Remote Sensing

Electromagnetic Radiation and Spectral Reflectance

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In this module we will explore the key, physical concepts important to remote sensing. Specifically, we will explore the nature of electromagnetic (EM) radiation and how it interacts with the atmosphere and Earth's surface.

After completing this module, you will have an understanding of spectral reflectance and/or emittance of different Earth surface materials and how a subset of this information can be represented as a multiband image.

Module Topics

1. The remote sensing system
2. Electromagnetic radiation
3. Stefan-Boltzmann Law
4. Wien's Displacements Law
5. Atmospheric absorption
6. Spectral reflectance
7. Spectral reflectance of vegetation; water, snow, and clouds; minerals, rocks, and soil; and man-made materials
8. Image data structure

These are the topics covered in this module.

Electromagnetic Radiation

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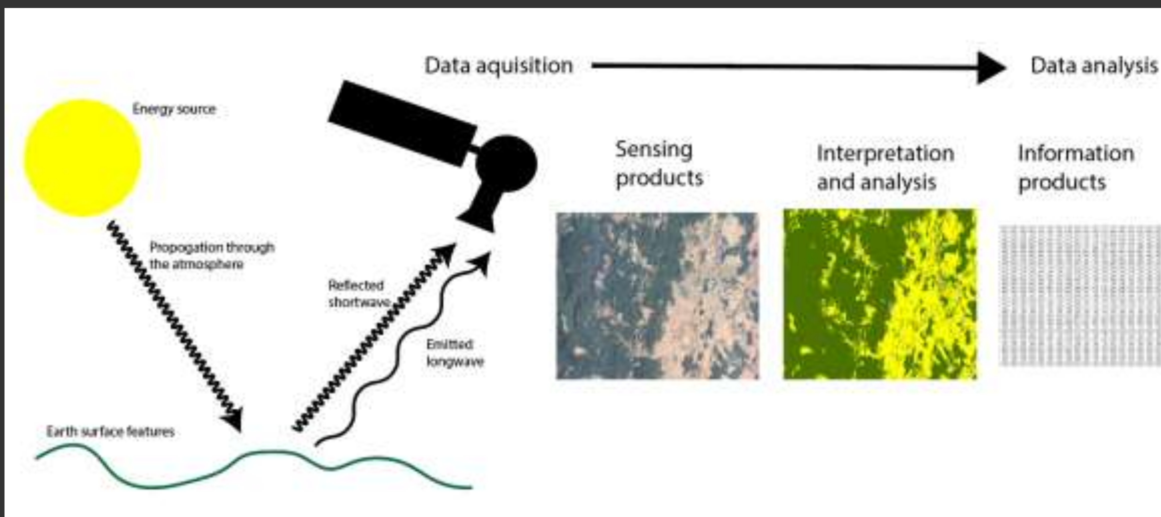
The Remote Sensing System



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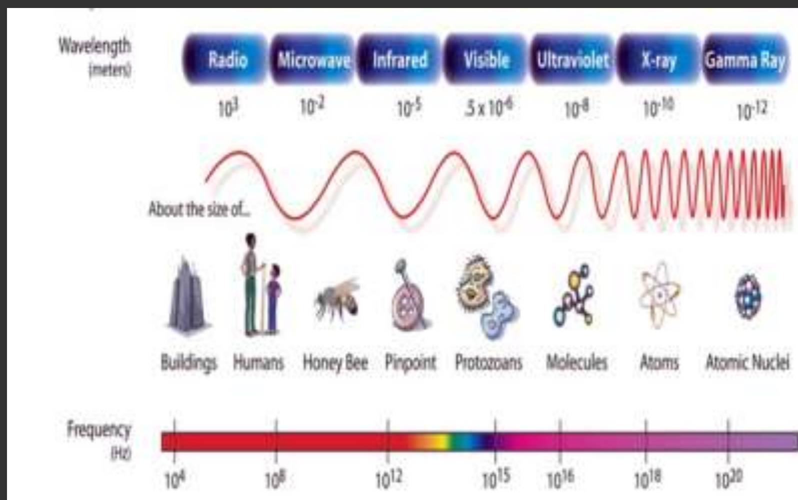
This slide shows a conceptual model of the remote sensing system. First, an energy source must illuminate the target or Earth's surface. For passive remote sensing, this is generally the Sun. For active remote sensing, the illumination is provided by the sensing system, such as laser pulses for LiDAR or radio waves/microwaves for SAR.

This radiation travels from the source to the surface of the Earth. The sensor then detects the proportion of this energy that reflects off the Earth's surface and toward the sensor. In other words, it can detect energy that is emitted from the Earth's surface after it has subsequently absorbed the incoming energy.

The collected information is then stored as digital data, such as a multiband image. These data can then be used to make interpretations or undertake analyses, which allows us to generate information to make informed decisions and understand the Earth's surface and its processes.

Electromagnetic Spectrum



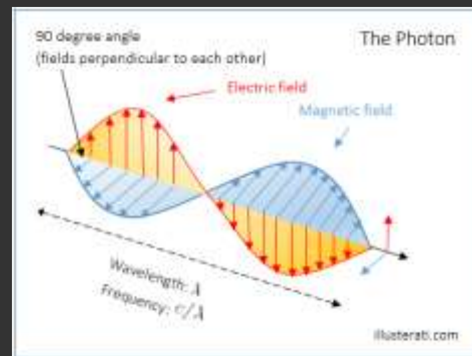
https://commons.wikimedia.org/wiki/File:EM.png

Visible light, which our eyes have evolved to sense, is a thin sliver of a wide range of EM radiation types including radio waves, microwaves, infrared, ultraviolet, x-rays, and gamma rays.

What differentiates these ranges of EM radiation?

Electromagnetic Wave

- Wavelength = Distance between the crests of two waves
  - meters (m)
  - centimeters (cm)
  - micrometers (µm)
  - nanometers (nm)
- Frequency = Number of waves passing a point in a given time
  - Hz = waves/second
- Speed of Light = Wavelength x Frequency



https://commons.wikimedia.org/wiki/File:The_Photon.png

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Different types of electromagnetic radiation will vary in regards to wavelength and frequency. EM radiation is generally conceptualized as an oscillating wave with crests and troughs. The wavelength of a wave is the distance between the same point on two adjacent waves, for example the distance from crest-to-crest or trough-to-trough. Since this is a distance, it is measured in distance units, such as meters, centimeters, micrometers, or nanometers. EM radiation can also be characterized by frequency, which is the number of waves passing a point in a given time. This is commonly measured in waves per second, one over seconds, or Hertz (Hz).

All radiation travels at the same speed in a vacuum, regardless of the frequency or wavelength. Further, they travel very fast at 3 times 10 to the 8th meters per second. Multiplying the wavelength and frequency will yield the speed of light. Wavelengths are measured in length units, for example meters, while frequency is measured in Hertz, or one over seconds. So, multiplying these measures together will yield meters per second, or velocity.

Wavelength and frequency are inversely related. As one goes up the other goes down. For example, radio waves have a long wavelength but a low frequency. In contrast, x-rays have a high frequency and a short wavelength.

Short wavelength or high frequency waves are higher energy radiation. For example, gamma rays, x-rays, and ultraviolet are high energy and potentially damaging. For example, ultraviolet radiation can damage our DNA. This is why we are supposed to use sunscreen while outside. We also worry about x-ray exposure; this is why the technician or dentist will leave the room when you get a dental x-ray. In contrast, long wavelength or low frequency radiation is low energy. We don't generally worry about radio wave or infrared exposure.

So, wavelength and frequency are inversely or indirectly related. As one goes up, the other goes down. They multiply to the speed of light. Energy and frequency are directly related. High frequency means high energy. Energy and wavelength are inversely or indirectly related. Long wavelength indicates low energy.

One analogy I find useful is comparing EM radiation to a train. Imagine a train is pulling coal cars that are all the same length. In this analogy, the length of each coal car would be analogous to the wavelength. Now, imagine two trains traveling at the same speed. One has shorter coal cars compared to the other. Which one will have more cars pass a point in a given amount of time? The answer is the train with the shorter cars. So shorter coal cars, or wavelength, yields a higher frequency.

Length Unit Comparison

Unit	Distance
Kilometers (km)	1,000 or 1 X 10^{3} m
Meters (m)	1 or 1 X 10^{0} m
Centimeters (cm)	0.01 or 1 X 10^{-2} m
Millimeters (mm)	0.001 or 1 X 10^{-3} m
Micrometers (or microns) (μm)	0.000001 or 1 X 10^{-6} m
Nanometers (nm)	0.000000001 or 1 X 10^{-9} m
Ångstrom (Å)	0.0000000001 or 1 X 10^{-10} m

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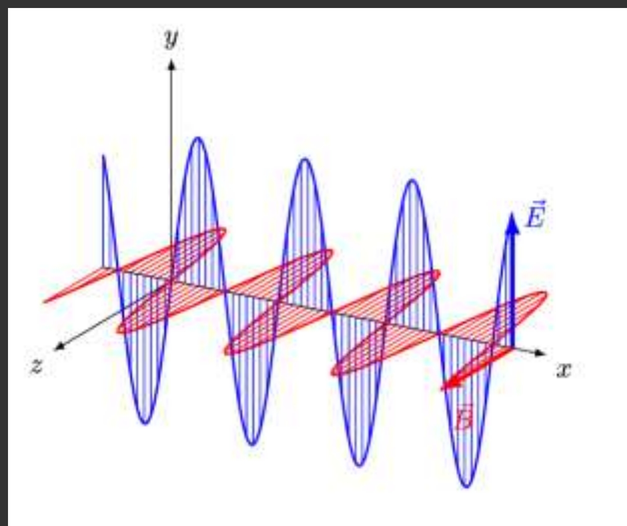
In remote sensing, we tend to define EM radiation in terms of wavelength as opposed to frequency. The table shows the different meters-based length measurements and how they relate to the base unit of meters.

In remote sensing, we tend to report wavelengths in micrometers (μm) or nanometers (nm). One micrometer is 1,000 nanometers.

For longer wavelengths, such as microwaves used to generate SAR data, it is common to report wavelengths in centimeters (cm).

Electromagnetic Waves



https://commons.wikimedia.org/wiki/File:EM-Wave.gif

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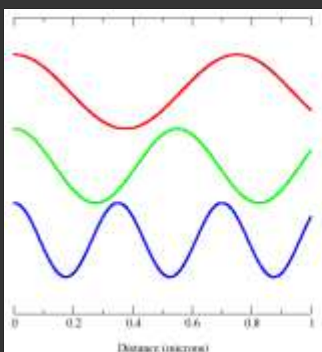
We do not talk about electrical waves and magnetic waves as separate entities. Instead, we talk about electromagnetic waves. This is because these two waves co-occur and travel at a right-angle to each other.

