Image from NASA:
https://commons.wikimedia.org/wiki/File:Earth_Western_Hemisphere_transparent_background.png#filelinks

Remote Sensing

Thermal, Hyperspectral, and SAR

In this course, we have primarily focused on the characteristics, collection, processing, and analysis of optical data collected in the visible, NIR, and SWIR ranges.

However, valuable and unique information can be obtained by investigating or measuring other regions of the electromagnetic spectrum.

In this module, I will provide an introduction to thermal, hyperspectral, and synthetic aperture Radar (SAR) data. This will not be an in-depth discussion; my primary goals are to introduced the key characteristics of these data and foster a conceptual understanding of the information obtained.

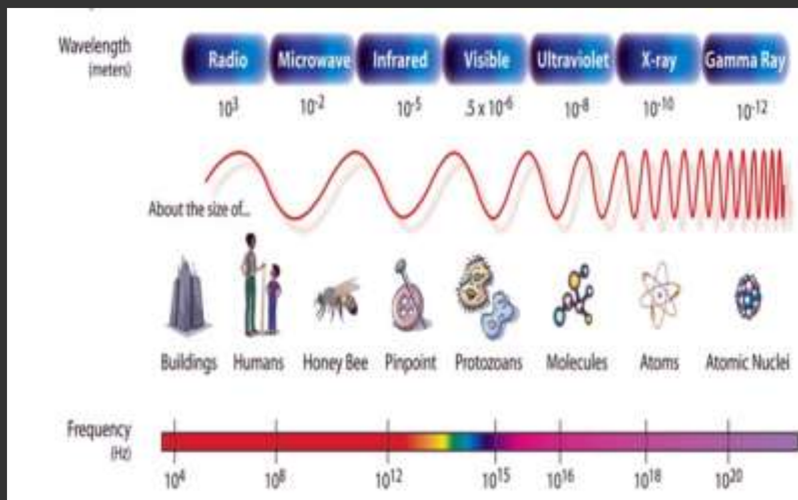
Module Topics

1. Temperature vs. heat
2. Heat capacity
3. Emissivity
4. Diurnal patterns and thermal data interpretation
5. Hyperspectral data cubes
6. Hyperspectral data processing
7. SAR bands
8. SAR collection geometry
9. SAR backscatter, polarization, and interpretation
10. SAR data processing
11. SAR for surface deformation analysis

These are the topics covered in this module.

Thermal

Electromagnetic Spectrum



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

4

We will begin with a discussion of thermal remote sensing.

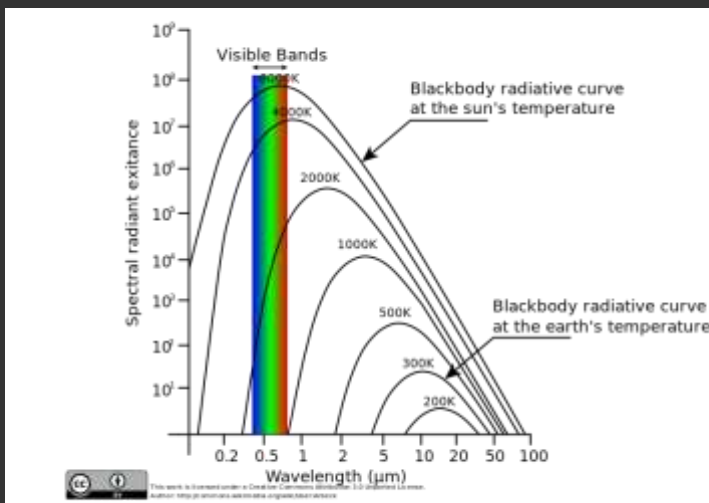
Electromagnetic Radiation of Interest in Remote Sensing

- Ultraviolet (UV) = less than 0.4 µm
- Visible Light = 0.4 to 0.7 µm
  - Blue = 0.4 to 0.5 µm
  - Green = 0.5 to 0.6 µm
  - Red = 0.6 to 0.7 µm
- Infrared (IR) = 0.7 to 14 µm
  - Near IR (NIR) = 0.7 to 1.3 µm
  - Mid IR/Shortwave IR (SWIR) = 1.3 to 3 µm
  - Thermal IR = 3 to 14 µm
- Microwaves = 1 mm to 1 m

5

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. The content covered in this section pertains to thermal IR radiation specifically.

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

6

Wien's Displacement Law states that the dominant or most abundant type of emitted radiation depends on the temperature of the emitting body. The hotter the object, the shorter the wavelength of the dominantly emitted radiation.

The Sun, because it is hotter, dominantly emits shorter wavelength visible light while the Earth, which is cooler, emits longer wavelength thermal infrared radiation. This is the source of energy for thermal remote sensing and the dominant source of heat energy in Earth's lower atmosphere.

Thermal vs. Optical

Characteristics	Thermal	Optical
Wavelength	Longer	Shorter
Active/Passive	Passive	Passive
Reflected/Emitted	Emitted	Reflected
Clouds	Impacted	Impacted

7

The table on this slide provides a comparison of thermal remote sensing and optical remote sensing of visible, NIR, and SWIR radiation.

Generally, both are passive, or rely on an external energy source. For optical remote sensing, this energy source is the Sun. For thermal remote sensing, we are measuring emitted radiation from the surface of the Earth. This energy is a result of the heating of Earth's surface by the shorter wavelength radiation emitted by the Sun. Some of this energy is absorbed, which provides an energy source for the long wavelength thermal radiation released by the Earth.

Note that both optical and thermal remote sensing are impacted by cloud cover. Or, we cannot see through the clouds using thermal data.

Some Uses

1. Rock type mapping/differentiation
2. Fire monitoring
3. Volcanology
4. Meteorology
5. Ecology
6. Heat loss from buildings

8

This slide describes some key uses of thermal data.

As mentioned in prior lectures, silicate rocks have diagnostic absorption features in the thermal range, so multispectral thermal data are sometimes used to map and differentiate rock types.

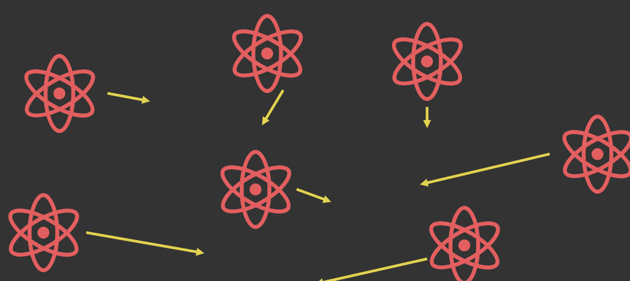
Any heat generating phenomenon may be studied with thermal sensors, such as forest fires and volcanoes.

Ecologically, thermal data can be used to map and identify animals on the landscape, which are generally hotter than their surroundings if they are warm blooded.

Thermal sensors can also be used to determine the source of heat loss from buildings. The results of such an analysis can then be used to suggest renovations that may make the building more energy efficient.

What is Temperature?

- Average kinetic energy of molecules
- Absolute Zero = no molecular motion (0 K)
- All objects with a temperature above absolute zero emit some radiation



9

What is temperature exactly? What does it physically measure?

