – Light from the sun is reflected by the blue building and illuminates the travel trailer.
- E – Light from the sun is reflected by the clouds and then by the roof on the building, and then illuminates the travel trailer.
- F – Light from the sun is reflected by the clouds and illuminates the travel trailer.

For simplicity, many illumination sources are not shown in the figure. For example, consider this source:

Sunshine is scattered by the atmosphere, then

Reflected by a cloud, then

Scattered again by the atmosphere, then

Reflected by the blue building, then

Scattered by the atmosphere, then

Reflected from the ground, then

Illuminates the travel trailer.

Every time light is scattered its wavelength composition changes. For example, atmospheric gas molecules scatter sunlight, but they scatter blue and violet light much more than other colors. (This is why the sky is blue– when we look at the sky we see scattered blue light.) So, by the time sunlight reaches the ground, some of its blue and violet wavelengths are already gone. They have been scattered or absorbed in interactions with all the things that make up the atmosphere–different gases, water vapor, dust, pollutants, etc.

We also know that *every time light is reflected, its wavelength composition changes*, based on the reflectance of the reflecting object.

4.3 Atmospheric Absorption

In addition to scattering light, the components in the atmosphere also absorb light. For example, oxygen, which makes up about 20% of earth's atmospheric gases, absorbs near infrared EMR at 762 nm. Water vapor in the air absorbs near infrared EMR at 720 nm, 810 nm, and 945 nm. The absorption at 945 nm is particularly strong. Thus, by the time EMR from the sun (solar illumination) reaches the ground, the atmosphere has absorbed some of the light at these and other wavelengths.

Figure 13 shows the effects of atmospheric scattering and absorption on solar radiation. The red line in the figure shows the wavelength composition of EMR from the sun that enters Earth's atmosphere. The black line shows the wavelength composition that reaches the ground. The blue vertical lines represent the lower and upper limits of the sensitivity range of a typical VNIR remote sensing system.

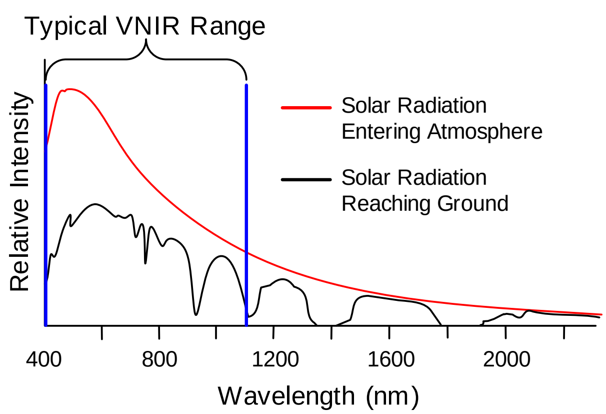

Figure 13. Atmospheric Effects on Solar Radiation

Observe that, near 1400 nm and 1800-1900 nm, no solar radiation reaches the ground. This occurs because carbon dioxide and water vapor absorb *all* the EMR at these wavelengths.

Figure 14 shows a detail view of the solar radiation reaching the ground. Note the steep drop-off at low wavelengths. This is caused by the great amount of blue light scattering that occurs in the atmosphere. The steep valleys in the curve are caused by absorption of specific wavelengths by water vapor and gases in the atmosphere.

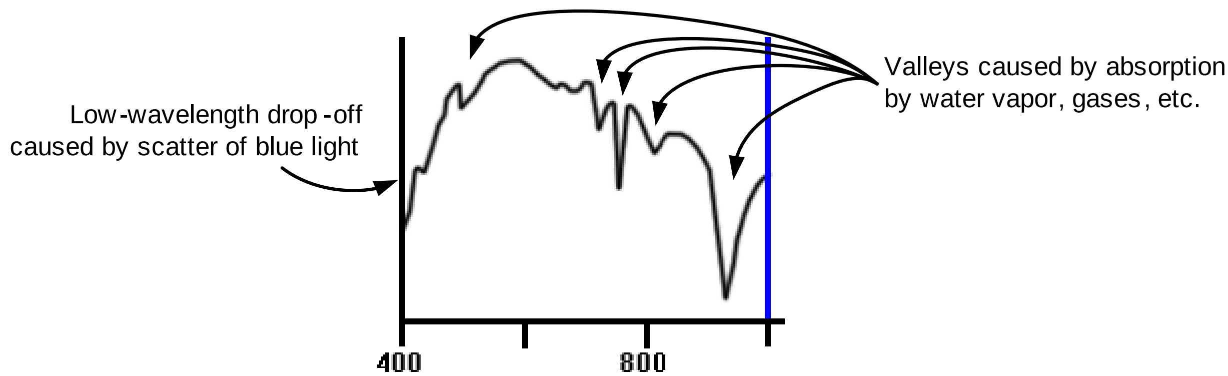

Figure 14. Detail of Solar Radiation Reaching Ground

So, objects on the ground are illuminated by the sun, but only some of the light is direct sunlight. Some of it is scattered light, and some of it is reflected light. Reflected light can have a big impact on illumination. For example, a white vehicle next to a blue building can appear to have a blue tint because it is illuminated partially by blue light that is reflected from the building.

Earth's atmosphere scatters blue light everywhere in the world. Likewise, it absorbs some specific wavelengths everywhere. These general effects affect everything equally throughout the world, so we needn't be concerned about them changing. However, some scattering and absorption effects can be localized to a geographic or urban region. Consider the following examples:

- The southeast USA is generally more humid than the southwest USA. Thus, in the southeast there is usually more water vapor in the air, so there is more absorption of certain wavelengths in the southeast than in the southwest. But, even in the southeast, occasionally there are days when the relative humidity is low or especially high, so the water vapor-related absorption and scattering effects can change from day to day.

- The air in some urban and industrial areas contains more pollutants than in rural areas. Some pollutants absorb and scatter light of various wavelengths, which affects illumination that reaches the ground. Changing weather conditions can clear out or concentrate regional air pollution, so the related scattering and absorption effects can change from day to day or even during a single day.

Two more things that change atmospheric absorption and scattering are the time of day and the time of year. These are called temporal effects because they are related to time. During the early and late parts of the day, sunlight travels farther through the atmosphere before it reaches a particular point on the ground than it does at midday. In the northern hemisphere, sunlight travels farther through the atmosphere during winter than during summer before reaching the ground. When sunlight travels farther through the atmosphere, more of the light is absorbed and scattered than would be if the sunlight traveled a shorter path, so the illumination at the ground is different. For both these cases, the illumination comes to the ground at a steeper angle, so there is less light available for reflection upward towards the HSI system. Thus, there is poorer illumination and poorer reflection during early morning and evening, and during winter time. Conversely, there is better illumination and better reflection during midday and during the summer.

So, the light that illuminates an object on the ground is not pure sunlight—it's a mish-mash of different wavelength compositions resulting from absorption, scattering, and reflection as the light travels from the sun to the object.

4.4 Reflection

As we have already learned, the light that is reflected by an object depends on the light that illuminates the object and on the object's reflectance. When an object is outdoors, we usually think that the object is illuminated directly by sunshine. However, as was shown in the previous section, there are many illumination sources that begin as sunlight but are changed before the light reaches the object.

We also know that wavelengths that are not present in the illumination cannot be reflected. And, now we know that when light reaches an object, the intensities of certain wavelengths have been reduced from absorption and scattering, and some wavelengths may have higher intensities caused by reflection from nearby objects.

4.5 Atmospheric Absorption and Scattering

The atmospheric absorption and scattering effects that occur between the Sun and the ground also occur between the ground and the remote sensing system. However, because the ground-to-system distance is so much less than the distance from the top of the atmosphere to the ground, the effects are not as great.