According to Faraday's Law, oscillating or changing magnetic fields induce an electrical field. According to Maxwell's Law, oscillating or changing electrical fields induce a magnetic field. So, these fields or waves co-occur. We take advantage of this to generate electrical currents. For example, in a power plant coal can be burned to generate heat. This heat energy is then used to heat water and create steam, which is used to spin a turbine. This spinning turbine moves a magnet. Moving the magnet can create an electrical current.

It should be noted that EM radiation has been shown to act as a wave and as a particle, as noted by quantum mechanics. This is known as the dual nature of light. Both natures are important in explaining the behavior of EM radiation. Here, we will mainly focus on the wave conceptualization of EM radiation.

Visible Spectrum

- A thin sliver of the electromagnetic spectrum that our eyes can sense
- Lots of information is available outside the visible spectrum, and we can build sensors to measure it



https://commons.wikimedia.org/wiki/File:Visible_EM_modes.png

https://www.wnycstudios.org/story/211178-rip-rainbow/

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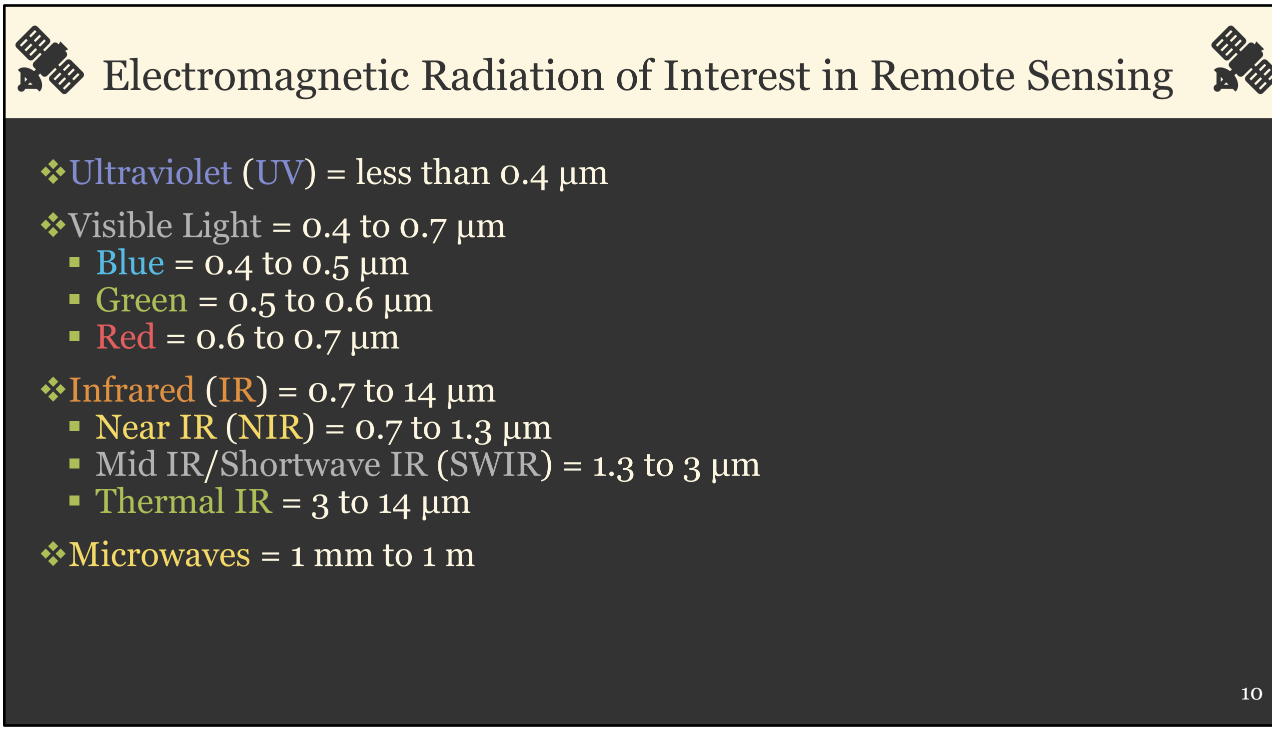
As mentioned above, visible light is a thin sliver of all EM radiation. Our eyes have evolved to see this thin sliver of the electromagnetic spectrum. However, lots of useful information is available outside of this range. Luckily, we can design sensors that detect and measure this radiation, even though we can't detect it with our own eyes. If you are interested in this topic, I would suggest listening to the podcast linked here by RadioLab.



In remote sensing, we tend to work predominantly with visible light and infrared radiation. However, we also use microwaves to collect SAR data.

Visible light can be broken into blue, green, and red ranges, as the additive primaries. Blue is defined as wavelengths between 0.4 to 0.5 µm or 400 to 500 nm. Green is defined as wavelengths between 0.5 to 0.6 µm or 500 to 600 nm. Red is defined as wavelengths between 0.6 to 0.7 µm or 600 to 700 nm. So, blue represents higher frequency, higher energy, and shorter wavelength visible light. This is why the hottest part of a flame is blue. Ultraviolet radiation represents wavelengths just shorter than the extreme end of the blue or violet wavelengths. Red, in contrast, represents low frequency, lower energy, and longer wavelength visible light. Infrared radiation represents wavelengths that are not visible to humans and are just longer than red light.

The infrared range can be broken into three regions as defined here. It is a general misconception that infrared radiation is synonymous with heat or heat energy. It is only the longer wavelength infrared, or thermal infrared radiation, that is sensed as heat. Other parts of the infrared range include the shortest wavelength near infrared, or NIR, and the medium wavelength shortwave infrared, or SWIR.

Note that the breaks between different portions of the electromagnetic spectrum are not always clearly defined. So, you may see different values in different texts or sources.

Particle Theory

- Electromagnetic radiation is composed of discrete units
- Photons or quanta

$$Q = \frac{hc}{\lambda}$$

Q = energy of a quantum (J)

h = Planck's constant (6.626×10^{-34} J sec)

c = speed of light (3×10^{8} m/s)

λ = wavelength (m)

$$Q = h\upsilon$$

Q = energy of a quantum (J)

h = Planck's constant (6.626×10^{-34} J sec)

υ = frequency (Hz)

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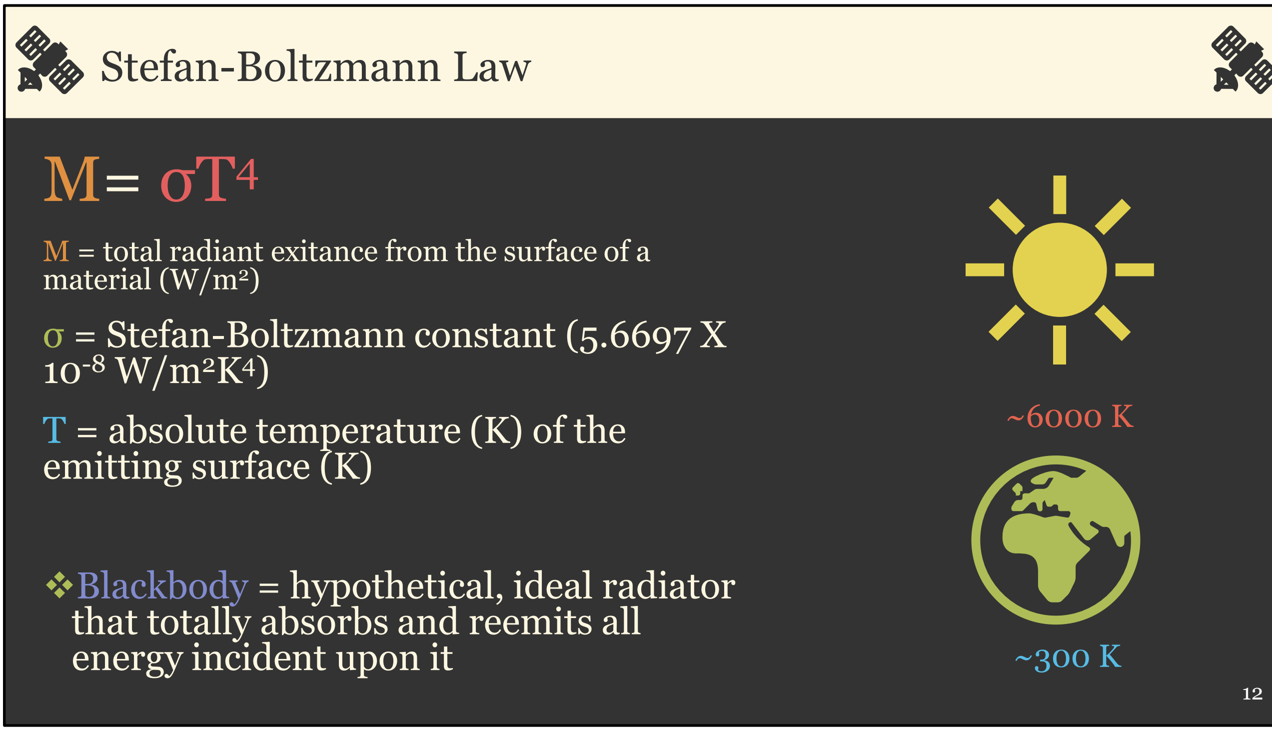
In this course, we will predominantly rely on the wave theory of electromagnetic radiation, as previously described. However, light can also behave as a particle. In this model, electromagnetic energy is conceptualized as a particle, known as a photon. On this slide, I have provided two version of the Plank Equation, which quantifies the energy (Q) associated with each "chunk", quanta, or photon of radiation. Based on these equations, high energy radiation are those with a higher frequency and a shorter wavelength.

How is it that light can behave as both a wave and a particle? This is odd and not completely understood. This partial understanding of the dual nature of EM radiation developed during the mid-1900s as a component of quantum mechanics. Many scientists contributed to this work, including Max Plank, Albert Einstein, Philipp Lenard, Robert Millikan, Louis de Broglie, and Werner Heisenberg.

This wave-particle duality is not unique to EM radiation. For example, an electron has both a wave and particle nature. In short, a full understanding of the physical behavior of light requires that it be treated as both a wave and a particle, and the same is true for the electron.

Lucky for us, the wave theory of electromagnetic radiation is most useful for understanding how EM radiation interacts with the Earth's surface, so we will primarily stick with the conceptualization of EM radiation as a wave. However, I will refer to photons of radiation throughout the course. For example, when discussing LiDAR, it is common to conceptualize each transmitted laser pulse as a photon or chunk of EM energy.