Temperature is a measure of the average kinetic energy of molecules in a substance. Kinetic energy is energy associated with motion.

Kinetic energy can be calculated as $1/2mv^2$, where m is mass and v is velocity. So, kinetic energy is present anytime an object, or mass, is in motion, and a measure of the average kinetic energy of the molecules that make up a substance (such as a glass of water) is its temperature.

When there is no molecular motion, the temperature of a substance will be 0 Kelvin; however, generally there is some molecular motion, so we don't observe 0 K in nature. However, we have gotten close with lab experiments.

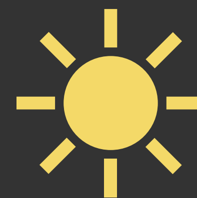
Wien's Displacements Law

$$\lambda_m = \frac{A}{T}$$

λ_m = wavelength of dominant emitted radiation (μm)

A = 2898 μm K

T = Temperature (K)



~6000 K

~300 K

10

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. This is the energy being sensed using thermal remote sensing.

What is Heat?

- Thermal energy transferred from a hotter to a cooler system that are in contact
- Measured in energy units (Joules or Calories)

$$\text{Heat } (q) = mC\Delta T$$

q = Heat
m = Mass
C = Specific heat capacity
ΔT = Change in temperature

11

The concepts of temperature and heat are commonly confused, since we use these terms interchangeably in day-to-day conversation. However, in physics the concepts of temperature and heat refer to different, but related measures.

Thermal energy is energy that can be transferred from a hotter to a cooler system when those systems are in contact. For example, if you boil a pot of water, then the water molecules will have a higher kinetic energy, or temperature, than your body. So, if you touch the water, heat energy will transfer from the water to your body, which could result in a burn.

So, heat measures a certain type of energy associated with temperature differences.

The provided equation shows how a change in thermal energy or heat content relates to mass and temperature. Change in heat content varies directly with mass and change in temperature. So, if more mass undergoes a greater temperature change, then there will be a greater change or transfer in heat energy than if a smaller mass undergoes the same temperature change or less temperature change.

Since heat is a form of energy, it is measured in energy units, such as Joules (K) or Calories (C). In contrast, temperature is measured in units of Kelvin (K), Celsius (C), or Fahrenheit (F).

Imagine you have two bodies of water. One is a glass of water and the other is a large swimming pool of water. If you take the temperature of each with a thermometer, you find that they have the same temperature. Does this mean they have the same amount of thermal energy or heat content? No. They do have the same temperature, or average kinetic energy; however, since the swimming pool contains a much larger mass of water, then the heat content would be much greater.

Specific Heat Capacity

- Energy required to change the temperature of sample per unit mass (J/K g)

Substance	Specific Heat Capacity
Water	4.1813
Wood	1.2 to 2.9
Asphalt	0.920
Brick	0.840
Concrete	0.880
Sand	0.835
Aluminum	0.897
Gold	0.129
Steel	0.466

12

Another useful physical concept for understanding thermal remote sensing is the concept of specific heat capacity.

Heat capacity is the amount of energy required to change the temperature, or average molecular kinetic energy, of a substance. Specific heat capacity is the amount of energy required to raise the temperature of a substance by 1 degree Celsius or Kelvin per unit mass. It is measured in units of J/K g, or energy (J) per unit change in temperature (K) per unit mass (g).

If a substance has a high specific heat capacity, then it takes more energy to change its temperature. This means that it has more thermal inertia, or it loses or gains energy slowly. In contrast, if a substance has a low heat capacity, then it can change temperature quickly.

Water is an example of a substance with a high specific heat capacity (4.1813 J/Kg, as noted in the provided table). This means that it takes time to heat water up and let it cool down. In contrast, gold has a very low specific heat capacity (0.129 J/Kg), meaning that it can change temperature rapidly with little required energy input or output.

This is important for thermal remote sensing, as you will see in later slides.

Kinetic vs. Radiant Temperature

- Kinetic Temperature = temperature of a body (internal manifestation of energy)
- Radiant Temperature = emitted energy as an external manifestation of an object's energy state
- Remote sensing measures total radiant exitance

$$M = \sigma T^4$$

M = total radiant exitance from the surface of a material (W/m^2)
σ = Stefan-Boltzmann constant ($5.6697 \times 10^{-8}\ W/m^2K^4$)
T = absolute temperature (K) of the emitting surface (K)

Assuming object acts as a blackbody radiator, kinetic temperature can be inferred from radiant temperature

13

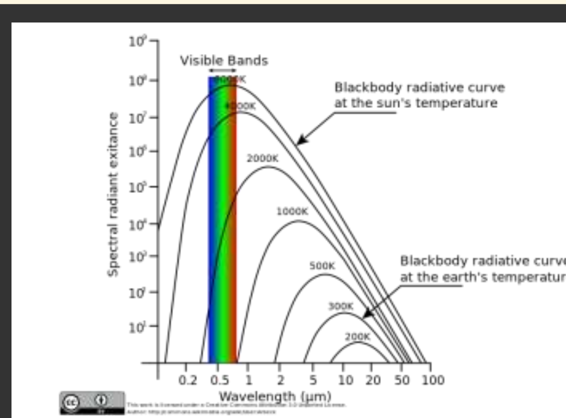
The internal temperature of a body is known as kinetic temperature. Again, you can think of this as the average molecular motion within the substance. However, when we use a sensor to measure emitted thermal radiation, we are actually measuring total radiant exitance (M from The Stefan-Boltzmann Law), which is the total energy emitted per unit time per unit area. Generally, this is related to the radiant temperature of an object, which is an external manifestation of an object's energy state. Kinetic temperature and radiant temperature are not equivalent, except in the case of a black body radiator.

So, thermal remote sensing is complicated by the fact that we measure M, which is related to radiant temperature, but we want to be able to estimate kinetic temperature. As a result, we need to be able to estimate kinetic temperature from the radiant temperature.

Let's explore this concept a bit further.

Blackbody Radiators

- Idealized physical body that absorbs all incident EM radiation regardless of the wavelength or angle of incidence
- When in thermal equilibrium, emitted radiation spectrum depends only on temperature
- Ideal emitter
- Diffuse emitter
- White body = body that reflects all incident EM radiation completely and uniformly



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

14

To foster a deeper understanding of thermal remote sensing, we will need to return to the concept of a blackbody radiator. As mentioned early in the class, this is an idealized, conceptual model that assumes a substance absorbs all incident EM radiation regardless of the wavelength or angle of incidence. When this idealized state is met, the emitted radiation spectrum only depends on the temperature of the substance, and kinetic temperature (T) can be inferred from the total radiant exitance (M). Unfortunately, this idealized model does not occur in nature. However, it is useful for understanding and simplifying our understanding of thermodynamics. Wien's Law and the Stefan-Boltzmann Law greatly simplify reality by assuming an object is a blackbody radiator.

In contrast, a white body does not absorb any radiation. Instead, it reflects all incoming radiation uniformly and completely. Again, this is also an idealized conceptualization. Blackbodies and white bodies are endmembers, and real substances are neither.