However, there is another scattering effect between the ground and the remote sensing system. Even though the system sensors may look straight down from an aircraft or satellite, reflected light from the surroundings is scattered into the system sensors. This effect is called *path radiance*. Path radiance is illustrated in Figure 15.

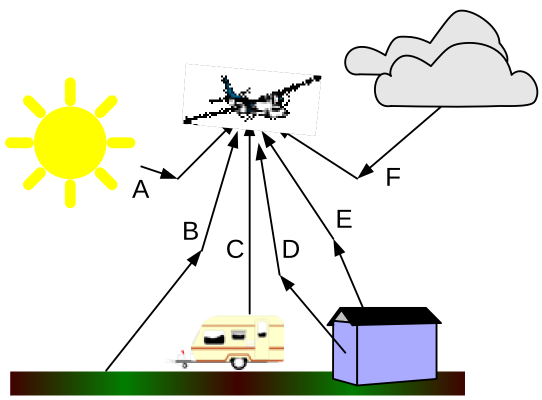

Figure 15. Reflection and Path Radiance

Of the six EMR sources entering the remote sensing system in Figure 15, only one – C – is light reflected directly from the object on the ground. All the others are sources of extraneous light that enter the system sensors. As labeled in the figure, the light sources that make up path radiance are as follows:

- A – Sunshine is scattered into the sensor path
- B – Light reflected from the ground is scattered into the sensor path
- D – Light reflected from the blue building is scattered into the sensor path
- E – Light reflected from the roof is scattered into the sensor path
- F – Light reflected from the clouds is scattered into the sensor path

Scatter from ground reflections (effects B, D, and E) are the major contributors to path radiance. We will look at these effects in more detail shortly.

4.6 Sensor Effects

So far we have addressed the light that reaches the ground, the light that is reflected by an object, and the light that reaches the HSI system sensors. The next effect is from the sensors themselves.

You will have noticed by now that the behavior of EMR when it interacts with matter depends very much on the wavelength of the EMR. This is true also for the materials that are used to focus, disperse, and measure the various wavelengths of light that enters the hyperspectral sensor.

For most materials, there is a specific wavelength at which the interaction of EMR results in the greatest response. At wavelengths close to this optimal wavelength, the response is not as great. The response falls off as the wavelength of the EMR is farther and farther from the optimal wavelength.

Every individual component that interacts with the sensed light in the hyperspectral sensor has an optimal wavelength. In fact, sensor manufacturers select materials that have optimal responses in the EMR range of interest. For most VNIR systems, the range of interest is about 400 nm to about 1100 nm. The sensor response has been optimized for this range by the selection of materials. However, because of accuracy requirements, some VNIR systems limit their calculation ranges to narrower spans of the VNIR spectrum. For example, one typical VNIR system is sensitive to EMR wavelengths ranging from 500 to 100 nm, but it only performs processing calculations in the wavelength range from 500 nm to 960 nm. The overall spectral response of such a sensor is shown in Figure 16.

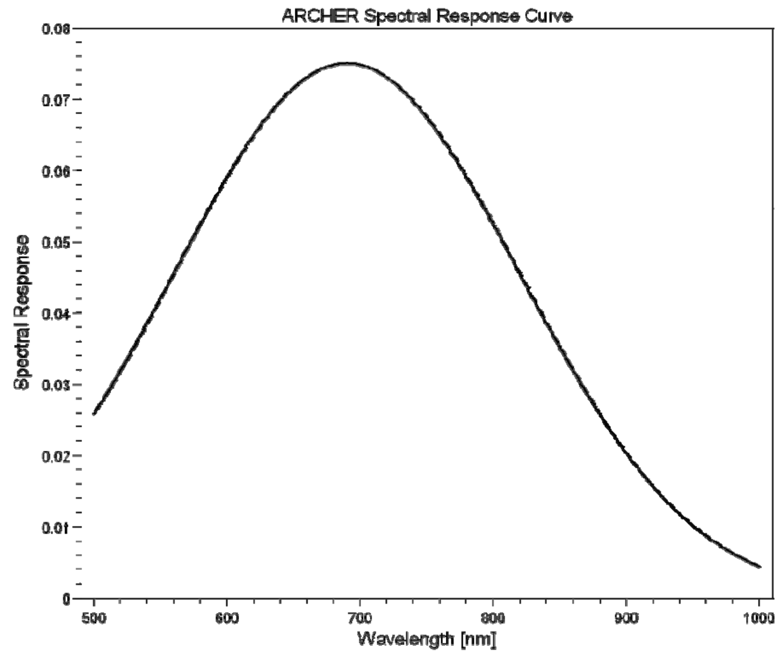

Figure 16. Typical HSI Sensor Overall Spectral Response

From Figure 16 we can see that the optimal wavelength for spectral response is about 700 nm. This is good, because the best response is near the center of the useful range of interest—500 nm to 960 nm.

EMR wavelengths in the middle of the range drive a good sensor response, while EMR at either end of the band receives a much lesser response. However, because the sensor always responds the same way to the same wavelengths of EMR, software programs can compensate for the lower response at the edges of the range.

4.7 Spectral Signatures in the Field

Now, let's tie all these remote sensing effects together, and see how they affect the spectral signature of a blue Cessna cowling.

When searching for something using an HSI system, the object of interest isn't expected to be in the middle of a bare patch of ground. There will be natural elements surrounding it. These natural elements will reflect light that will be scattered into the HSI sensor. For simplicity, we will use healthy vegetation and dry grass as examples. So, let's look at the spectral signatures of a blue cowling, healthy vegetation, and dry grass. These spectral signatures are shown below in Figure 17. Note that all three spectral signatures indicate high reflectance of near infrared wavelengths.

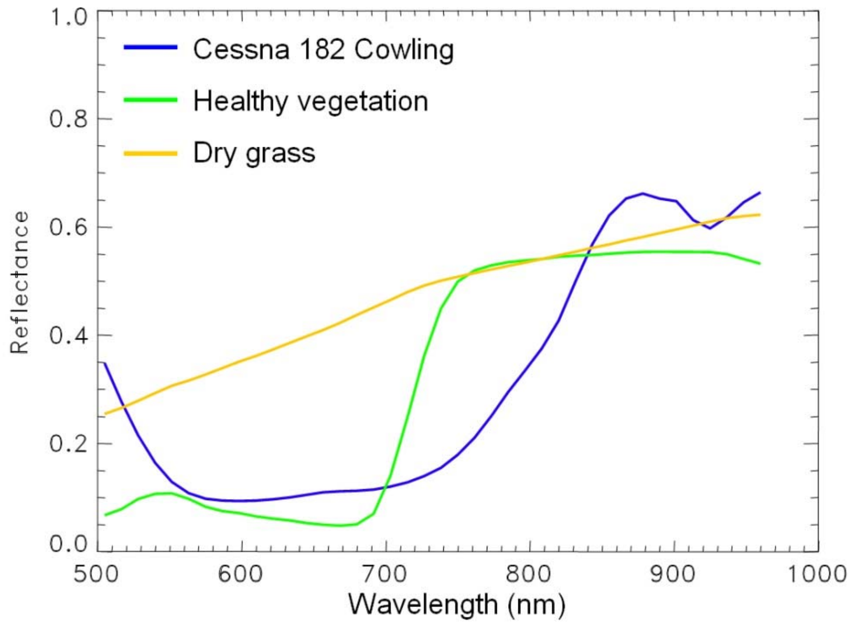

Figure 17. Sample Spectral Signatures

To understand the challenges that complicate remote sensing, we must look at the wavelength composition effects of the illumination-reflection-analysis process. The three parts of the process are:

- The Light That Illuminates an Object. Recall that the light that illuminates the ground starts as sunlight, but is modified by atmospheric absorption and scattering. Reflection and scattering from nearby objects also contribute to illumination. Thus, the illumination of an object depends on atmospheric conditions and the surroundings. See Figure 12 on page 15 for an illustration of these effects.
- The Light That is Reflected From an Object. Recall that the light that is reflected from an object starts out as illumination, but is modified by the object's reflectance. Thus, the light that is reflected by an object depends on the illuminating light and the object's reflectance.
- The Light That Reaches the Sensor. Recall that the light that reaches the sensor starts out as the light that is reflected by the object, but it is modified by atmospheric conditions and by light that is scattered into the sensor field of view by the surroundings (path radiance). Thus, light measured at the sensor depends on light that is reflected by an object, atmospheric conditions, and the surroundings.