The total amount of energy that a material emits is related to its temperature. Specifically, hotter objects emit more energy. In fact, they tend to emit a lot more energy; in the Stefan-Boltzmann Law provided on the slide, the energy released is related to the object's temperature raised to the fourth power. Total radiant energy exitance just means total energy emitted.

For our purposes, this law tells us that the Sun, which has a surface temperature of around 6,000K releases a lot more energy per unit area per unit time than the Earth. This makes sense, as we are able to stand on the surface of the Earth but not the surface of the Sun.

Note that this law is specific to a blackbody radiator, which is a hypothetical, ideal radiator that totally absorbs and subsequently reemits all energy that comes in contact with it or is incident upon it. Real-world materials do not behave as perfect blackbody radiators: this is simply a conceptualization that simplifies calculations and the quantification of the relationship between energy and temperature.

A quick note on units. W indicates Watts, which is a unit of power (like a light bulb). Power is energy released per unit time, or Joules of energy per second. So, M in the equation is the amount of energy (Joules) released per unit time (seconds) per unit area (square meters). Temperature here is represented in

Kelvin. On this scale, absolute zero is 0 K. The unit of the constant in the equation is W/m^2K^4. So, multiplying this constant by temperature in Kelvin raised to the fourth power will yield back the correct units of M.

Wien's Displacements Law

- $\lambda_m = \frac{A}{T}$
- λ_m = wavelength of dominant emitted radiation (µm)
- A = 2898 µm K
- T = Temperature (K)

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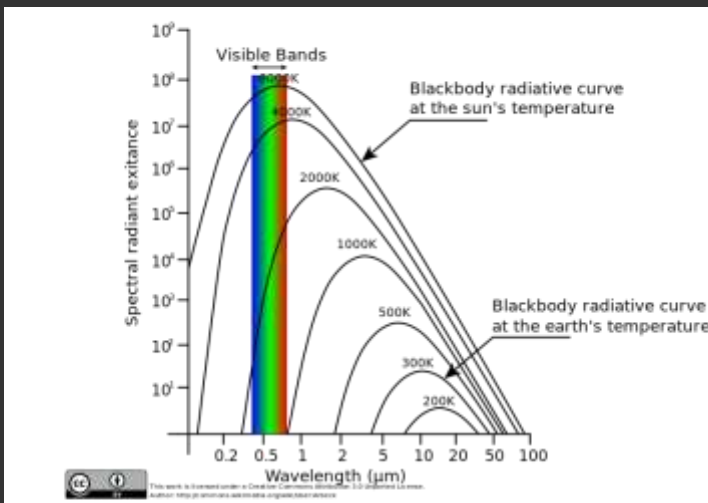
The Stefan-Boltzmann Law describes the total amount of energy emitted. In contrast, Wien's Displacement Law relates to the dominant, or most abundant, wavelength of EM energy released. As quantified by this law, hotter objects will dominantly emit shorter wavelength, higher frequency, higher energy EM radiation. In contrast, cooler objects will dominantly emit longer wavelength, lower frequency, lower energy radiation.

The Sun has a surface temperature of around 6,000 K. Using Wien's Law, this means that the dominant wavelength released would be 0.48 µm, or bluish-green light. In contrast, the Earth has a surface temperature of around 300 K and would release energy with a dominant wavelength of around 9.6 µm, or thermal infrared radiation.

So, the hotter Sun dominantly emits visible light: that is why it looks like it is glowing. In contrast, the Earth releases longer wavelength heat energy, which warms the lower atmosphere. The Earth does not appear to glow, because it is not releasing radiation that our eyes can sense.

Wien's Displacement Law



$$\lambda_{max} = \frac{0.0029Km}{T}$$

λ_{max} = wavelength of maximum emission

T = temperature in Kelvin

https://commons.wikimedia.org/wiki/File:Blackbody_emission.svg

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The graph on this slide further conceptualizes Wien's Law. Again, according to Wien's Law, hotter objects tend to emit dominantly shorter wavelength radiation. All objects that have a temperature above 0 Kelvin will emit some electromagnetic radiation, and the dominant or peak type of radiation will have a shorter wavelength with increased temperature.

Atmospheric Absorption

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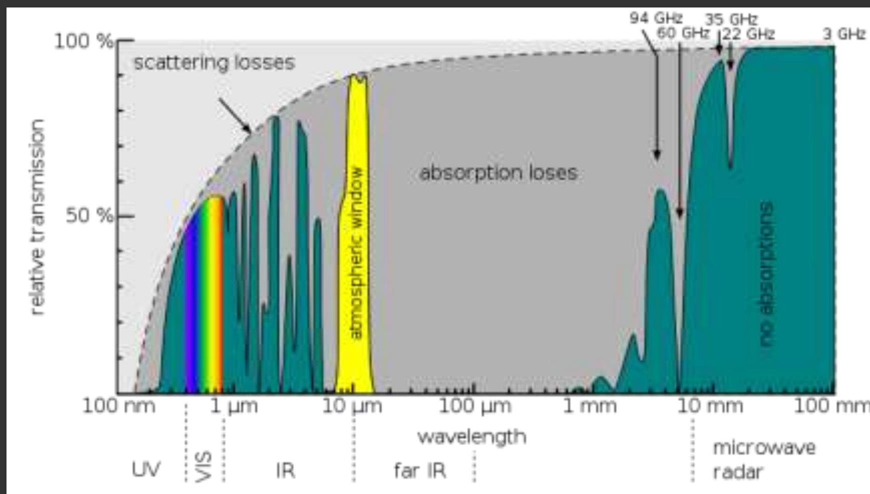
Atmospheric Windows



https://commons.wikimedia.org/wiki/File:Atmospheric_window_EN.svg

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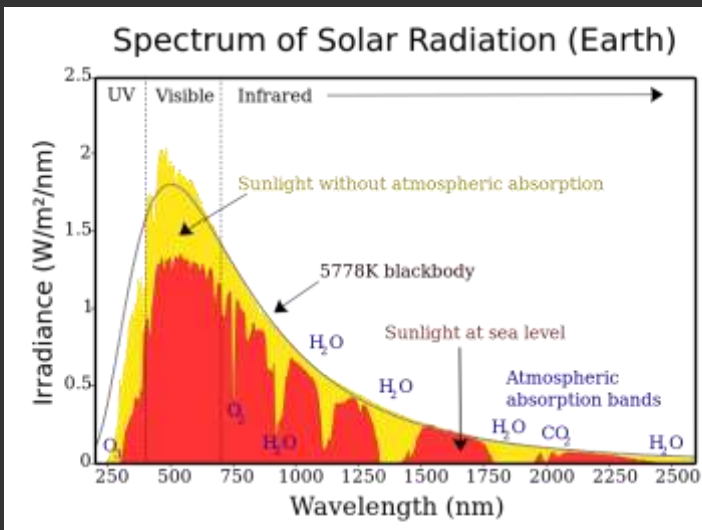
As we have already discussed, the Sun emits EM radiation that then travels through the vacuum of space. This radiation can then strike the surface of the Earth and subsequently be absorbed or reflected. However, I've left out an important detail. This radiation must also pass through the atmosphere, which complicates matters. We will now explore this complication.

Not all radiation passes through the atmosphere



Light can be scattered by the atmosphere:

- Rayleigh scattering
- Mie scattering
- Non-selective scattering

- Light can also be absorbed by the atmosphere.

https://commons.wikimedia.org/wiki/File:Solar_spectrum_en.svg

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Electromagnetic radiation can interact with the gases and particles that make up our atmosphere in different ways. First, this radiation can be scattered. Second, it can be absorbed. Further, many of these processes are wavelength specific, meaning that the effect of the atmosphere on EM radiation depends on the type of radiation in question.

Energy Interactions in the Atmosphere

- Rayleigh Scattering
  - Caused by particles smaller in diameter than wavelength of the interacting radiation
  - Explains why the sky is blue
  - Explains red/orange skies at dusk
  - Causes haze in images
- Mie Scattering
  - Caused by particles with diameters similar to wavelength of the interacting radiation
  - Water vapor/dust
  - Issue when overcast
  - Influence longer wavelengths compared to Rayleigh scattering
- Nonselective Scattering
  - Caused by particles larger in diameter than wavelengths of the interacting radiation
  - Water droplets
  - Scatter all visible, near, and mid-infrared wavelengths equally
  - Explains why fog and clouds are white
- Absorption
  - Certain gases in the atmosphere absorb certain wavelengths
  - Wavelengths ranges not absorbed by atmospheric gases = atmospheric windows

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There are three types of scattering that can occur in the atmosphere.

Rayleigh scattering is caused by particles that are smaller in diameter than the wavelength of interacting radiation. It tends to have a larger impact on shorter wavelength radiation than longer wavelength radiation. This explains why the sky is blue, as the shorter wavelength blue radiation is scattered more than other wavelengths. This also explains red or orange skies at dusk. Late in the day, the radiation enters the atmosphere at a shallower angle and must pass through a longer column of atmosphere. So, most of the blue is scatter out resulting in a red or orange appearance. The Sun appears yellow to us from the surface of the Earth since the blue is being scattered by the atmosphere. White light minus blue yields yellow. This phenomenon also explains atmospheric haze, which can reduce contrast. This is one reason why driving and aviation sunglasses are often amber tinted. The amber tint blocks the shorter wavelength ultraviolet and blue light, which reduces haze and increases contrast.

Mie scattering is caused by particles with diameters similar to the wavelength of interacting radiation and is caused by water vapor and dust in the atmosphere. It tends to impact longer wavelengths than Rayleigh scattering and explains overcast skies.

Nonselective scattering is caused by large diameter particles and water droplets and impacts all visible, near infrared, and mid-infrared wavelengths equally. It causes fog and clouds to appear white, since all visible wavelengths are scattered.

Specific gases in the atmosphere can also absorb specific wavelength ranges. These are known as atmospheric absorption features. It doesn't make sense to design sensors to measure these wavelengths since they don't pass through the atmosphere. This would be like taking a picture in the dark. Instead, we tend to make measurements within atmospheric windows, or portions of the electromagnetic spectrum that do pass through the atmosphere.

Measuring Electromagnetic Radiation

- We generally measure portions of the electromagnetic spectrum that get through the atmosphere

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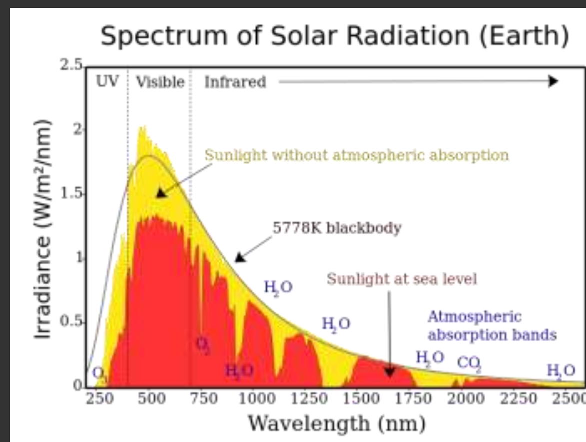
In summary, we generally measure portions of the electromagnetic spectrum that get through the atmosphere since our goal is to image, map, and measure the Earth's surface.