Emissivity

- Emitting ability of a material as compared to an idealized blackbody at the same temperature

$$\varepsilon(\lambda) = \frac{\textit{Radiant exitance of an object at a given temperature}}{\textit{Radiant exitance of a blackbody at the same temperature}}$$

Substance	Emissivity
Water	0.90 – 0.95
Wood	0.80 – 0.95
Asphalt	0.90 – 1.00
Concrete	0.95
Sand	0.80 – 0.90
Aluminum (rough)	0.10 – 0.30
Gold	0.05

15

Emissivity can be thought of as a measure that allows us to correct for non-idealized emission of radiation, assuming that a blackbody is the ideal.

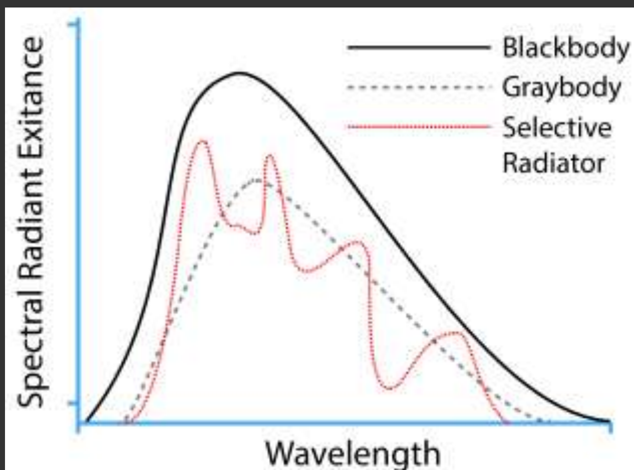
It is a unitless ratio that compares the radiant exitance of an object at a specific temperature with that for a blackbody at the same temperature; it is a ratio of how much actual energy is emitted per unit time per unit area in comparison to a blackbody under the same conditions.

Larger values indicate behavior that is closer to that of a blackbody while lower values indicated behavior much different than a blackbody. Note the scale is 0 to 1: it is not possible for an object to emit more energy per unit time per unit area than a blackbody at the same temperature.

So, water, with an emissivity between 0.90 and 0.95, emits 90% to 95% the amount of energy as a blackbody radiator at the same temperature. In contrast, gold, with an emissivity of 0.05, emits much less energy than the blackbody conceptual model.

Note that emissivity values are derived experimentally using laboratory techniques.

Graybody



- ❖ Body with emissivity less than 1 and constant at all wavelengths
- ❖ Selective Radiator = emissivity varies with wavelength

16

Real-world substances or bodies can behave as graybodies: they emit less radiant energy per unit time per unit area than the idealized blackbody. Also, this reduction in emittance is consistent across different wavelengths.

Alternatively, a selective radiator is one in which the emissivity varies with wavelength. Again, silicate rocks would be a good example here, since there are absorption features in the thermal range that can be used to differentiate these rock types.

Kirchhoff Radiation Law

$$\rho(\lambda) + \tau(\lambda) + \alpha(\lambda) = 1$$

Reflectance + Transmittance + Absorbance = 1

$$\varepsilon(\lambda) = \alpha(\lambda)$$

Emittance = Absorbance

$$\rho(\lambda) + \tau(\lambda) + \varepsilon(\lambda) = 1$$

Replace Absorbance with Emittance

$$\rho(\lambda) + \varepsilon(\lambda) = 1$$

Transmittance is negligible

- Spectral emissivity = spectral absorption
- Good absorbers are good emitters

17

Kirchoff's Law states that good absorbers of radiation tend to also be good emitters of radiation. Or, if a substance absorbs a lot of radiant energy, it also tends to emit a lot of radiant energy. Let's work through this logic.

If the total amount of energy incident on an object is equal to 1, then the total of reflected, transmitted, and absorbed energy must sum to 1, since energy is conserved.

Emittance is equivalent to absorbance if a substance is in thermal equilibrium; the amount of energy absorbed will be equivalent to the amount of energy emitted. This is required so that the internal temperature does not change.

If we replace absorbance with emittance in the equation, then the total of reflected and transmitted incident energy plus the emitted energy will sum to 1.

If we assume that transmittance is negligible for an opaque object, then reflectance plus emittance must sum to 1.

So, assuming the energy of emittance is equal to the energy absorbed, then substances that absorb a lot of energy will also emit a lot of energy.

Estimate Temperature

- Sensors measure M
- Blackbody

  Radiant Temperature = Kinetic Temperature

  $M = \sigma T^4$
- Real Objects

  Radiant Temperature = $\varepsilon^{1/4}$ X Kinetic Temperature

  $M = \varepsilon \sigma T^4$
- Thermal sensors detect radiation from the surface (approximately the first 50 µm) of the ground object

18

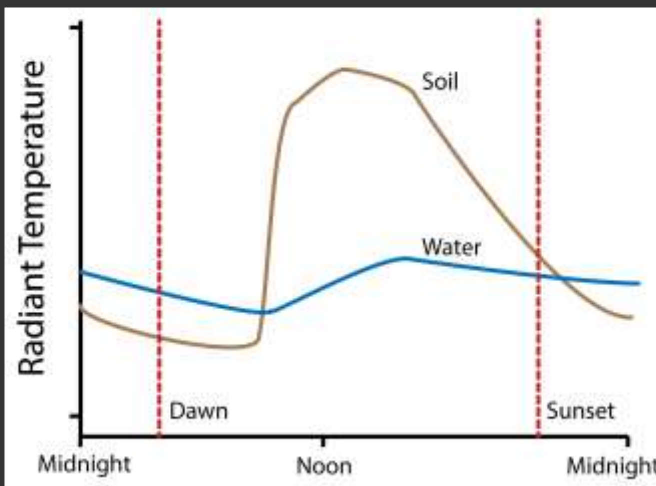
To wrap this up, a thermal sensor is measuring the amount of energy per unit time per unit area, or M from the Stefan-Boltzmann Law. Assuming an object is an idealized blackbody radiator, then this measured energy emission can be used to estimate kinetic temperature (T) using the Stefan-Boltzman Law. This assumes that radiant temperature is equal to kinetic temperature.

However, real-world substances and bodies are not perfect blackbody radiators. So, the energy measured (M) cannot be used to directly estimate kinetic temperature. However, in the case of a graybody radiator, the introduction of emissivity into the equation will allow us to estimate kinetic temperature from the measured exitance energy (M). This is more complicated for selective radiators, since emissivity varies by wavelength.

So, with a well calibrated thermal sensor, it is possible to estimate the radiant energy of a body. If it is or is assumed to be a graybody radiator, and we know the emissivity, then we can adjust the radiant temperature and estimate the kinetic temperature.

Thermal sensors generally detect radiation from the surface (approximately the first 50µm) of ground objects. So, we are attempting to estimate the kinetic temperature near the surface. The interior temperature may be higher.

Diurnal Patterns



❖Higher thermal inertia = more stable surface temperatures

19

One of the interesting aspects of thermal data is the ability to measure temperature changes throughout a day. Understanding this diurnal cycle can allow us to differentiate surface materials and better understand the energy balance across the landscape.