The three parts of the illumination-reflection-analysis process are illustrated in Figure 18.

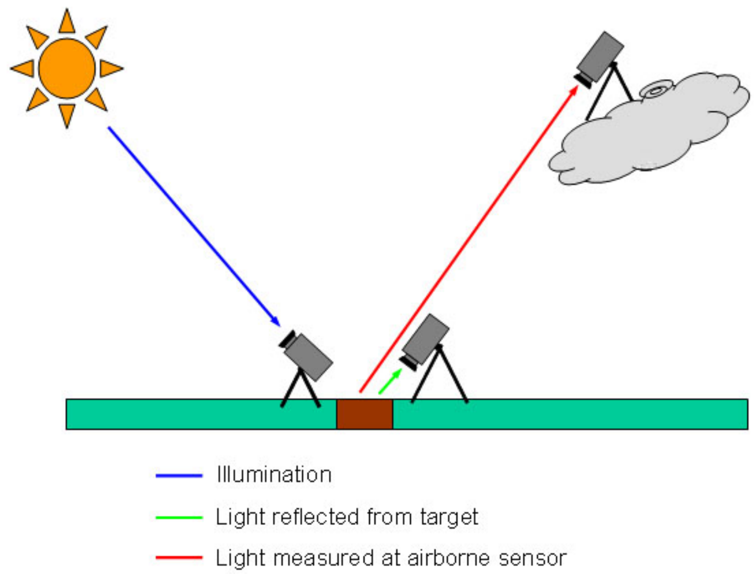

Figure 18. Light Measurement Locations

We start with the cowling reflectance, shown above in Figure 17. The next figure shows the light that illuminates the cowling, the light that is reflected from the cowling, and the light that reaches the sensor. Figure 19 shows data for mid-day clear sky conditions with the cowling surrounded by healthy vegetation.

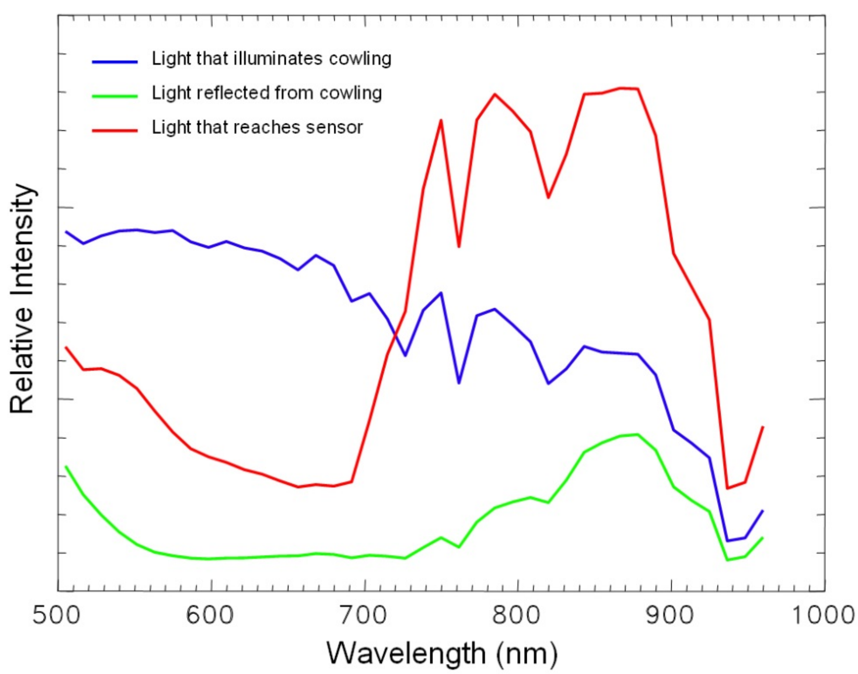

Figure 19. Illumination, Reflection, and Sensed Light for a Cessna Cowling

The blue line in the figure represents the wavelength composition of the light that illuminates the cowling. The absorption bands at 762 nm, 810 nm, and 945 nm are apparent.

The green line represents the wavelength composition of the light that is reflected from the cowling. Keep in mind that for light of a particular wavelength to be reflected, it must be present in the illumination.

The red line shows the wavelength composition of the light that reaches the sensor. Clearly, this graph needs some explaining! We will return to it shortly.

First, let's compare the light that is reflected from the cowling with the reflectance of the cowling. Figure 20 shows the reflectance of the Cessna cowling (from Figure 17) and the light reflected from the cowling (from Figure 19).

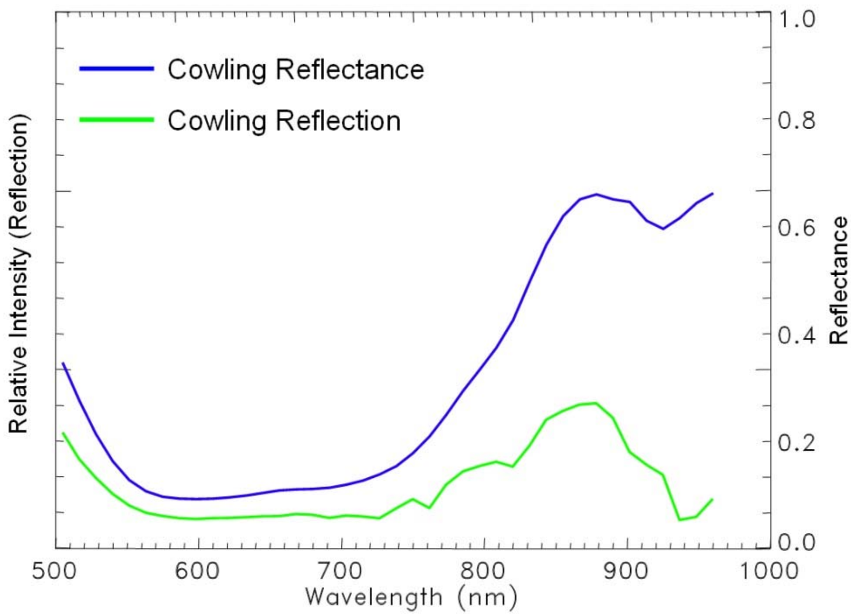

Figure 20. Reflectance and Reflection for a Cessna 182 Blue Cowling

Note that the reflection from the cowling follows the same general curve shape as the reflectance. There are, however, some significant differences. For example, the 945 nm absorption band pretty much prevents reflection of this wavelength. And, even though the cowling reflectance in the NIR range is high, the generally weak NIR content of the illumination prevents the cowling from reflecting much light in this band.

Next, the reflection from the cowling (green line in Figure 20) combines with the path radiance to form the light that is measured at the sensor. The light captured at the sensor is shown in Figure 21.