Summary

- Solar illumination peaks in visible
- Water
  - 0.9 µm
  - 1.1 µm
  - 1.4 µm
  - 1.9 µm
  - 2.6 µm
- CO_2
  - 2.0 µm
- Ozone
  - 0.3 µm
- Trace Gases (O_2, CH_4)



https://commons.wikimedia.org/wiki/File:Solar_spectrum_en.svg

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This slide lists the key absorption features associated with the gases that make up the atmosphere, including water vapor, carbon dioxide, and ozone. Here are a few notes.

First, it generally doesn't make sense to build Earth observation sensors that measure reflected radiation at these wavelengths. This would be like taking a picture in the dark: the energy is absorbed by the atmosphere and only a small proportion of it will reach the Earth's surface.

This also explains why the ozone hole is an issue. Ozone absorbs energy around 0.3 µm, which corresponds to ultraviolet radiation that has enough energy to damage our DNA and tissue. This type of damage can result in sun burns, skin cancer, and cataracts. So, ozone's absorption of ultraviolet radiation protects our cells from damage. Some have argued that the evolution of life on Earth would have been greatly hindered if there was no ozone layer.

Surface Reflectance

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What happens when radiation hits the surface?

- Transmission = energy passes through a target
- Absorption = energy is trapped and held by a target
- Reflection = energy bounces off a target
- Incident Energy = the total amount of energy (per wavelength) that interacts with an object
- $I = R + A + T$
- Spectral Reflectance = the percentage of the total incident energy that is reflected from a surface
- $SR = (R/I) \times 100$

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When a specific wavelength of electromagnetic radiation strikes an object, three things could happen. The energy could be reflected off the object, it could be absorbed by the object, or it could transmit through, like light passing through a window. The total amount of energy at a specific wavelength that interacts with or strikes an object is the incident energy. This total incident energy will be reflected, absorbed, and/or transmitted in different proportions.

The total reflected, absorbed, and transmitted energy must sum to the total incident energy since energy is conserved. With the exception of emitted long wave thermal infrared radiation, we are generally interested in measuring the reflected radiation. Spectral reflectance is the percentage of the total incident energy that is reflected from a surface at a particular wavelength. 100% reflectance would indicate that all the energy at that wavelength is reflected whereas 0% would indicate that no energy at the wavelength is reflected back, or that it is absorbed or transmitted.

Again, this is wavelength specific. So, different surface materials will show different spectral reflectance at different wavelengths.

What happens when radiation hits the surface?

- $E_I(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda)$
- $E_I(\lambda)$ = Incident Energy
- $E_R(\lambda)$ = Reflected Energy
- $E_A(\lambda)$ = Absorbed Energy
- $E_T(\lambda)$ = Transmitted Energy

Spectral Reflectance

$$\rho_\lambda = \frac{\text{Energy Reflected}}{\text{Energy of Incident Energy}} \text{ X } 100$$

* Spectral reflectance is wavelength specific

- $E_R(\lambda) = E_I(\lambda) - [E_A(\lambda) + E_T(\lambda)]$

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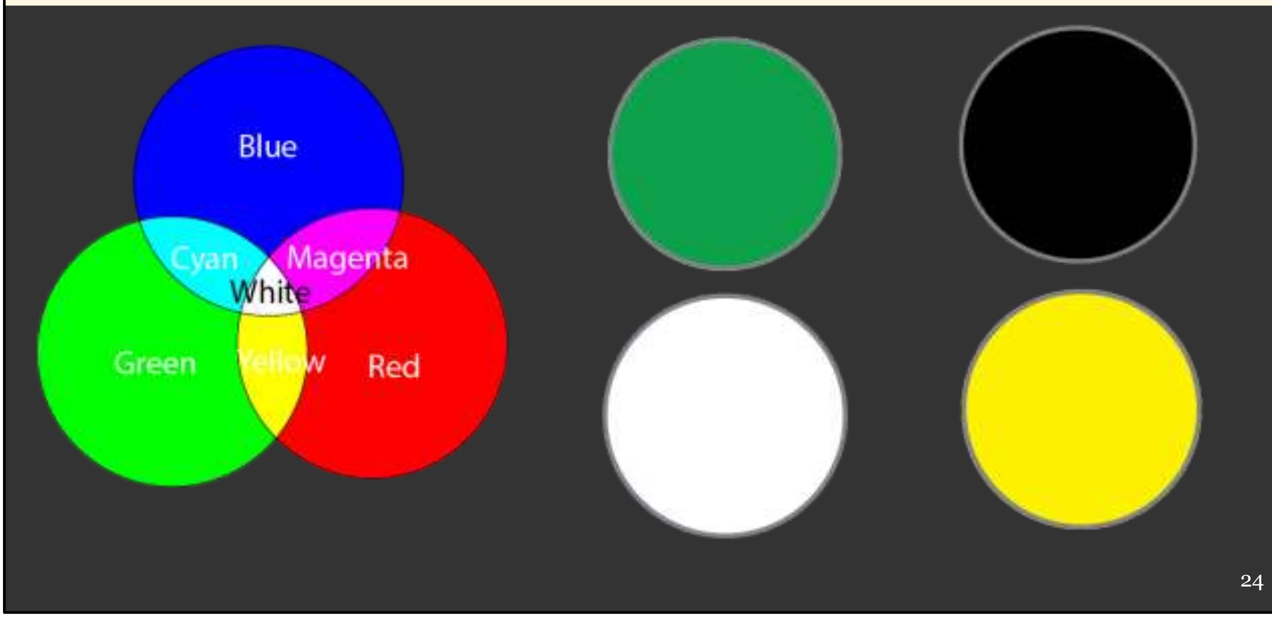
This slide provides some equations to elaborate on the information presented in the previous slide. Again, the sum of reflected, absorbed, and transmitted energy at a specific wavelength must sum to the total incident energy at that wavelength. Spectral reflectance is the percentage of the incident energy that is reflected. This is wavelength specific.

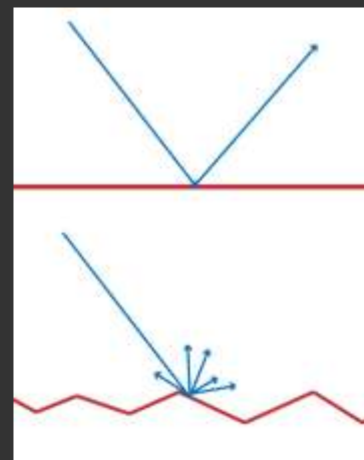
Why do objects look a certain color?



An opaque object, or an object that you can't see through, takes on the color that it reflects back. Or, white light minus the colors that are absorbed. So, a white object appears white because it is reflecting back all visible light. In contrast, a black object appears black because it is absorbing all visible wavelengths. A green object is absorbing the blues and reds but not the greens. A yellow object absorbs the blue wavelengths but not the greens and reds. Green plus red yields yellow. Note that the color of an object does not tell you anything about absorption or reflection outside of the visible spectrum. Since we can't see or sense these wavelengths, they have no impact on our visual perception.

Specular vs. Diffuse Reflectance

- Specular = mirror-like, angle of reflection = angle of incidence
- Diffuse = reflectors are rough surfaces that reflect uniformly in all directions
- Real features generally have reflectance characteristics between these two extremes
- This is wavelength specific
- In remote sensing, we are commonly interested in measuring diffuse reflection



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When EM radiation reflects off a surface, how it reflects is impacted by the roughness of the surface relative to the wavelength being reflected.

Specular reflectance is mirror-like and tends to occur for smooth surfaces. In this case, the angle of reflectance is equal to the angle of incidence, or the energy is reflected at the same angle but in the opposite direction of the incoming energy.

Diffuse reflectance occurs for rougher surface. In contrast to specular reflectance, the energy is reflected in many directions, or diffused.

These are endmembers. Most real surfaces have reflectance characteristics between these two extremes. Also, as already mentioned, this is wavelength specific. For example, visible light would pass through a satellite dish made of metal netting. However, radio waves, which have a longer wavelength would not pass through and would be reflected. This reflectance would be mainly specular since the surface of the metal netting is smooth in comparison to the long wavelength of radio waves. This allows the parabolic dish to reflect and concentrate incoming radio waves at a detector.

Impact of atmosphere on recorded reflectance

$$L_{tot} = \frac{\rho E T}{\pi} + L_p$$

- L_{tot} = total spectral radiance measured by sensor
- ρ = reflectance of object
- E = irradiance on object, incoming radiation
- T = transmission of atmosphere
- L_p = path radiance, from the atmosphere and not the object

The energy recorded by a sensor is always modified to some extent by the atmosphere

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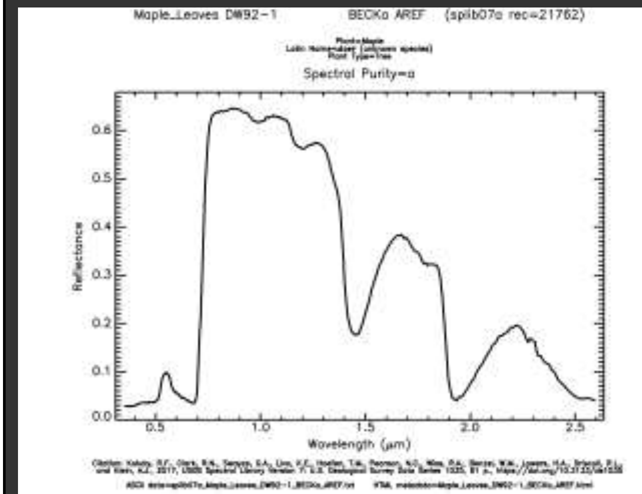
Before we move on, it is important to note that the atmosphere complicates the sensed reflected EM radiation. Since the atmosphere also interacts with EM radiation, the signal reaching the satellite will consist of signals from the Earth's surface and the atmosphere.

In the provided equation, the total spectral radiance (or, reflected energy) is the sum of reflectance from the Earth's surface and the atmosphere. The reflectance from the Earth's surface at a specific wavelength depends on the incoming radiation (E), the reflectance of the object (ρ), and the transmission of the atmosphere (an object can only reflect the energy that reaches it). The atmospheric component, or path radiance, is energy reflected or scattered by the atmosphere as opposed to the Earth's surface.