In the provided conceptual example, I am comparing the radiant temperature of soil and water throughout a day. At night, the temperature of the water tends to be higher than the temperature of the soil. However, during the day the soil temperature tends to be higher than that of the water.

This observation is primarily explained by the differences in specific heat capacity between the materials. Water has a high specific heat capacity, so it tends to warm and cool slowly. In other words, it tends to “hold its heat.” So, it does not warm as much during the day as the soil does, but it holds heat energy throughout the night while the soil loses it.

Thus, the diurnal variability of water is moderated by its high specific heat capacity. In contrast, soil, with a lower specific heat capacity, shows large fluctuations throughout the day and night, since it gains and loses energy more readily.

Diurnal Patterns

Landsat 8 Band 10 Daytime

Landsat 8 Band 10 Nighttime

20

These two images further elaborate on the impact of heat capacity.

The image on the left is a Landsat 8 TIRS thermal image taken during the daytime. In this image, which includes the area around San Diego, California, the land is hotter during the day than the water. In contrast, at night, we see that the near-shore water has a higher or more comparable temperature to that of the land.

It also appears as if the road network maintains its heat content to a greater degree than the surrounding vegetation through the night. Also, forested areas remain cooler during the day and warmer at night than other vegetation.

Multispectral Thermal

- Multiple bands in the thermal range
- Valuable for rock differentiation
- Example: Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

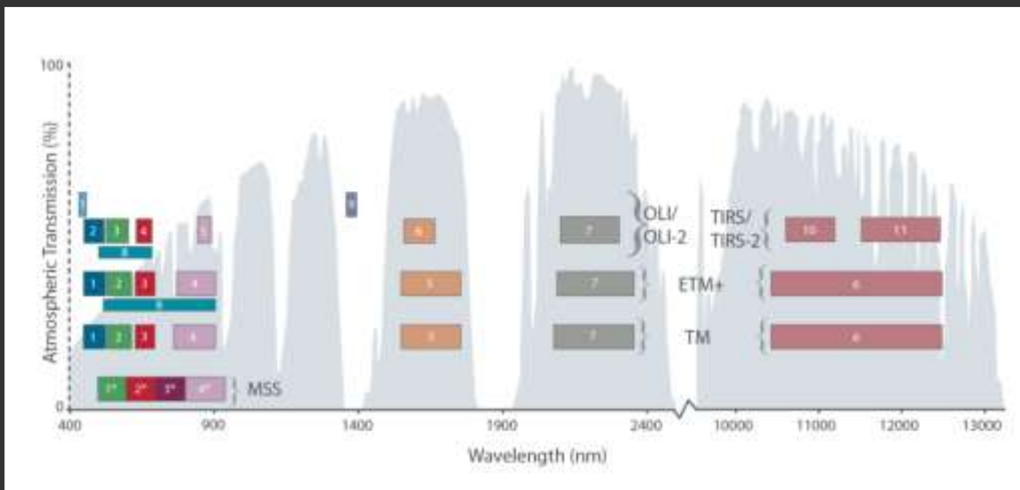
Band	Wavelengths (μm)	Spatial Resolution
10	8.125 - 8.475	90 m
11	8.475 - 8.825	90 m
12	8.925 - 9.275	90 m
13	10.25 - 10.95	90 m
14	10.95 - 11.65	90 m

21

Again, rock differentiation and analysis can be conducted using multispectral thermal data.

One example of such a dataset is the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). This instrument is carried onboard Terra and offers a thermal spatial resolution of 90 meters across five spectral bands.

Landsat



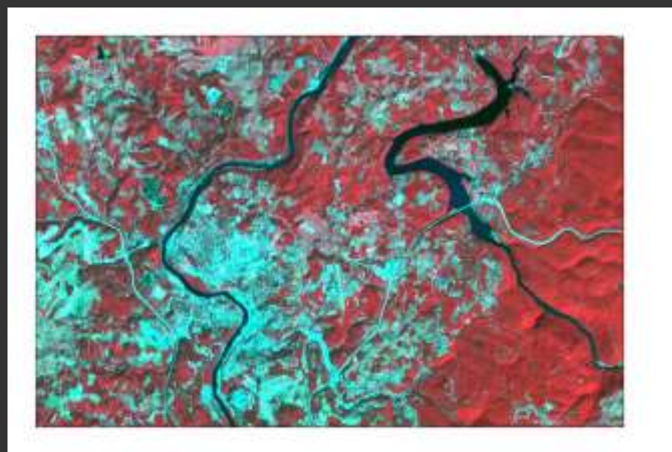
https://landsat.gsfc.nasa.gov/landsat-9/landsat-9-spectral-bands/

22

The Landsat missions also provide thermal data. Beginning with the Thematic Mapper (TM) sensor onboard Landsat 4 and 5 and continuing with the Enhanced Thematic Mapper Plus (ETM+) sensor onboard Landsat 7, 1 thermal band was collected that covered a broad spectral range.

The Landsat 8 and 9 missions carries the Thermal Infrared Sensor (TIRS) and Thermal Infrared Sensor-2 (TIRS-2), respectively, which provides two thermal bands.

Landsat Standard False Color Composite

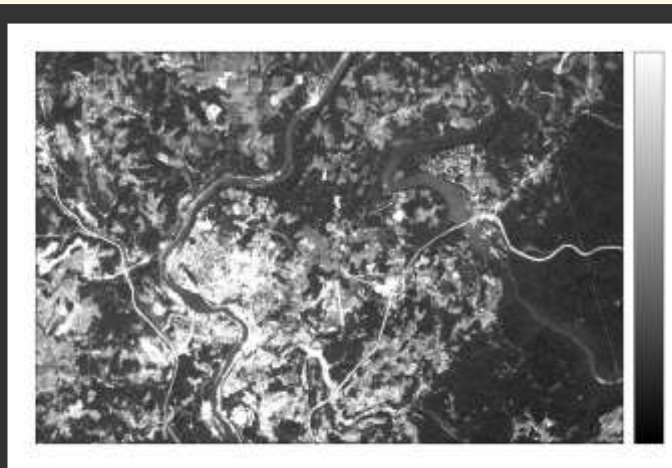


12 September 1999, approx 10 am

23

This image is an example of a Landsat 7 ETM+ standard false color composite of the Morgantown, WV area collected on September 12, 1999 at around 10 AM. Here, we are visualizing reflected energy in the visible and NIR ranges.