Note the large near infrared (NIR) component between 700 nm (top of the visible band) and 1,000 nm (top of the VNIR sensor detection range). This infrared component is not present in large amounts in either the illumination or the reflection. From where does it come?

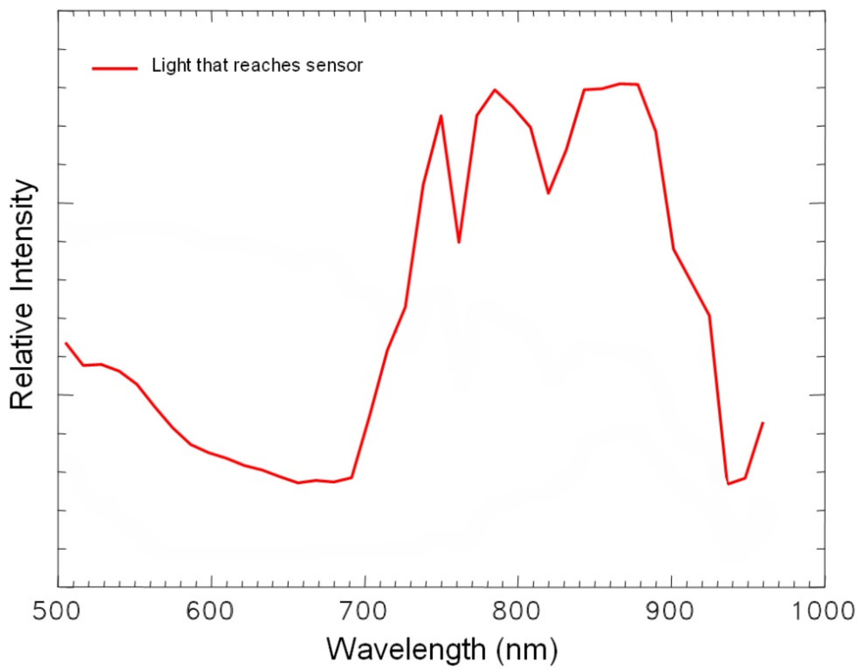

Figure 21. Light Reflected From Blue Cowling Measured at Sensor

The answer is: it comes from the surroundings! Recall that light scattered into the sensor field of view (path radiance) depends on the things that surround the target—healthy vegetation around a Cessna cowling in this example. Take another look at Figure 17 (page 22) and compare the spectral signature of the cowling with the spectral signature of healthy vegetation. They both have high peaks in the near infrared range, and the NIR response for healthy vegetation is very broad. However, the illuminating light does not have strong near infrared wavelengths, so the cowling cannot reflect much near infrared light. The reason that healthy vegetation can reflect so much near infrared light is that there is considerably more vegetation than there is blue cowling.

For example, imagine a cowling lying in a pasture. The reflective surface of the surrounding vegetation is very large compared to the reflective surface of the cowling. Even though the illumination is somewhat deficient in near-infrared light, every small patch of vegetation reflects some NIR. With all the surrounding vegetation, the total amount of NIR light that is reflected is very large. A lot of this reflected NIR light is scattered into the HSI sensor, contributing to path radiance. This causes the high, broad peak of NIR light that is measured at the sensor.

Note also that the light reaching the sensors exhibits the atmospheric absorption bands described in earlier sections.

Now we have an idea for what happens to light when it enters the atmosphere, illuminates a Cessna cowling, is reflected, and then reaches a remote sensor. But, we are not done yet. The next step is to assess the effects of the sensor itself on the measured light.

Figure 22 shows the spectral response of our typical VNIR sensor and the light reflected from the Cessna cowling that reaches the sensor.

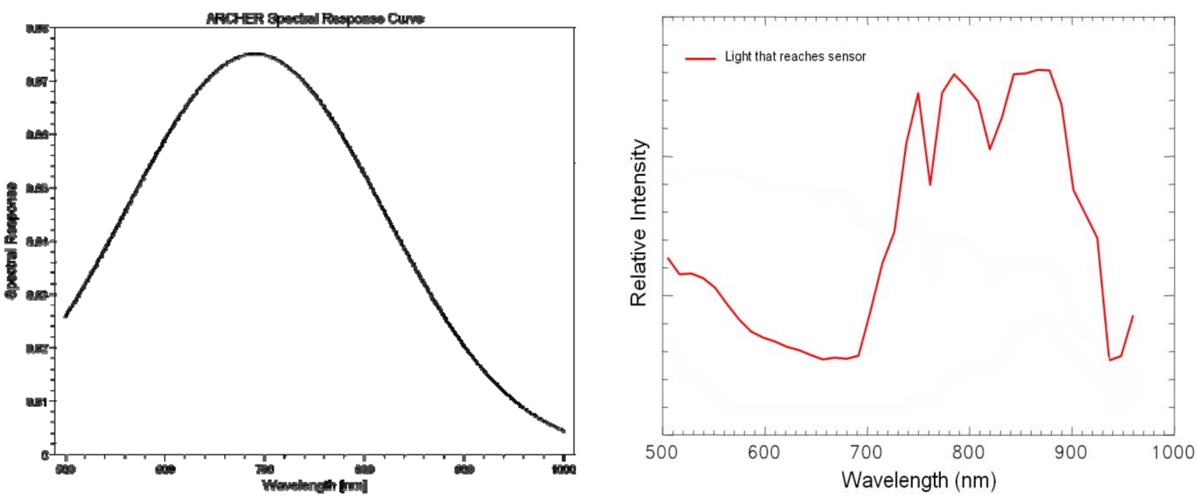

Figure 22. Sensor Spectral Response and Light Reaching the Sensor

When the wavelength composition of the light is actually measured by the sensor, the response characteristics of the HSI system affect the spectral data that are output by the sensor. The spectral shape that is reported by the HSI sensor is called a *spectral intensity*. The spectral intensity for an object differs from the spectral signature—*the spectral intensity includes all the environmental and sensor effects that impact our ability to measure a spectral signature*. The spectral intensity chart for the blue Cessna cowling is shown below in Figure 23.

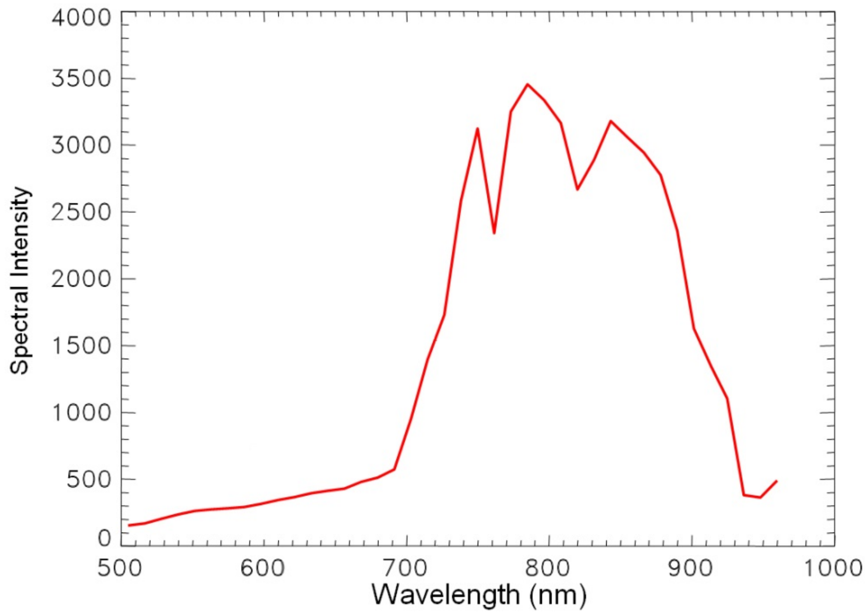

Figure 23. Spectral Intensity of Cessna Blue Cowling

The spectral intensities are collected by the HSI sensor, and then are used by the processing software to detect specific objects and anomalies.