In order to estimate spectral radiance associated with just the Earth's surface, the atmospheric component must be removed. This is the primary purpose of atmospheric correction.

Spectral Reflectance is Wavelength Specific



- X-axis = wavelength
- Y-axis = % spectral reflectance

Example: Maple Leaf
Data from USGS Spectral Library Version 7

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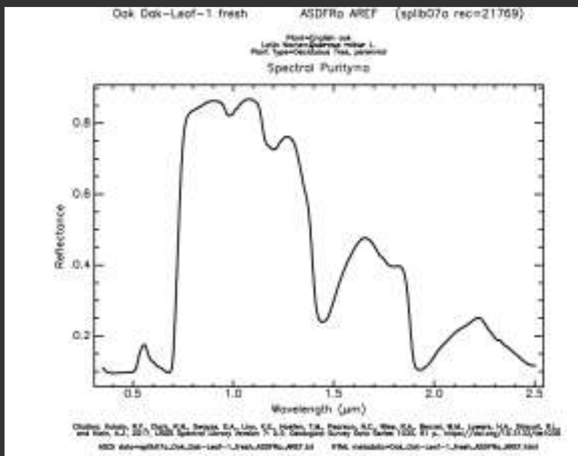
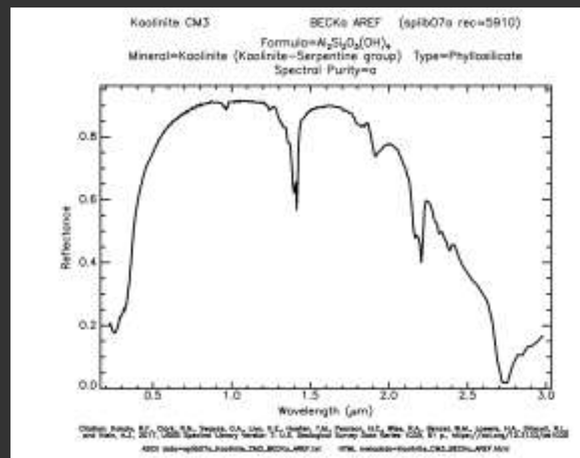
A spectral reflectance curve represents spectral reflectance at different wavelengths for a material. The x-axis represents wavelengths or types of EM radiation. The y-axis represents the spectral reflectance as a proportion or percentage of incident energy. Troughs indicate absorption whereas peaks indicate reflectance.

The provided example is for a maple leaf and was provided by the US Geological Survey Spectral Library. As this graph demonstrates, the amount of reflected energy varies greatly based on wavelength.

Different materials have different reflectance properties





Example: Oak Leaf
Data from USGS Spectral Library Version 7

Example: Kaolinite

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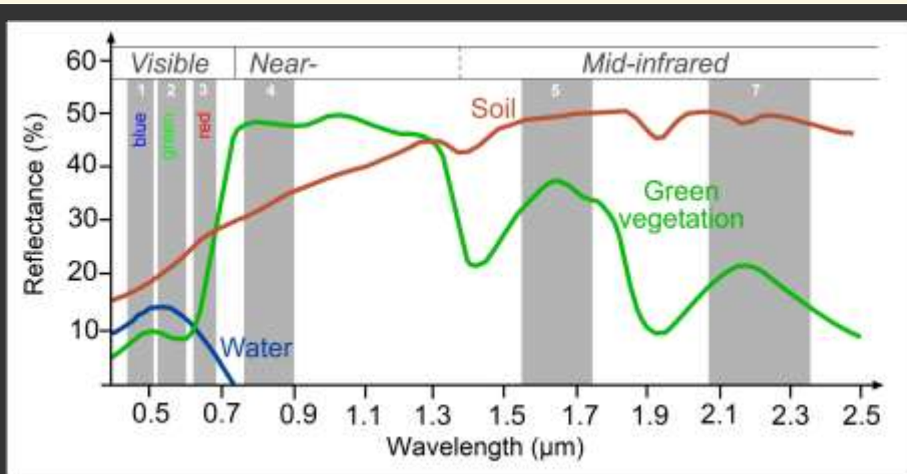
Different materials will have different spectral reflectance patterns. For example, this slide provides a comparison of an oak leaf and the clay mineral kaolinite. Very different patterns are observed. This is one reason why we are interested in making these measurements: they can allow us to map and differentiate different landscape features and surface materials.

Different materials have different reflectance properties



http://www.seos-project.eu/modules/classification/classification-c01-p05.html

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This graph provides another comparison. Soil tends to show greater spectral reflectance in the shortwave infrared range in comparison to near infrared or visible wavelengths, a pattern that is very different from green vegetation. Water tends to absorb most near infrared and shortwave infrared radiation. So, using these patterns, we could potentially differentiate these unique surface materials.

You may notice some small troughs in the shortwave range for soil that align with the deeper troughs for green vegetation. This results from water in the soil, just as the troughs in the green vegetation curve relate to water in the plant tissue.

30

This slide shows the use of a field spectrometer and was provided by Dr. Tim Warner, who is pictured in the left image. This device allows for the measuring of spectral reflectance from materials. These measurements are collected at multiple wavelengths and allow for the approximation of a spectral reflectance curve.

Since we are sensing the object at close proximity and an illuminating source is provided, the atmosphere does not have a large impact of these measurements.

Vegetation

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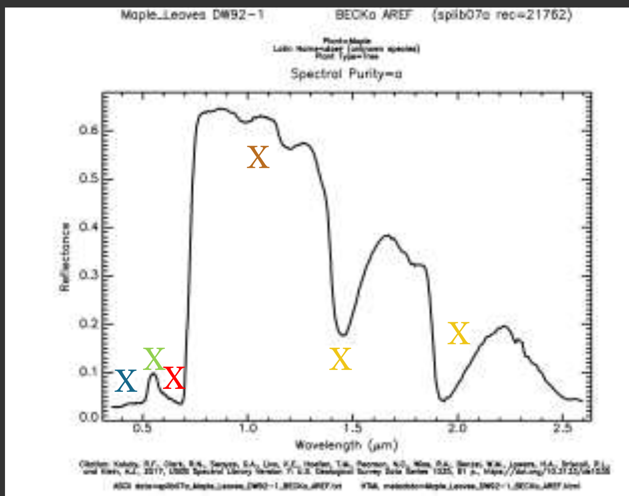
We will now explore spectral reflectance characteristics for common materials. We will begin with vegetation.

Spectral Reflectance of Vegetation



- Blue = absorption by pigments
- Green = less absorption by pigment
- Red = absorption by pigments
- Near Infrared = reflect and
- scattered by interior cell walls
- Shortwave Infrared = absorption by water in plant tissue

Example: Maple Leaf
Data from USGS Spectral Library Version 7

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Let's explore the spectral reflectance of this maple leaf further.

Here, I have color coded different spectral ranges with different color "Xs."

This leaf tends to absorb as opposed to reflect a lot of visible radiation. However, it absorbs more blue and red in comparison to green. This is why leaves appear green to us. This absorption results from the pigments in the leaf, such as chlorophyll, that interact with sunlight in the process of photosynthesis to make energy and sugars for the plant. During the winter, when the tree is not photosynthetically active, the leaf will no longer appear green to us.

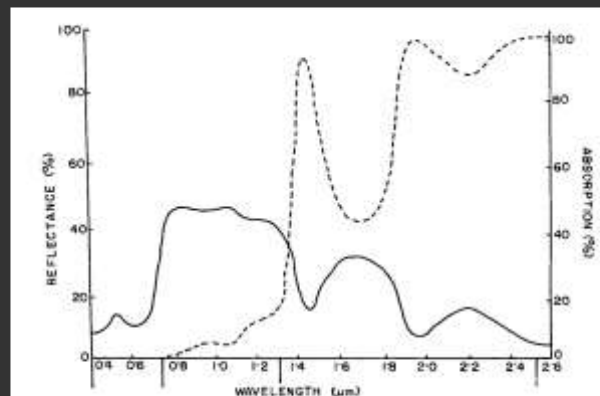
Green, healthy, and photosynthetically active leaves tend to scatter or reflect a larger proportion of incident near infrared radiation in comparison to visible light due to how this radiation interacts with cell walls. So, if we could sense near infrared radiation, a leaf would appear to be near infrared as opposed to green. However, this has no physical meaning since we can't see near infrared radiation.

In the shortwave infrared range, there are some absorption features associated with water in the plant tissue.

This graph highlights the wavelength specific nature of spectral reflectance.

Spectral Reflectance of Vegetation

- Visible
  - Absorption for photosynthetic activity
  - Pigments (chlorophylls, xanthophylls, and carotenoids)
  - Absorb ultraviolet, blue, and red
- NIR
  - Spongy mesophyll
  - 30 to 70% reflectance
  - Scattered by interior cell walls
- SWIR
  - Absorption by water (1450, 1950, and 2660 nm)



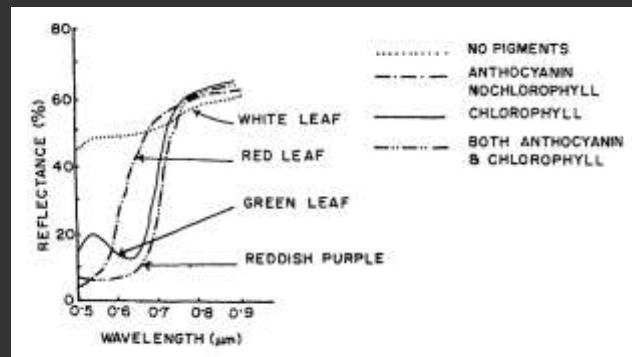
Roy, P.S., 1989. Spectral reflectance characteristics of vegetation and their use in estimating productive potential. *Proceedings: Plant Sciences*, *99*(1), pp.59-81.

33

This slide provides some additional explanations of spectral reflectance of vegetation. Again, absorption in the visible spectrum is controlled by photosynthetic pigments. There is more reflectance and scattering in the NIR range in comparison to the visible. This reflection and scattering is associated with spongy mesophyll in the leaf's interior and scattering of NIR radiation by cell walls. Absorption features in the SWIR range are associated with water in the plant tissue with dominant absorption features at 1450, 1950, and 2660 nm.

Fall Colors

- Relative balance between pigments



Roy, P.S., 1989. Spectral reflectance characteristics of vegetation and their use in estimating productive potential. *Proceedings: Plant Sciences*, *99*(1), pp.59-81.