Landsat ETM+ Thermal Band

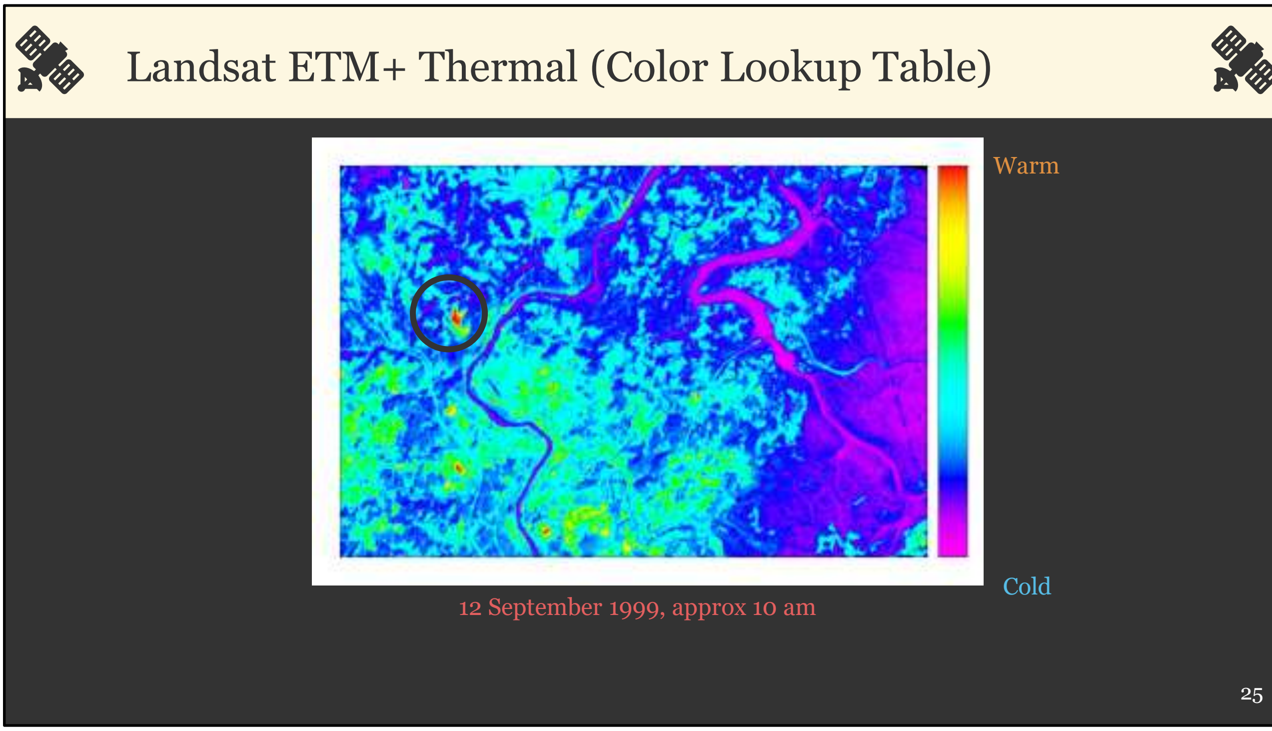


12 September 1999, approx 10 am

24

This image is the thermal band associated with the standard false color composite shown in the prior slide. Since this is a daytime image, we see higher thermal emission from features with a low specific heat capacity, such as pavement and developed areas. In contrast, the forested areas are dark while water is moderate.

How might you expect this image to differ from one collected at night?



This slide shows another representation of the same data using a lookup table to apply a color ramp.

Again, we can see differences in surface temperature based on land cover conditions. Elevation also plays a role, as the area in the eastern part of the image is higher than the area in the west.

I have circled an area that is particularly warm. It contains some exposed coal waste that is very dark. Because it is so dark and also has a low specific heat capacity, it will absorb and subsequently emit a lot of radiation. So, this is a good example of the Kirchhoff Radiation Law.

MODIS

Band	Wavelength Range (µm)
20	3.660–3.840
21	3.929–3.989
22	3.929–3.989
23	4.020–4.080
24	4.433–4.498
25	4.482–4.549
20	3.660–3.840
21	3.929–3.989
22	3.929–3.989
23	4.020–4.080
24	4.433–4.498
25	4.482–4.549

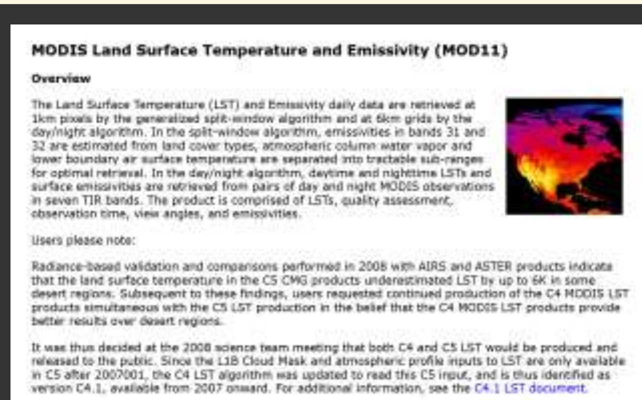
- Bands 20 – 25 and 27 – 26
- 1,000 meter spatial resolution
- Daily return interval

26

MODIS, onboard the Terra and Aqua satellite platforms, offers several thermal bands at a 1 km spatial resolution. It also has a daily return interval.

MODIS

- Land Surface Temperature/Emissivity
- 1 to 6 km spatial resolution
- Daily, 8-day, monthly
- Onboard Terra and Aqua



MODIS Land Surface Temperature and Emissivity (MOD11)

Overview

The Land Surface Temperature (LST) and Emissivity daily data are retrieved at 1km pixels by the generalized split-window algorithm and at 6km grids by the day/night algorithm. In the split-window algorithm, emissivities in bands 31 and 32 are estimated from land cover types, atmospheric column water vapor and lower boundary air surface temperature are separated into tractable sub-ranges for optimal retrieval. In the day/night algorithm, daytime and nighttime LSTs and surface emissivities are retrieved from pairs of day and night MODIS observations in seven TIR bands. The product is comprised of LSTs, quality assessment, observation time, view angles, and emissivities.

Users please note:

Radiance-based validation and comparisons performed in 2008 with AIRS and ASTER products indicate that the land surface temperature in the C5 CMG products underestimated LST by up to 6K in some desert regions. Subsequent to these findings, users requested continued production of the C4 MODIS LST products simultaneous with the C5 LST production in the belief that the C4 MODIS LST products provide better results over desert regions.

It was thus decided at the 2008 science team meeting that both C4 and C5 LST would be produced and released to the public. Since the L1B Cloud Mask and atmospheric profile inputs to LST are only available in C5 after 2007001, the C4 LST algorithm was updated to read this C5 input, and is thus identified as version C4.1, available from 2007 onward. For additional information, see the C4.1 LST document.

https://modis.gsfc.nasa.gov/data/dataprod/mod11.php

27

Instead of using the raw MODIS bands, it is common to use derived products as input into analyses. For example, MODIS data products are often used for analysis of continental to global scale climatological and land surface processes.

One example MODIS product is the Land Surface Temperature/Emissivity products. This product, which is derived from the thermal bands, offers 1 to 6 km spatial resolution and daily, 8-day, and monthly surface temperature estimates.

AVHRR

- Sea surface temperature
- Land surface temperature

Band #	NOAA-6,8,10	NOAA-7,9,11,12,14	NOAA-15,16,17,18
Sensor	AVHRR/1	AVHRR/2	AVHRR/3
4 (Thermal)	10.50 - 11.50 µm	10.3 - 11.3 µm	10.3 - 11.3 µm
5 (Thermal)		11.5 - 12.5 µm	11.5 - 12.5 µm

28

The Advanced Very High Resolution Radiometer (AVHRR) is a coarse spatial resolution sensor, similar to MODIS. However, it has a longer historic record than that made available by MODIS. So, it can be useful for change detection and time series analysis. It also provides thermal bands, which allow for the estimation of surface temperature.