4.8 General Environmental Effects

In addition to the atmospheric and sensor effects described in the previous section, there are other environmental effects of a more general nature. These general effects are the following:

- *Because the VNIR sensor depends on reflected light, adequate illumination must be available*. For example, missions cannot be flown at night. And, solar illumination is more intense at midday than early morning or late evening. It is also more intense during the summer than in the winter and more intense on sunny days than cloudy days. The different illumination intensities affect the intensity of reflected light, and so also affect the intensity of light measured by the sensor. This is shown below in Figure 24, where the only difference between the two graphs is the time of season and time of day. Note how the reduced illumination causes significant reductions in spectral intensity.

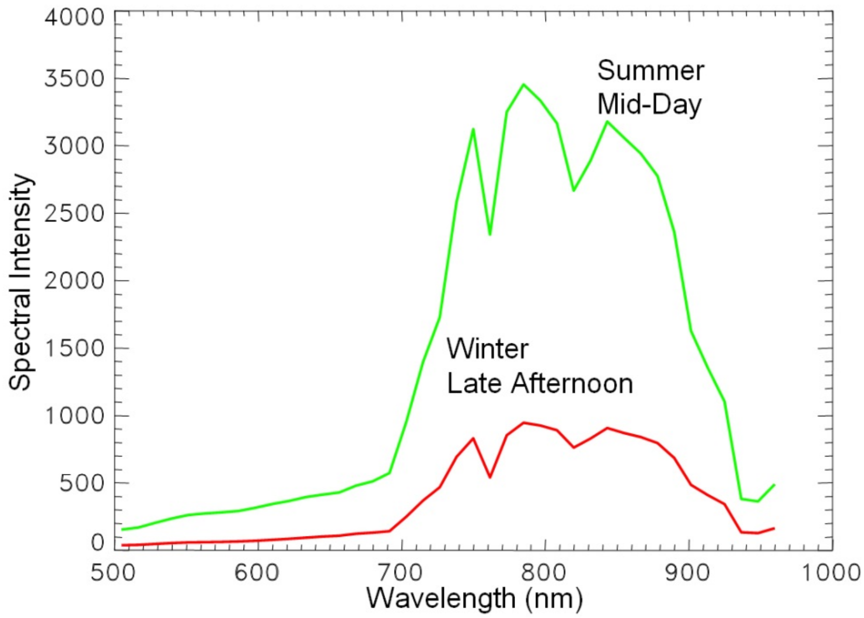

Figure 24. Spectral Intensities for Different Illumination Conditions
Blue Cowling Surrounded by Healthy Vegetation; Clear Skies

- *The natural surroundings in a search area have a significant impact on spectral intensities*. Recall that healthy vegetation produces a very broad, high amplitude peak in the near-infrared wavelengths. This is caused by NIR light being scattered into the sensor field of view (path radiance). Dry grass has a different spectral signature, and will cause different path radiance. For example, Figure 25 shows the spectral intensities for a Cessna blue cowling under the same illumination conditions as Figure 24, but the cowling is now surrounded by dry grass.

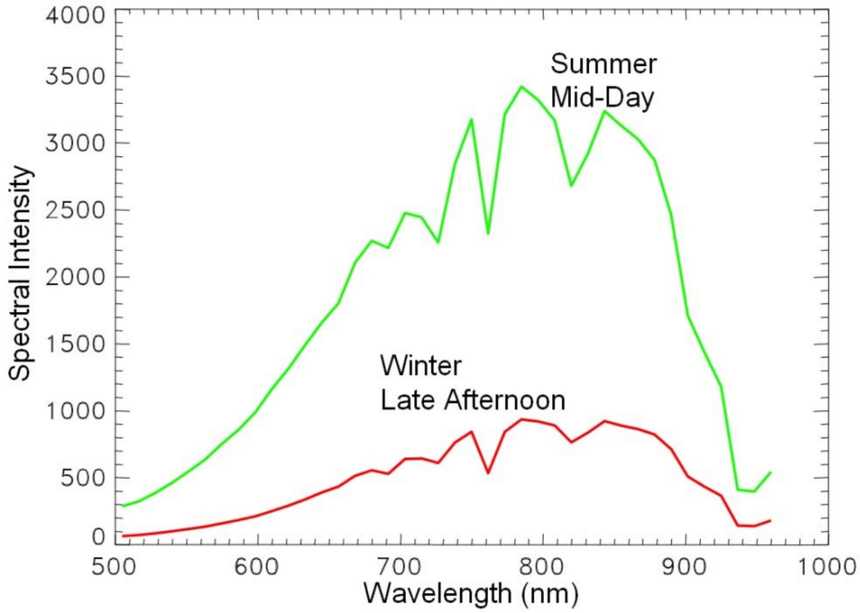

Figure 25. Spectral Intensities for Different Illumination Conditions
Blue Cowling Surrounded by Dry Grass; Clear Skies

Note how the maximum intensity has shifted to the left with dry grass surrounding the cowling. (You may want to take another look at the spectral signature for dry grass in Figure 17 on page 22.)

- *Relative humidity and haze vary regionally in the United States*. Arid regions, such as the desert southwest, experience less absorption of light by water vapor in the atmosphere than do humid regions in the eastern and southern parts of the US. Because higher humidity and haze cause more absorption and more scattering of light, less of the reflected light from a target reaches the sensor. Figure 26 and Figure 27 illustrate the downward shift in spectral intensities from summer mid-day clear sky conditions to summer mid-day haze conditions. Figure 26 shows the shift for a Cessna cowling surrounded by healthy vegetation. Figure 27 shows the same data with the cowling surrounded by dry grass.

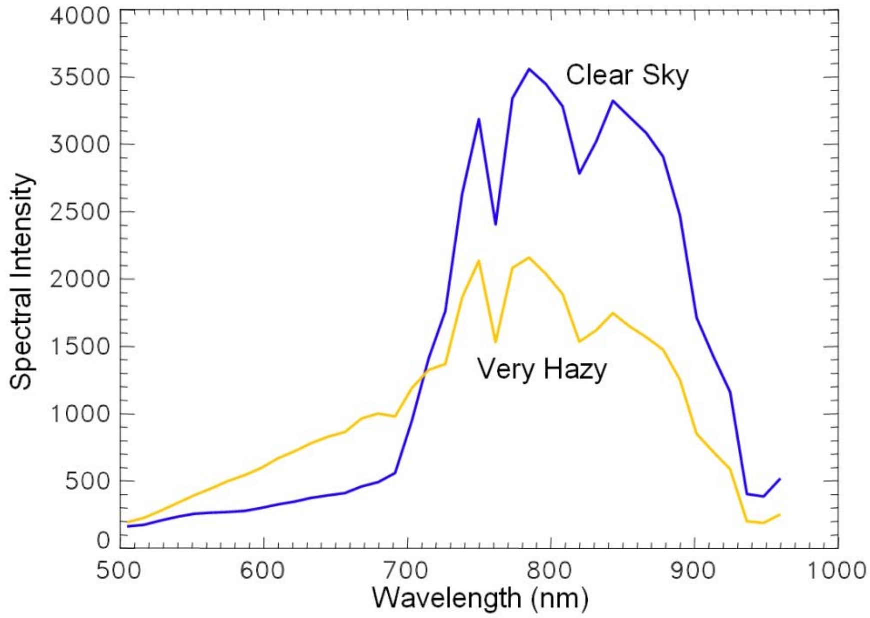

Figure 26. Spectral Intensities for Different Sky Conditions
Blue Cowling Surrounded by Healthy Vegetation; Mid-Day Summer