34

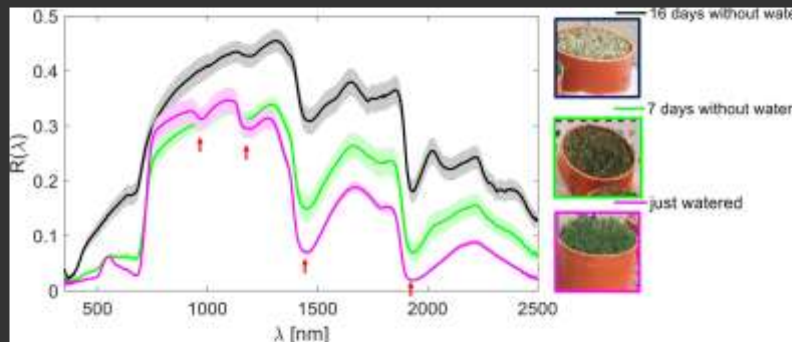
Fall color, or fall senescence, in plants is explained by the reduced activity of chlorophyll, which allows the absorption characteristics of other, less dominant pigments to become more noticeable. The result is a change in perceived leaf color. In the provided example, changes in leaf color are related to active pigments. For example, a red color is observed when Anthocyanin is active but Chlorophyll is not.

Spectral reflectance in the visible range increases when no pigments are active, resulting in the brown color of a dead leaf.

These color changes can be useful for identifying plant species and/or plant communities with correctly timed imagery that captures key seasonal changes, such as fall colors.

Moisture Content

- Increased reflectance when dried
- Increased SWIR reflectance when dried



Caturegli, L., Matteoli, S., Gaetani, M., Grossi, N., Magni, S., Minelli, A., Corsini, G., Remorini, D. and Volterrani, M., 2020. Effects of water stress on spectral reflectance of bermudagrass. *Scientific Reports*, *10*(1), pp.1-12.

35

When the moisture content of a plant decreases, we generally observe increases in reflectance in the visible, NIR, and SWIR ranges. Specifically, the SWIR water absorption features become less pronounced. Thus, multispectral remote sensing can be useful for assessing water stress in agricultural fields and forests.

Stacking

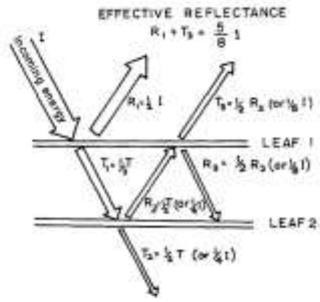
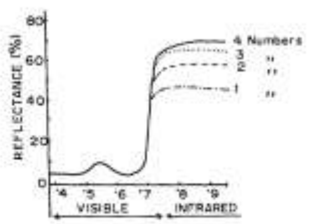


Figure 6. Spectral reflectance from different layers of leaves.



❖Decreases NIR reflectance

Roy, P.S., 1989. Spectral reflectance characteristics of vegetation and their use in estimating productive potential. *Proceedings: Plant Sciences*, *99*(1), pp.59-81.

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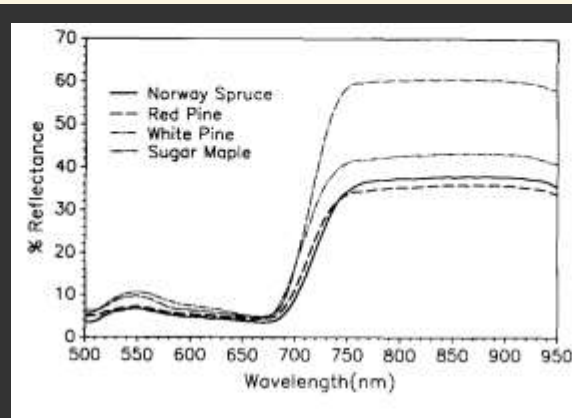
When leaves are stacked, we tend to see a reduced spectral reflectance in the NIR range. This is because more energy is scattered by interacting with multiple leaves.

Conifers vs. Deciduous

- Conifers have lower NIR reflectance than deciduous



Williams, D.L., 1991. A comparison of spectral reflectance properties at the needle, branch, and canopy level for selected conifer species. *Remote Sensing of Environment*, *35*(2-3), pp.79-93.

37

Coniferous trees tend to have lower spectral reflectance than deciduous trees in the NIR range. Thus, NIR imagery can be useful for differentiating conifers and deciduous trees.

The images on this slide are from the Landsat 5 Thematic Mapper (Red Channel = NIR, Green Channel = Red, Blue Channel = Green). The darker areas represent conifer forests. The dark spot circled in the top image is a stand of Norwegian Spruce trees in the Fernow Experimental Forest near Parsons, WV. Note that this area contrasts with the surrounding deciduous forest. The dark areas in the lower image are stands of Spruce trees near the Snowshoe Ski Resort in Pocahontas County, WV.

Summary

1. Visible absorption dominated by pigments
2. Less green absorption than blue or red
3. Leaves change color as pigments become inactive
4. Vegetation reflects/scatters a lot of NIR radiation
5. SWIR absorption dominated by water
6. Decreased moisture content increases reflectance, especially SWIR
7. Stacking decreases NIR reflectance
8. Conifers have lower NIR reflectance than deciduous trees

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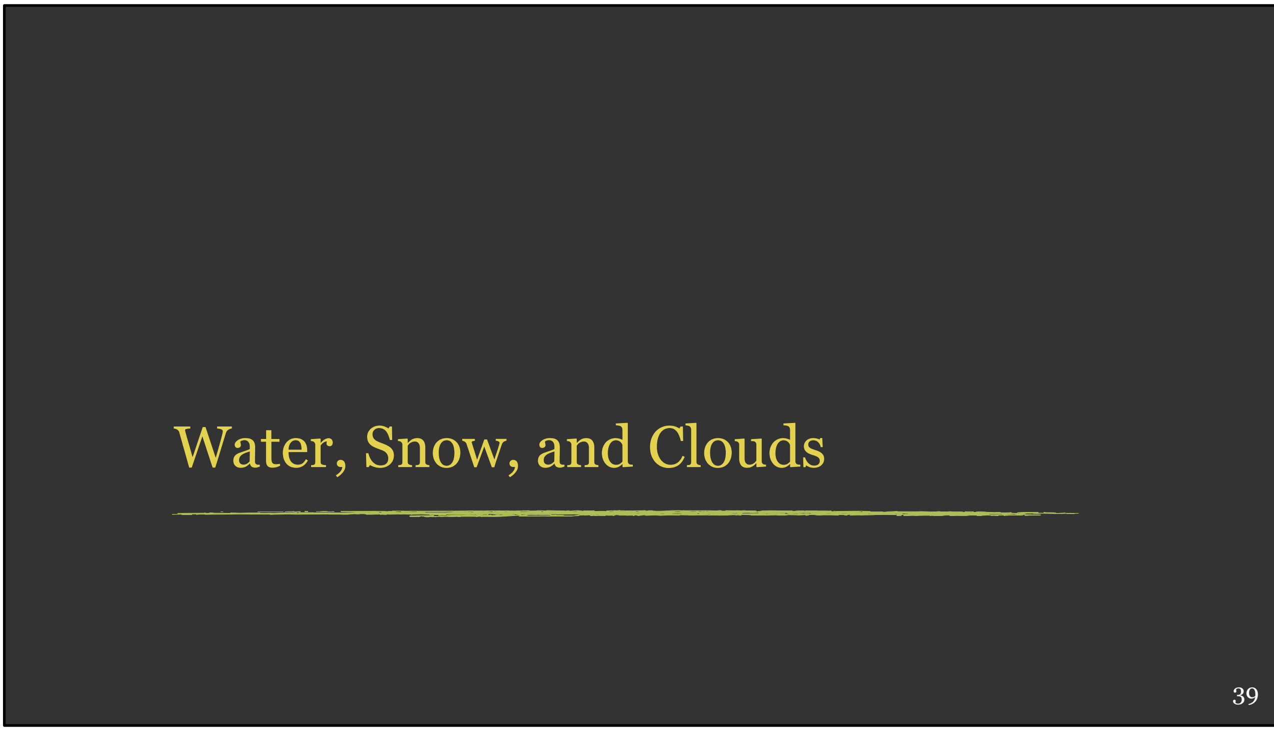
This slide describes the key spectral reflectance characteristics of vegetation.


Water, Snow, and Clouds
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Water Spectral Properties

- Absorption = UV and Yellow to NIR (> 0.6 μm)
- Scatter = blue and violet
- Clear water = strong green, red, and NIR absorptance
- Turbid water = increased green and red reflectance

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Water tends to absorb UV and yellow to NIR radiation. In contrast, it scatters blue and violet wavelengths, which is why water appears blue.

Clear water specifically tends to have strong green, red, and NIR absorptance. In contrast, turbid or muddy water will show decreased green and red absorptance, resulting in the brown look of turbid water.

Sun Glint

- Specular reflectance off water

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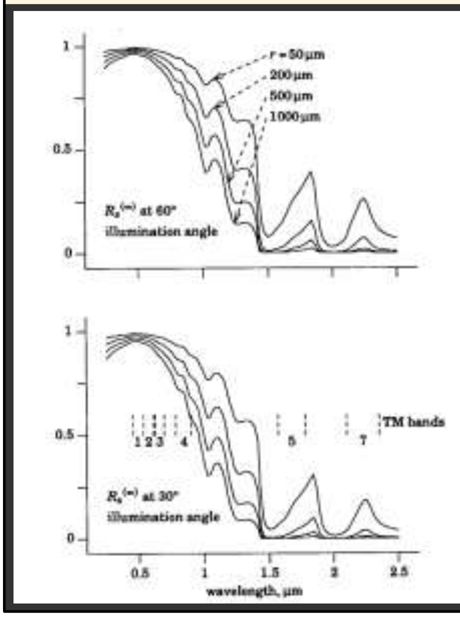
Sun glint occurs as a result of specular reflectance of visible EM radiation off the surface of water. When this happen, the characteristic absorption of green and red radiation and scattering of blue radiation is replaced by a strong visible reflectance signal. So, sun glint complicates the spectral reflectance characteristics or signature of water.

Snow Grain Size



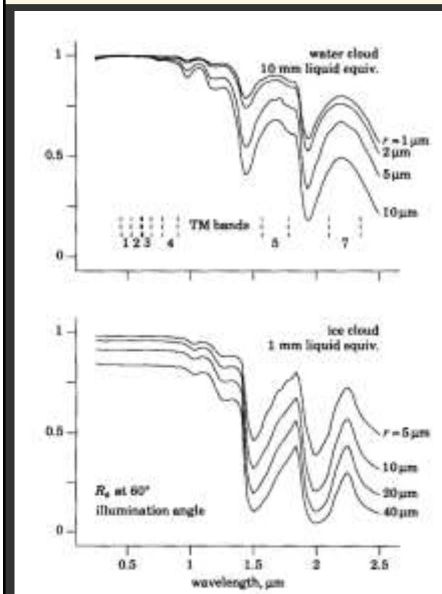
- Larger grain size = reduced spectral reflectance (SWIR)

Dozier, J., 1989. Spectral signature of alpine snow cover from the Landsat Thematic Mapper. *Remote sensing of environment*, *28*(1), pp.9-22.