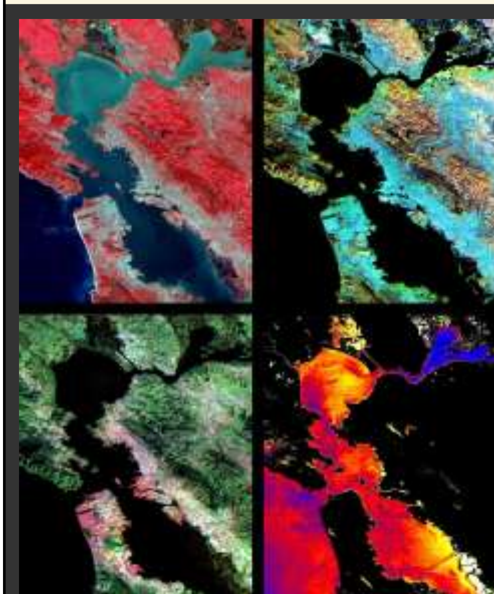
ASTER

Band	Wavelengths (µm)	Spatial Resolution (meters)	Explanation
1	0.52 - 0.60	15 m	Visible and Near-Infrared
2	0.63 - 0.69	15 m	Visible and Near-Infrared
3N	0.78 - 0.86	15 m	Visible and Near-Infrared
3B	0.78 - 0.86	15 m	Visible and Near-Infrared
4	1.600 - 1.700	30 m	Shortwave Infrared
5	2.145 - 2.185	30 m	Shortwave Infrared
6	2.185 - 2.225	30 m	Shortwave Infrared
7	2.235 - 2.285	30 m	Shortwave Infrared
8	2.295 - 2.365	30 m	Shortwave Infrared
9	2.360 - 2.430	30 m	Shortwave Infrared
10	8.125 - 8.475	90 m	Thermal Infrared
11	8.475 - 8.825	90 m	Thermal Infrared
12	8.925 - 9.275	90 m	Thermal Infrared
13	10.25 - 10.95	90 m	Thermal Infrared
14	10.95 - 11.65	90 m	Thermal Infrared

- Advanced Spaceborne Thermal Emission and Reflection Radiometer
- Onboard Terra
- Also used to produce DEMs

As mentioned above, ASTER, which is onboard Terra, offers multispectral thermal data at a 90 m spatial resolution. It also collects data in the visible, NIR, and SWIR ranges. Due to the availability of stereo data collection, it can also be used to create digital elevation models (DEMs).

ASTER



- Advanced Spaceborne Thermal Emission and Reflection Radiometer
- Onboard Terra
- Also used to produce DEMs

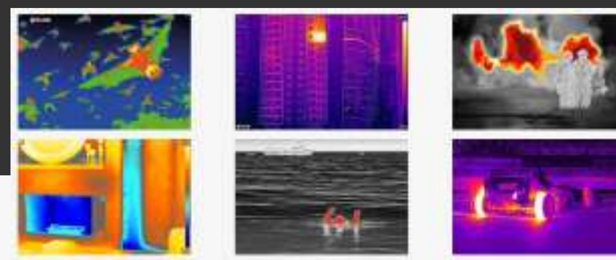
https://asterweb.jpl.nasa.gov/

30

This slide shows an ASTER image displayed with different band combinations. Thermal data are represented in the bottom-right image.

Ground/Aerial/Drone

- FLIR = Forward-Looking Infrared



https://www.flir.com/oem/thermal-by-flir/

https://www.flir.com/

31

Thermal sensors can also be attached to drones, other aerial platforms, and be implemented as hand-held devices.

One example of this technology is FLIR instruments, or Forward-Looking Infrared.

Such technology has a wide range of applications. For example, they can be used to assess heat loss from buildings to make recommendations for increasing efficiency. They can also be used in ecology for detecting warm-bodied organisms or warmer areas of water that may be important aquatic habitat.

Aircraft - Slow Stall Speed, Ruggedized Landing Gear

32

This set of slides show some photos from a thermal data collection from an aerial platform.

Liquid N Cooled Thermal Scanner

Collecting Liquid N from an insulated flask

Belly-mounted thermal scanner

33

To reduce the impact of emitted radiation from the sensor, it is cooled to a very low temperature using liquid nitrogen. It is then mounted to the bottom of the plane.

Operation of Scanner in Flight

34

This images shows the instrumentation. Note the modern systems often take up much less space and are generally easier to operate.

Tape Storage, Monitor

Reel to reel tapes
- perhaps 30MB storage
(early 1980s)

35

This older system relied on magnetic tape to record the data, which offered only 30 MBs of storage!

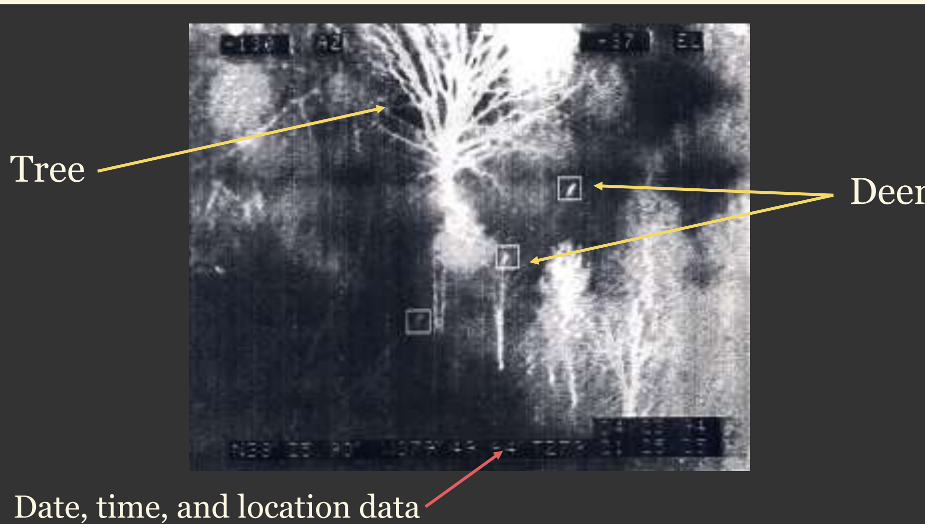
Aerial Thermal Image Acquisition

Transvaal, South Africa (now North-West Province)

Here is an example of the collected thermal data showing pre-dawn conditions. In comparison to aerial imagery over the same area, a lot of additional information is provided. For example, soil moisture levels are obvious.

Note that the water in the river channel is hotter at night then the surrounding landscape. Again, this is explained by its high specific heat capacity.

Wildlife Survey Using Thermal Video



37

Thermal data can also be useful for monitoring organisms for ecological and wildlife studies. In this image, deer can be observed due to their warmer temperature. Note also that the vegetation tends to be warmer than the ground, which is partially explained by water content.