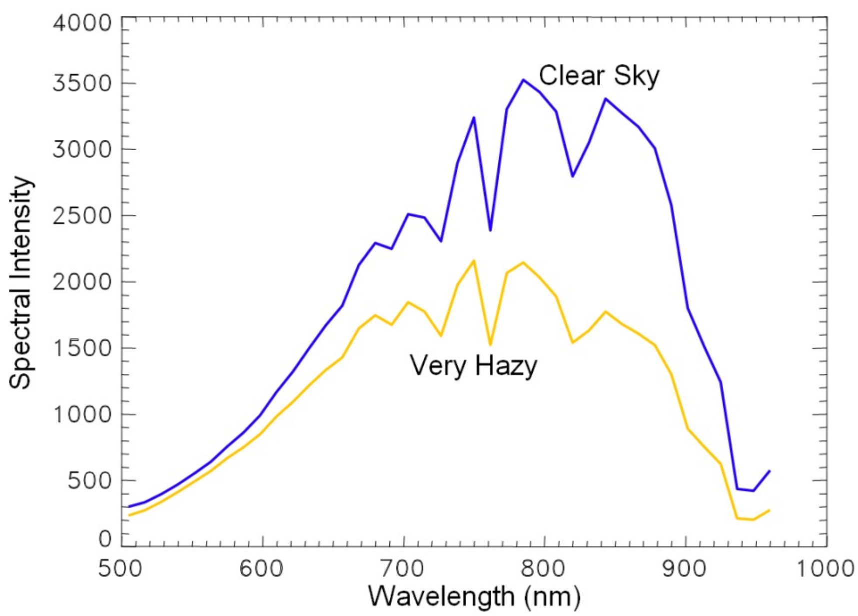

Figure 27. Spectral Intensities for Different Sky Conditions
Blue Cowling Surrounded by Dry Grass; Mid-Day Summer

4.9 Changing Reflectance

The reflectance of an object can be changed by changing its color. When the color of an object is changed, the wavelengths that are absorbed and reflected are changed. This also changes the spectral signature.

Remember: reflectance is a property of the object's surface. The surface color determines what wavelengths are absorbed or reflected. Anything that changes the surface of an object or a substance will change its reflectance. For example, all the following surface changes will change the reflectance of an object:

- Adding a coat of paint (most coatings will also change reflectance in the near infrared band)
- Rust or other corrosion
- Dust accumulation

There are only two ways to change reflection. They are: (1) change the illumination; or (2) change the reflectance.

4.10 Summary

If an object was illuminated by balanced white light, and if there was no atmospheric absorption or scatter, and if the sensor was perfect, then the wavelength composition of reflected light detected by an HSI sensor would match the reflectance, or spectral signature. But, since nothing in the real world is perfect, we end up with scene intensity spectra that look very different from spectral signatures. The good news is that software can correct for these effects in real time as the collected EMR is analyzed.

5.0 Hyperspectral Imagery (HIS)

Now that the fundamentals have been addressed, it is time to tie them all together to see how hyperspectral imaging works.

First, why is hyperspectral imaging called "hyperspectral" imaging? Hyperspectral refers generally to the number of bands into which the spectra are divided. Multi-spectral imaging, which binned the spectrum into a handful of bands, preceded current technology. Hyperspectral imaging uses a far larger number of spectral bands—a typical VNIR HSI sensor may bin the spectral data into 40-60 bands for wavelengths ranging from 500 nm to 1100 nm. Because it divides the spectra into so many bands, it is called *hyperspectral*.

The key component for hyperspectral imaging (HSI) is the HSI sensor. The HSI sensor receives light that is reflected from below and converts it to electrical signals. It accomplishes this with the following components:

- Lenses that focus the incoming light
- A slit that limits the incoming light stream to a very thin but wide beam
- A diffraction grating that disperses the thin, wide beam into its spectra
- Photo-receptors that collect light in specific wavelength ranges (bands) and convert the band intensities to electrical signals

A very simplified diagram of the components is shown below in Figure 28. The figure is followed by a more detailed explanation of how the HSI sensor works.

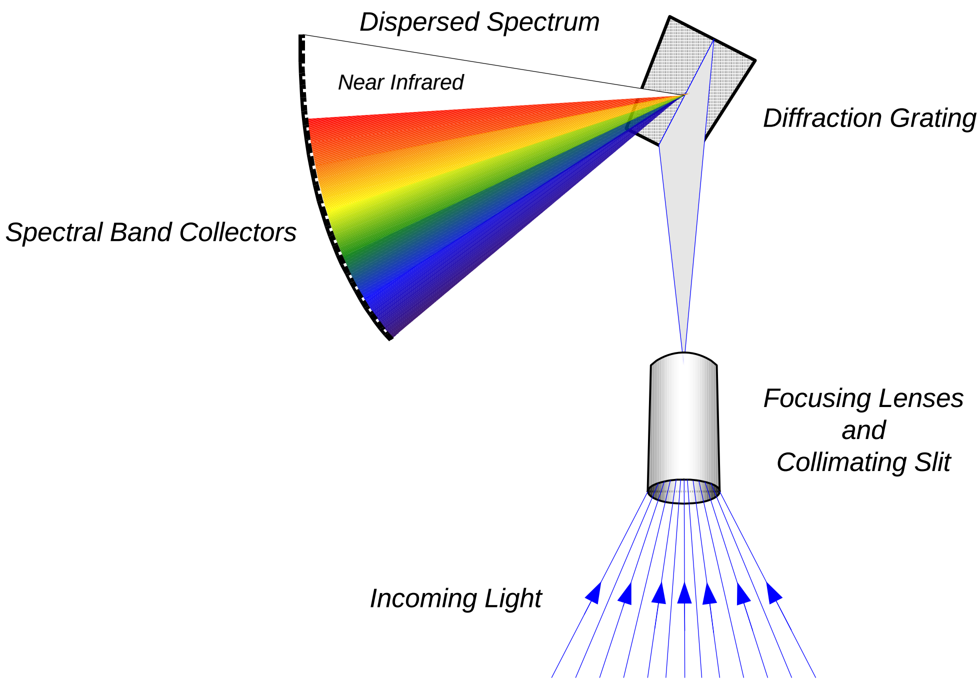

Figure 28. Simplified Diagram of Hyperspectral Imaging Sensor

Sunlight illuminates the ground and objects on the ground. As the aircraft or satellite with the sensor flies over an area, reflected light is collected by the HSI sensor lens. The collected light passes through a set of lenses. The lenses focus the light to form an image of the ground. After passing through the lenses, the light enters a slit that allows only a very thin, flat beam to pass.

The thin, flat beam of light is projected onto a diffraction grating. Recall that a diffraction grating in a very finely etched reflecting surface that very accurately disperses light into its spectra (see page 8). The diffraction grating in a typical VNIR sensor is designed to disperse the visible and near infrared spectra, from 500 nm to 1100 nm. For simplicity, Figure 28 shows only the spectrum dispersal for a very narrow part of the flat beam. In actuality, the entire flat beam is spread into its spectra by the diffraction grating.

The dispersed light is spread across a charge-coupled device (CCD). A CCD is the image receptor in a typical digital camera. Unlike typical digital cameras, however, the CCD in an HSI sensor is also sensitive to wavelengths that are not visible to the human eye.