42

Snow with larger grain sizes tends to have reduced SWIR reflectance in comparison to snow with smaller grain sizes.

Water vs. Ice



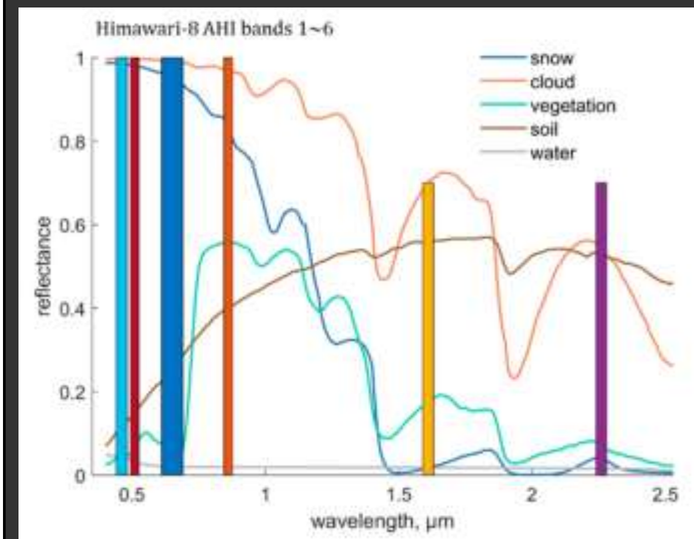
- Water more reflective than ice (SWIR)
- Reflectance decreases with grain size (SWIR)

Dozier, J., 1989. Spectral signature of alpine snow cover from the Landsat Thematic Mapper. *Remote sensing of environment*, *28*(1), pp.9-22.

43

Liquid water tends to be more reflective than ice in the SWIR range. Also, ice reflectance decreases with grain size.

Clouds vs. Snow



- Clouds more reflective than snow (SWIR)

Wang, G., Jiang, L., Shi, J., Liu, X., Yang, J. and Cui, H., 2019. Snow-Covered Area Retrieval from Himawari–8 AHI Imagery of the Tibetan Plateau. *Remote Sensing*, *11*(20), p.2391.

44

Clouds tend to be more reflective than snow in the SWIR range.

Summary

1. Water absorbs yellow to NIR
2. Water scatters violet and blue
3. Turbidity increases green and red reflectance
4. Sun glint caused by specular reflectance
5. SWIR reflectance decreases with increased snow grain size
6. SWIR reflectance higher for water vs. ice
7. SWIR reflectance for clouds higher than snow

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This slide highlights the key spectral reflectance characteristics of water, snow, and ice. Note the importance of SWIR data for differentiating liquid water, snow, and ice.

Minerals, Rocks, and Soil

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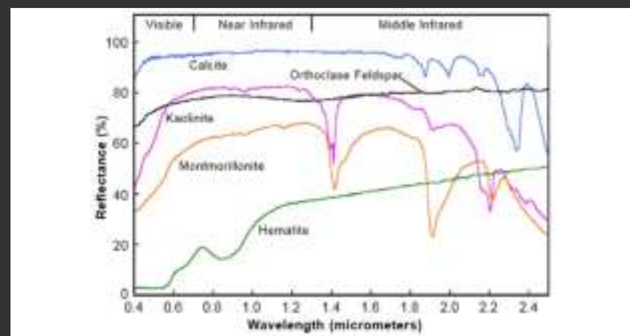
Minerals

- Requires hyperspectral data

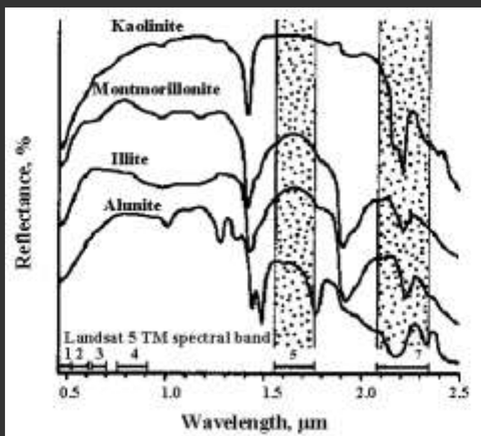


Clark, R.N., 1999. Spectroscopy of rocks and minerals, and principles of spectroscopy. *Manual of remote sensing*, *3*(3-58), pp.2-2.

47

Some minerals have characteristic absorption features. Generally, hyperspectral data are necessary to differentiate minerals, since the spectral detail of multispectral data is not adequate to characterize key absorption features.

Clay



Sabins, F.F., 1999. Remote sensing for mineral exploration. *Ore geology reviews*, *14*(3-4), pp.157-183.

- Absorption features in SWIR
- 2.2 µm

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As a specific example, clay minerals have a characteristic absorption feature at 2.2 µm in the SWIR range.

Rocks

- Multispectral thermal data
- Absorption features shift to longer wavelength with reduced silica content

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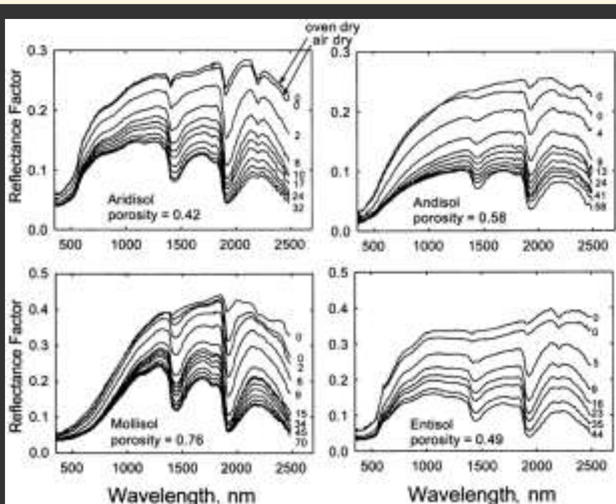
Silicate rock types have absorption features in the thermal range. Generally, multispectral thermal data are needed to differentiate silicate rocks.

Thermal absorption features tend to shift to longer wavelengths with reduced silica content.

Soil



Lobell, D.B. and Asner, G.P., 2002. Moisture effects on soil reflectance. *Soil Science Society of America Journal*, *66*(3), pp.722-727.

- May see clay absorption feature in SWIR
- May see water absorption features in SWIR
- Wetter = reduced spectral reflectance (SWIR)
- Organic content = reduced spectral reflectance (visible)
- Iron Oxides
  - Red reflectance
  - 0.9 μm NIR absorption
- Finer texture = brighter

50

This slide highlights some key absorption features associated with soils. First, because clay is a common component of soils, the 2.2 μm clay absorption feature is commonly observed. Also, due to water content in clay, the characteristic SWIR water absorption features are observed.

With wetter conditions, SWIR absorption tends to increase due to the SWIR water absorption features. With increased organic content, visible spectral reflectance tends to decrease (organic-rich soils tend to be visibly darker).

Oxidation, rusting, or the occurrence of iron oxides tends to yield a red color, resulting from reduced red absorption. There is also a NIR absorption feature at 0.9 μm associated with iron oxides.

Lastly, finer texture generally results in more reflectance across the visible, NIR, and SWIR ranges.

Summary

- Hyperspectral data for mineral detection
- Clays have distinctive narrow spectra at 2.2 µm
- Rocks require multispectral thermal
- Rock absorption features shift to longer wavelength with reduced silica content
- Soils may have SWIR water and clay absorption features
- Wetter soil = less reflective
- More organic content = less reflective
- Iron oxides in soil = red reflectance, 0.9 µm absorption
- Finer texture = brighter

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This slide summarizes spectral reflectance features for minerals, rocks, and soil.

Man-Made Materials

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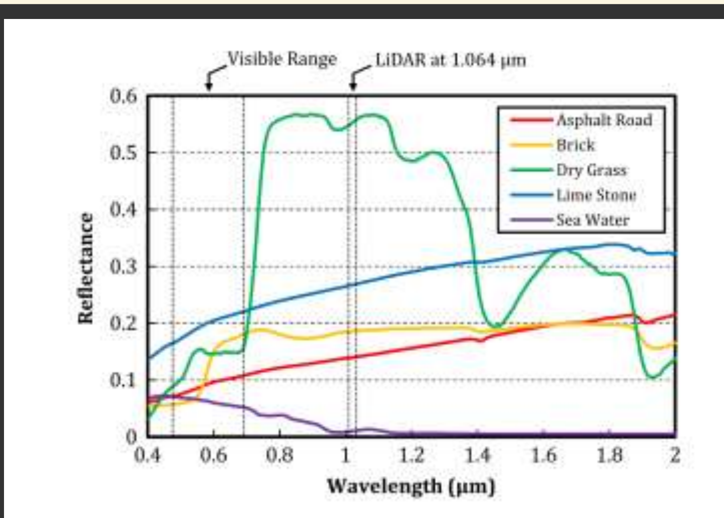
Materials Comparison



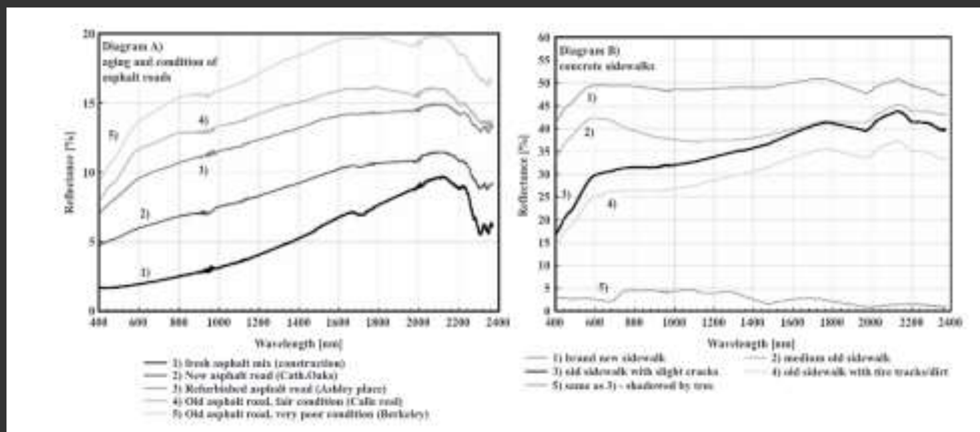
Yan, W.Y., Shaker, A. and El-Ashmawy, N., 2015. Urban land cover classification using airborne LiDAR data: A review. *Remote Sensing of Environment*, *158*, pp.295-310.