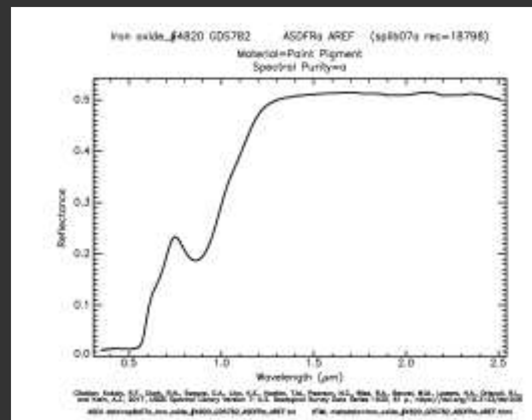
Hyperspectral

38

Hyperspectral Characteristics

- Many bands (10s to 100s)
- Narrow ranges
- Approximate spectral reflectance curve
- USGS Spectral Library:

https://www.usgs.gov/labs/spec-lab/capabilities/spectral-library



https://crustal.usgs.gov/speclab/data/HTML metadata/Iron_oxide_%234820_GDS782_ASDFRa_AREF.html

Iron Oxide
USGS Spectral
Library Version 7

39

I will now provide a brief introduction to hyperspectral remote sensing.

Hyperspectral remote sensing, or imaging spectroscopy, involves the collection of a large number of image bands that more closely approximates the spectral reflectance curve at the pixel location in comparison to the limited number of wide bands collected by a multispectral sensor.

Hyperspectral images can include 10s to 100s of bands that cover a wide range of wavelengths.

Spectrometers can also be used in the field and lab to collect reference spectral reflectance for different materials. The USGS Spectral Library provides a database of such measurements. On this slide, I have provided an example for iron oxide.

Data Cubes

- X = Width
- Y = Length
- Z = Bands

Dr. Nicholas M. Short, Sr. - NASA http://rst.gsfc.nasa.gov/

40

Given the large data volume, hyperspectral data can be complex. They are generally stored as a data cube, which is effectively a multidimensional array. The x- and y-dimensions define the spatial dimensions. The z-dimension represents the spectral dimension. Each layer represents measurements in a specific, narrow spectral range.

Some Uses

1. Surface mineralogy
2. Water quality
3. Bathymetry
4. Soil types and erosion
5. Vegetation type
6. Plant stress
7. Leaf water content
8. Canopy chemistry
9. Crop type and condition
10. Snow and ice properties

41

Hyperspectral data have many uses.

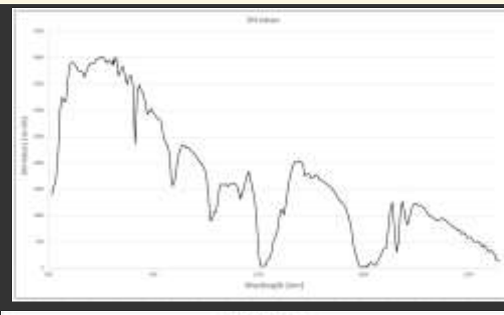
They can used to assess surface mineralogy, water quality, water depths, soil types, and soil loss.

For vegetation applications, they have been used to differentiate vegetation types; assess plant stress resulting from water loss, nutrient depletion, or disease; understand forest canopy chemical dynamics; and evaluate crops to support research and precision agriculture.

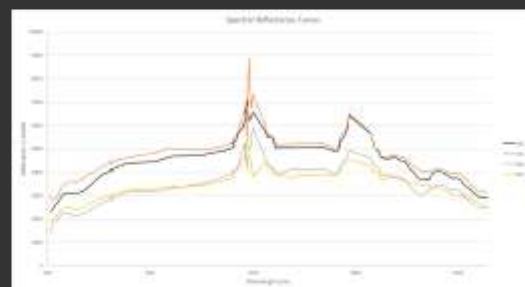
It is likely that the applications of hyperspectral data will expand as we continue to develop techniques to analyze them. Progress has been hindered by limited computational power and lack of data.

Complexities

- ❖Large data volume
- ❖Atmospheric correction
- ❖Converting to surface reflectance



FLASH module in ENVI to convert data to reflectance



42

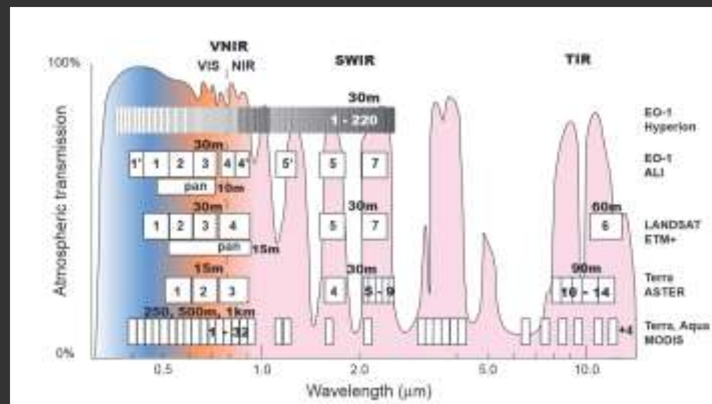
Hyperspectral data are very powerful and have many uses. However, they can be complicated to work with due to large data volume. There are also issues associated with the complexity of atmospheric correction and estimation of surface reflectance.

On this slide, I show two representations of hyperspectral data. The top graph represents DN values. You can clearly see the impact of atmospheric absorption and amount of incoming energy. The second graph represents the data once converted to surface reflectance.

The other image on this slide is a screen capture from the FLASH module in the ENVI software, which can be used to convert DN values to radiance and surface reflectance.

Hyperion

- ALI (Advanced Land Imager)
- Onboard NASA’s Earth Observing-1 (EO-1) satellite
- 242 bands
  - 70 channels in visible to NIR
  - 172 channels in SWIR
- 0.4 µm to 2.5 µm
- 30 meter spatial resolution
- 16 day revisit
- Launches 11/21/2000
- Decommissioned 3/30/2017



Casey, K.A., Kääb, A. and Benn, D.I., 2012. Geochemical characterization of supraglacial debris via in situ and optical remote sensing methods: a case study in Khumbu Himalaya, Nepal. *The Cryosphere*, *6*(1), p.85.

There are a wide variety of hyperspectral sensors and missions. I will just provide a few examples here.

Hyperion was onboard NASA’s Earth Observing-1 (EO-1) satellite. It offered 242 bands, with 70 channels in the visible and NIR ranges and 172 bands in the SWIR range. It offered a spatial resolution of 30 meters with at 16-day revisit time, similar to the Landsat missions.

It was launched in 2000 and decommissioned in 2017.

Ground/Aerial/Drone

https://www.harrisaerial.com/solutions-applications/hyspex-mjolnir-v-1240-hyperspectral-camera/

HYPERSPECTRAL SENSOR COMPARISON	Corning® microHSI™ 410 SHARK	Headwall® VNIR E-Series
Spectral Range	400-1000 nm	400-1000 nm
Max. Frame Rate	>300 Hz (profile dependent)	250 Hz
Weight	1.5 lbs (standard lens, data storage, INS)	3.1 lbs (weight without lens)
Compatible Drones	DJI Matrice 600, xFold Travel and Dragon	DJI Matrice 600, xFold Travel and Dragon

https://www.precisionhawk.com/sensors/advanced-sensors-and-data-collection/hyperspectral

44

Several commercial companies offer hyperspectral sensors that can be mounted to aerial platforms. There are even sensors that are light-weight and can be attached to drones.