The CCD measures the spectral intensities of the dispersed light. It converts the intensities to electrical signals. The CCD output consists of electrical signals for each of the spectral bands for each of the image pixels, as shown in Figure 29.

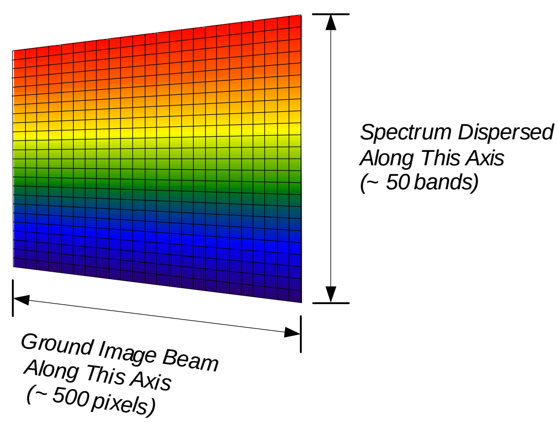

Figure 29. Spectral Dispersion on HSI Sensor CCD

The HSI system on-board computer typically records the CCD output signal sixty times each second. This timing is called a *frame rate*, and its value (60 times per second or 60 Hz) is important for image resolution. At an aircraft altitude of 2500 ft. AGL and a speed of 100 knots, a 60 Hz frame rate equates to a ground image resolution of approximately one square meter per pixel. Thus, every frame captured from the CCD contains the spectral data for a ground swath that is one meter long and 500 meters (~ ½ km) wide.

If the sensor collects spectral data from 500 nm to 1100 nm spread over 50 spectral bands, then each spectral band is about 12 nm wide. This band width is called *spectral resolution*.

Such an imaging system uses a *pushbroom* approach to image acquisition. Pushbroom gets its name from the sweeping movement of the sensor over an area. With the pushbroom approach, the focusing slit reduces the image height to the equivalent of one pixel in the HSI sensor. This forms the thin, wide beam that strikes the diffraction grating. The dispersed spectrum is captured in a frame from the CCD. The aircraft move forward and, 1/60th second later, the next frame is captured. Every 1/60th second, another frame is captured from the CCD. At a ground speed of 100 knots, every 1/60th second the aircraft moves forward about one meter. Figure 30 shows how the aircraft acquires a one-pixel deep by 500-pixels wide frame.

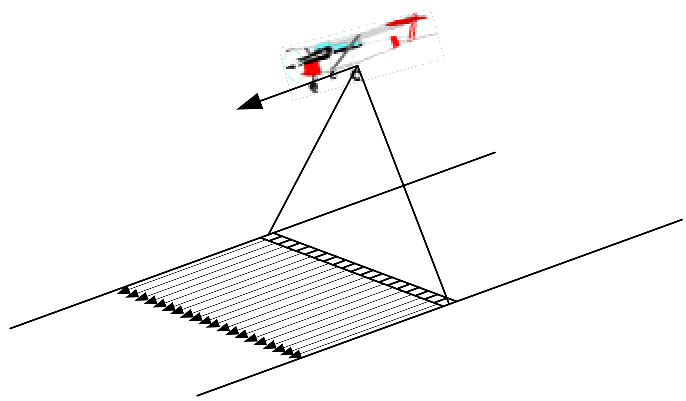

Figure 30. Pushbroom Image Acquisition

With each successive frame, the captured image grows from the top down. Such a top-down image presentation is called a *waterfall display*, because the image pixels appear at the top of the image and fall (move) downward as they are replaced by each new frame at the top. A representation of a waterfall display is illustrated in Figure 31. Note the small red dot that has been added to the lower left corner of the image to show how new frames push the older data downward on the display.

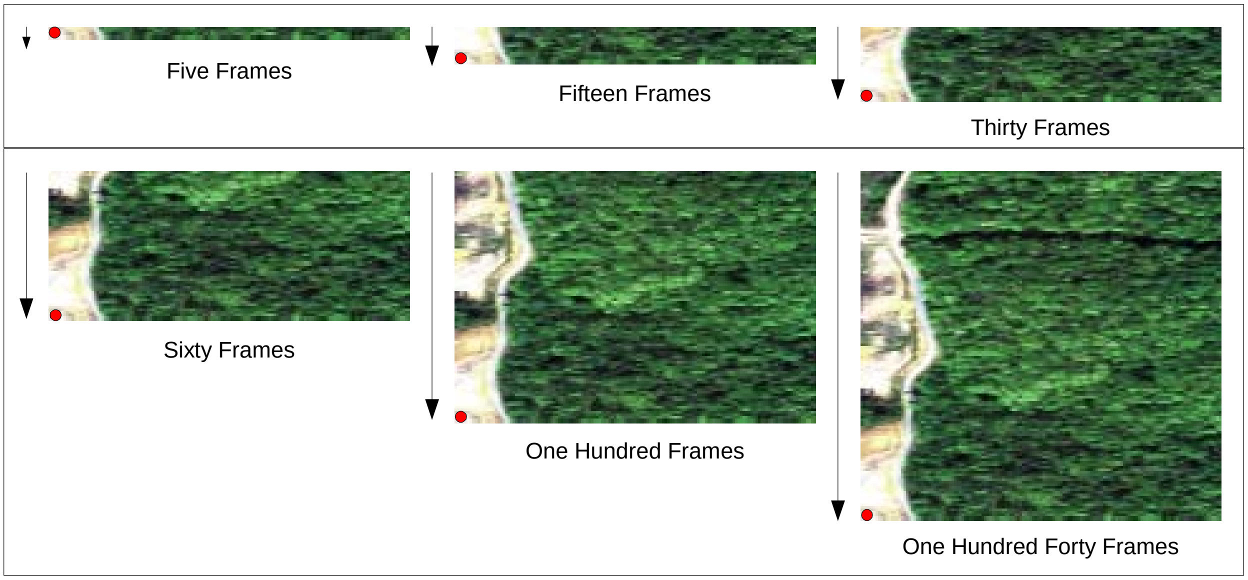

Figure 31. Image Acquisition and the Waterfall Display

Figure 32 shows an actual HSI waterfall display from an HSI sensor test flight conducted in the California desert. It is called a false-color image because the display colors are computer generated. The dark splotches are desert foliage. The thick lines are dirt roads. Can you find the vehicle in the figure? Note how the spectral differences between the vehicle and the desert foliage cause the vehicle to stand out from its surroundings.

Figure 32. Actual Waterfall Display from HSI Sensor Test Flight

In case you could not find the vehicle in the figure above, it is left of the T intersection in the left center of the image.

6.0 High Resolution Imagery (HRI)

To supplement the HSI display, HSI systems usually include a high-resolution (HRI) black-and-white, or *panchromatic*, camera. This camera is mounted adjacent to the HSI sensor to enable both sensors to capture the same reflected light.

The HRI sensor uses a pushbroom approach just like the HSI camera. It has a similar lens and slit arrangement to limit the incoming light to a thin, wide beam. However, the HRI camera does not have a diffraction grating to disperse the incoming reflected light. Instead, the light is directed to a wider CCD to capture more image data. Because it captures a single line of the ground image per frame, it is called a *line scan* camera.

An HRI CCD is usually several thousand pixels wide and one pixel high. It operates at a frame rate that is much faster than that of the HSI sensor–typically several hundred frames per second. The combination of more imaging pixels (several thousand) and the faster frame rate (several hundred Hz) results in a finer resolution that is on the order of a few inches per pixel. This high resolution adds the capability for a human operator to visually evaluate detected objects on the system display.