53

This slide shows some spectral reflectance curves for common Earth surface materials. We will specifically investigate man-made materials in this section.

As a first example, red brick tends to absorb the blue and green portions of the visible spectrum and reflect a larger proportion of red energy, which produces the red color. The spectral reflectance of red brick is very different from vegetation and water.

Impact of Age



Herold et al. 2004. Spectrometry for urban area remote sensing—Development and analysis of a spectral library from 350 to 2400 nm. *Remote Sensing of Environment* 91: 304-319.

54

As asphalt ages, it tends to reflect more visible, NIR, and SWIR radiation. This is why fresh asphalt looks dark to us, but older, warn asphalt looks brighter.

In contrast, concrete tends to darken with age.

Summary

- Complex spectral relationships
- Asphalt dark, brightens with age
- Concrete brighter, darkens with age

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This slide provides a summary of spectral reflectance for some man-made materials.

Image Data

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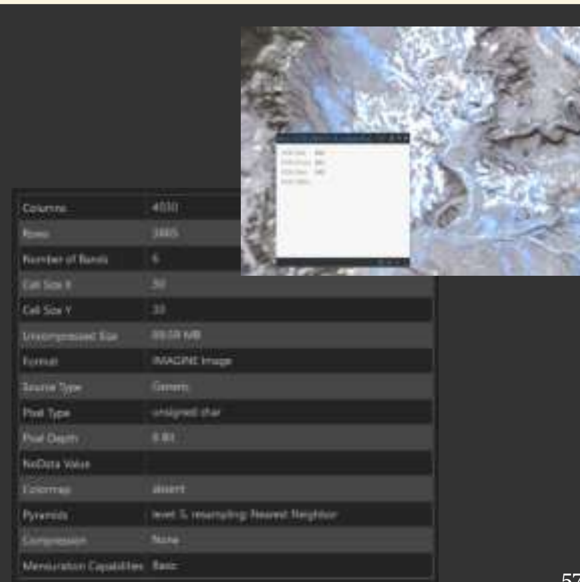
Digital Numbers (DN)

- Imagery = raster data
- Each band measures reflectance within a range of wavelengths
- A multispectral image is a stack of image bands
- Reflectance is represented as DN values
- Higher DN = more reflectance in the measured wavelength range
- DN values do not have physical units
- DN values are not percent reflectance values



57

How do we actually represent our spectral measurements as image data?

A multispectral image is essentially an array of values stored as a raster grid. Each separate band represents a measurement in a specific spectral range. Each cell or pixel stores a brightness or digital number (DN) value. Higher numbers represent a stronger or brighter signal. The levels of brightness that can be differentiated partially depends on the radiometric resolution. For example, an 8-bit image can only differentiate 256 brightness levels.

It is important to note that larger DN values indicate more radiance and reflectance. However, DN values do not represent physical units of reflectance or radiance.

What is actually stored on the pixel?

1. Brightness value as digital number (DN)
   - 8-bit
   - 16-bit
   - 32-bit
   - Float
2. A physical measurement
   - Radiance
     - the amount of radiation reflected from an area
     - Must apply gain and offset to pixel DN value
     - Example units: W/(steradian m^2 µm)
   - Reflectance
     - Proportion of the radiation striking a surface relative to the radiation reflected off of it
     - Top of Atmosphere = not corrected for atmospheric effects
     - Surface reflectance = atmospheric corrections are applied

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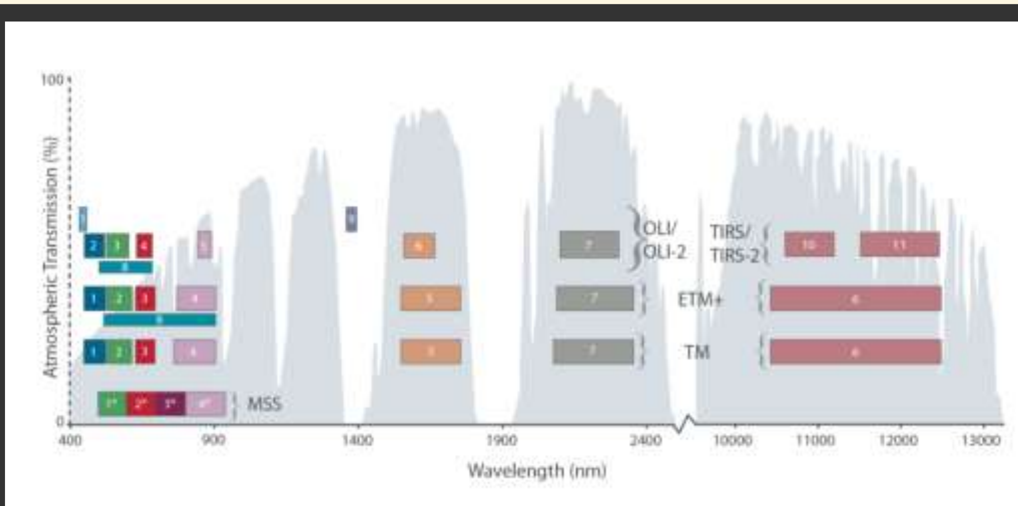
It is possible to estimate radiance and reflectance from DN values if the instrument is calibrated and enough metadata are provided.

Radiance represents the amount of radiation reflected from an area or pixel. The units of radiance are W/(steradian m2 µm). Or, it is energy (Joules) per unit time (seconds) (remember, Watts = Joules per second) per area (meters squared). Steradian corrects for the curved spherical surface of the Earth. This is like radians, but in 3D. Lastly, this is per wavelength. So, in summary, radiance is energy per unit time per unit area per wavelength (and corrected for the fact that the surface of the Earth is curved).

Reflectance represents the percent of the radiation at a specific wavelength that is reflected. Top of atmosphere (ToA) reflectance incorporates the signal from both the land surface and the atmosphere. Surface reflectance has been atmospherically corrected to factor out the impact of the atmosphere to more accurately approximate the surface reflectance of the Earth's surface at the pixel location.

In short, it is possible to estimate radiance and reflectance from DN values if a sensor is well calibrated. For example, spectral reflectance products are available for all Landsat, Sentinel-2, and MODIS data.

Landsat Program



https://landsat.gsfc.nasa.gov/landsat-9/landsat-9-spectral-bands/

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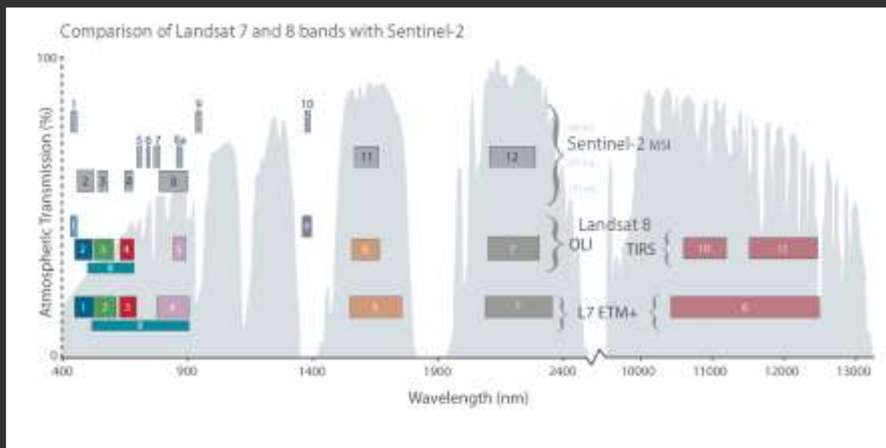
Before we end, I want to reiterate that multispectral data do not capture the full detail of the spectral reflectance curve at a pixel location. Instead, a finite number of measurements are made over a range of wavelengths.

For example, the NASA-generated figure on the slide shows the wavelength ranges sensed by each band for different Landsat missions. The Operational Land Imager (OLI) sensor onboard Landsat 8 collects bands representing wavelength ranges in the blue, green, red, NIR, and SWIR spectrum. It also has a blue edge band (Band 1) and a band for detecting cirrus clouds (Band 9). The panchromatic band (Band 8) offers a spatial resolution of 15 meters and is sensitive to the green, red, and part of the blue spectral ranges. The Thermal Infrared Sensor (TIRS) has two bands that are sensitive to different ranges of emitted thermal radiation.

So, the end result here is a subset of measurements within the spectral space, as opposed to the full spectral reflectance curve.

Sentinel-2

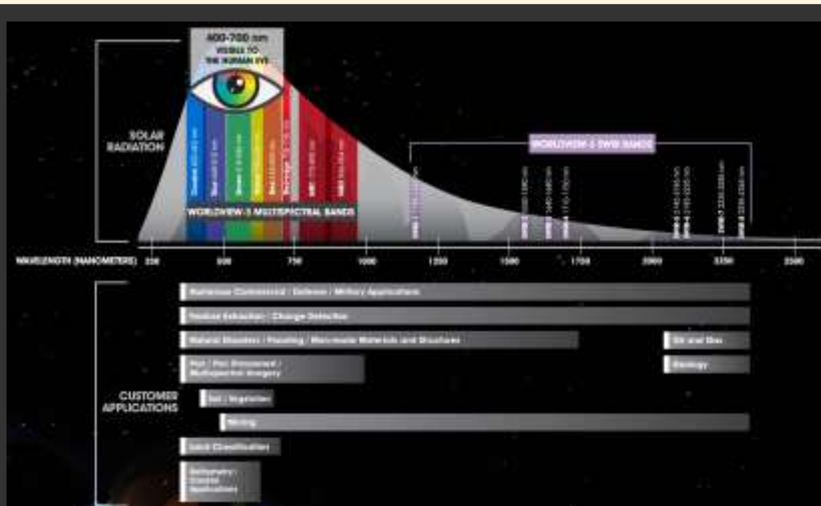


https://landsat.gsfc.nasa.gov/sentinel-2a-launches-our-compliments-our-complements/

60

This slide provides another example that compares the Multispectral Instrument (MSI) sensor onboard Sentinel-2A and 2B with the Landsat sensors. Here, different spectral ranges are sensed with some similarities with the Landsat missions.

WorldView-3



https://www.satimagingcorp.com/satellite-sensors/worldview-3/

61

Lastly, this image describes the bands collected by the commercial WorldView-3 sensor, which collects 8 bands in the visible/NIR range and 8 additional bands in the SWIR range.

This is the end of this lecture module.

Please return to the West Virginia View Webpage for additional content.

Thanks! Hope you found this useful.