7.0 Viewing a Target

With two imaging sensors (HSI and HRI), there are three ways to view a target image: the HSI image; the HRI image, and a combination of both, called a fused image. The three views are shown below in Figure 33 for the vehicle seen in the HSI waterfall display (Figure 32).

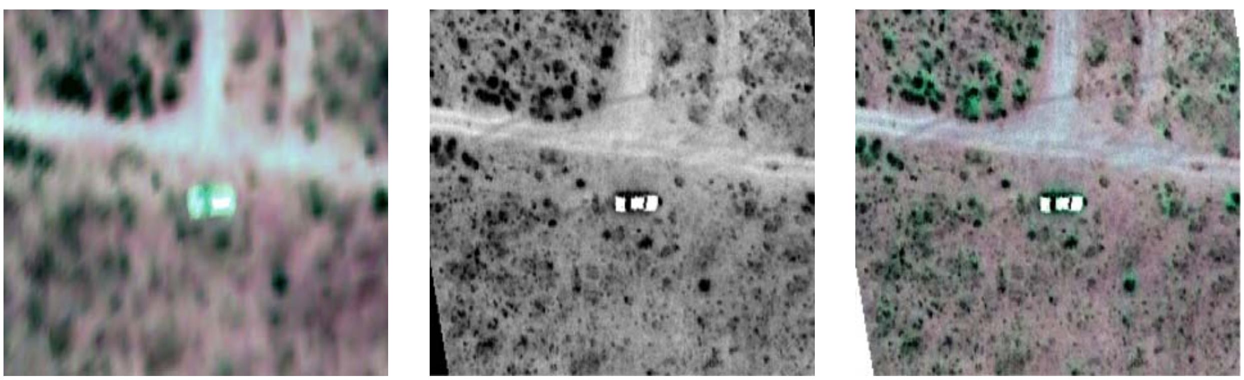

Figure 33. HSI (left), HRI (center), and Fused (right) Images

Notice the difference in resolution between the HSI and HRI images. Recall that the HSI resolution is typically one meter per pixel, and the HRI resolution is much finer: usually a few inches square per pixel. The fused image is usually best because it has high resolution from the HRI camera and color information from the HSI sensor. The combination gives the image good resolution and good contrast, which make image evaluation easier for humans.

An HSI system has two methods for finding things. The first method is by matching reflected light to spectral signatures. This method has already been discussed. It is called *signature matching* because the system uses the spectral signature of an object to detect spectrally similar objects. The second method is called *anomaly detection*. The anomaly detection method continuously calculates a statistical model using all the pixels in the image. For each pixel, it calculates a probability score that the pixel does not fit in the statistical model—that it does not belong in the scene. When the calculated probability is above an adjustable threshold, then the pixel is classified as an anomaly. Anomalies are highlighted on the display so they can be evaluated by the system operator.

The HSI sensor simply needs to capture reflected light to compare with spectral signatures and the statistical spectral model of the search area. When either a signature match or an anomaly is detected, the processor highlights the location of the detected target on the system display.

The HRI sensor must have higher resolution to give the operator an opportunity to identify the object, or at least decide whether or not it deserves closer inspection during the mission flight.

8.0 Current Applications of Hyperspectral Imagery

HSI technology has been around for a few years, but it has been dominated primarily by government agencies and the military. Most of the non-military applications have centered on agriculture and minerals. Real-time analysis of hyperspectral imaging data using commercial off-the-shelf computing equipment is a recent development.

One common HSI application is airborne crop measurement. This method involves flying over crop land with hyperspectral imaging equipment. The data obtained are compared to the spectral signatures of typical crops. Using this method, agrarian economists can more quickly estimate crop yields for the upcoming harvest.

Figure 34 shows a false color image of crops in California. The colored areas are crops that matched spectral signatures. Gray and black areas indicate crops for which there were no spectral signatures.

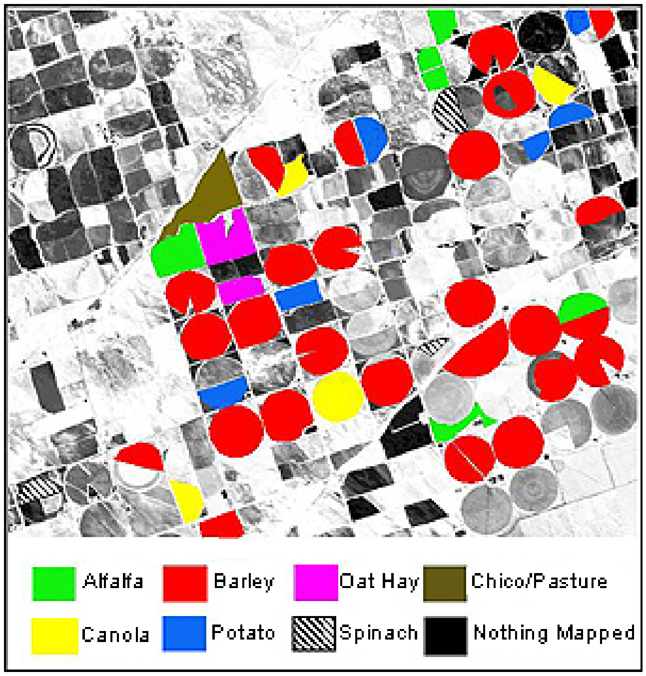

Figure 34. Agricultural Application of HSI

Following the terrorist attacks of September 11, 2001, HSI technology was used to assess the distribution of materials and dust from the World Trade Center (WTC) in New York City. Using spectral signatures for such things as concrete, cement, and gypsum wall board, the dispersion of debris could be tracked using hyperspectral imagery. A hyperspectral image of the WTC area is shown below in Figure 35. This image was acquired by satellite five days after the attacks.

Figure 35. Analysis of Materials from Destruction of the World Trade Center in New York

The world's first fully operational large-scale deployment of hyperspectral imaging technology was put into service by the Civil Air Patrol (CAP), the US Air Force Auxiliary, in 2005 and 2006. The program, named ARCHER (for *A*irborne *R*eal-time *H*yperspectral *E*nhanced *R*econnaissance), consists of 16 systems that have been are deployed across the USA in fixed-wing aircraft to enhance the CAP's capabilities for search and rescue, homeland security, and other missions. The ARCHER software was developed for CAP by Exelis' Space Computer Division of Los Angeles, CA.

9.0 Summary

Light that illuminates an object is reflected, absorbed, or transmitted. The light that is absorbed and reflected gives an object its characteristic color. The ability to reflect light of specific wavelengths is called reflectance. Reflectance is a physical characteristic of the object's surface. It is not affected by illumination.

Reflection is the product of illumination and reflectance. For any given wavelength to be reflected, it must be present in the illumination and be capable of reflection by the object.

Hyperspectral imaging technology uses the light reflected from objects to detect the objects or to discriminate between different objects. Light reflected from objects is dispersed into its spectra and then the intensities of certain precise spectral bands are measured. The resulting intensity values are characteristic of the reflecting objects.

HSI systems use two methods to detect objects: spectral signature matching and anomaly detection.

Spectral signature matching detects specific objects or substances. Spectral signatures for the specific objects or substances are loaded into the processor. When the light that is reflected from an object matches a spectral signature, then the system highlights the object on the system display.

Anomaly detection detects objects that don't belong in the area where they are located. While reflected light is being acquired, the spectral intensities are statistically combined. When detected spectral intensities deviate significantly from the calculated statistical model, the object is classified as an anomaly. Anomalies are highlighted on the system display.

In addition to the hyperspectral sensor, an HSI system includes a high resolution panchromatic camera. The HRI camera creates a high resolution digital image that the operator can use to identify an object or to determine whether or not an object should be further evaluated.

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