AVIRIS

Airborne Visible / Infrared Imaging Spectrometer

https://aviris.jpl.nasa.gov/

- Airborne Visible/Infrared Imaging Spectrometer
- NASA Jet Propulsion Laboratory
- 224 bands
- 0.4 to 2.5 µm
- Spectral resolution depends on flight height
  - 1 to 20 meters

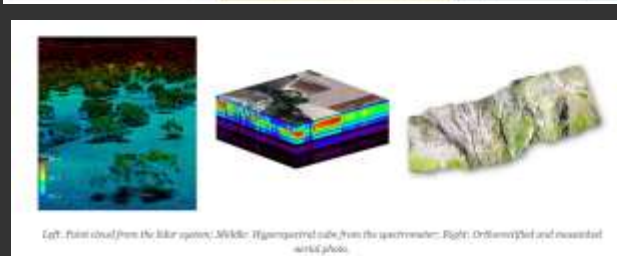
45

The Airborne Visible/Infrared Imaging Radiometer (AVIRIS) is operated by NASA's Jet Propulsion Laboratory. From an aerial platform, it collects 224 bands in the visible to SWIR ranges.

The spatial resolution of the data varies based on flight height, but is commonly between 1 and 20 meters.

NSF NEON

- ❖ Hyperspectral Data
  - ~ 1 meter spatial resolution
  - 420 spectral bands
  - 0.38 to 2.5 µm
- ❖ RGB Camera
  - ~6.6 to 10 cm spatial resolution
- ❖ LiDAR
  - 1 to 4 points per square meter
  - Discrete return and full waveform



https://www.neonscience.org/data-collection/airborne-remote-sensing

46

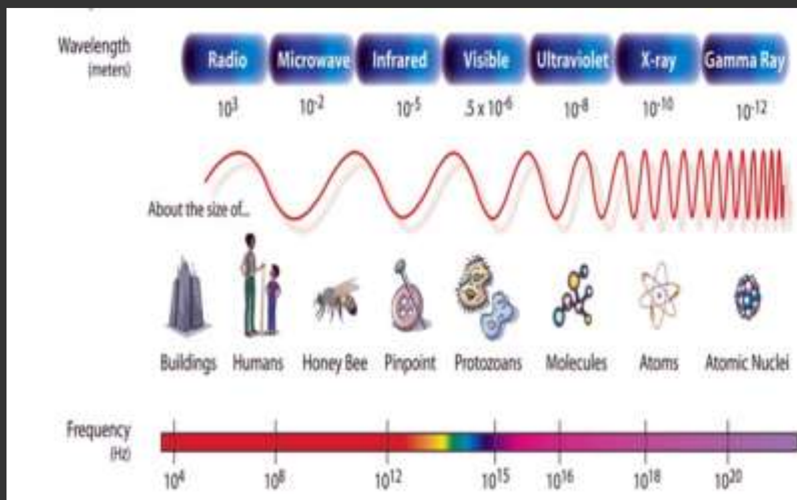
The National Science Foundation (NSF) NEON project offers repeat collection of hyperspectral, RGB, and LiDAR data over multiple study sites. The hyperspectral data consist of 420 bands covering the visible through SWIR ranges with a spatial resolution of around 1 meter.

The LiDAR data includes both discrete and full waveform products.

The NEON program can be contacted to obtain access to these data.

Synthetic Aperture RADAR (SAR)

Electromagnetic Spectrum



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

48

In this last section of the module, I will provide an overview of synthetic aperture radar (SAR). SAR makes use of EM radiation in the microwave range.

Electromagnetic Radiation of Interest in Remote Sensing

- Ultraviolet (UV) = less than 0.4 µm
- Visible Light = 0.4 to 0.7 µm
  - Blue = 0.4 to 0.5 µm
  - Green = 0.5 to 0.6 µm
  - Red = 0.6 to 0.7 µm
- Infrared (IR) = 0.7 to 14 µm
  - Near IR (NIR) = 0.7 to 1.3 µm
  - Mid IR/Shortwave IR (SWIR) = 1.3 to 3 µm
  - Thermal IR = 3 to 14 µm
- Microwaves = 1 mm to 1 m

49

In comparison to other wavelength ranges discussed in this class, microwaves have a longer wavelength, lower frequency, and lower energy. Wavelengths range from ~1 mm to ~1 m.

SAR vs. Optical

Characteristics	SAR	Optical
Wavelength	Longer	Shorter
Active/Passive	Active	Passive
Reflected/Emitted	Reflected	Reflected
Clouds	Not Impacted	Impacted

50

Here is a comparison of SAR and optical data used for visible, NIR, and SWIR sensing.

In contrast to optical data, SAR is an active technology. The sensor will release pulses of microwave radiation as opposed to relying on an external energy source.

One of the great benefits of SAR is that these data can be collected through cloud cover because these wavelength ranges are cloud penetrating. As a result, SAR data are of great value for mapping areas that have frequent or even continuous cloud cover.

Also, data can be collected on a regular basis to support change and time series analysis, which will not be interrupted by cloud cover.

Characteristics

Band Designation	Wavelength (cm)	Frequency (MHz)
K_a	0.75 – 1.1	40,000 – 26,500 MHz
K	1.1 – 1.67	26,500-18,000 MHz
K_u	1.67 – 2.4	18,000 – 12,500 MHz
X	2.4 – 3.75	12,500 – 8,000 MHz
C	3.75 – 7.5	8,000 – 4,000 MHz
S	7.5 – 15	4,000 – 2,000 MHz
L	15 – 30	2,000 – 1,000 MHz
P	30 – 100	1,000 – 300 MHz

- Microwave range
- Active
- Side-Looking
- Use motion of platform to synthesize a long antenna and improve spatial resolution
- Different wavelength ranges have letter designations

51

SAR make use of microwave EM radiation that is produced by the sensor. Different wavelengths are used for different applications. A lettering system was devised from early military applications.

For example, C-band SAR uses wavelengths between 3.75 and 7.5 cm while L-band uses wavelengths from 15 to 30 cm.

SAR is also side-looking. This is because it relies on backscatter. By transmitting signals at an angle relative to the ground, this allows for a better differentiation of the return locations. For example, if the energy was transmitted straight down, beams transmitted at the same angle but in opposite directions of nadir could return to the sensor at the same time, which would hinder differentiation.

What exactly does synthetic aperture mean? In order to obtain data with a higher spatial resolution, such as less than 50 meters, a long antenna is required (i.e., meters to tens of meters in length). This would hinder the use of such technology, especially for orbital deployment. Synthetic aperture means that a large aperture or antenna is synthesized using the forward motion of the sensor along its flight or orbital path. The mathematics of this is complicated. The key takeaway here is that this technology makes SAR a viable option for data collection as antennas can be much shorter and the system can be more easily deployed.

Uses

Band Designation	Wavelength (cm)	Frequency (MHz)	Applications
K_a	0.75 – 1.1	40,000 – 26,500 MHz	Airport surveillance
K	1.1 – 1.67	26,500-18,000 MHz	Water Absorption
K_u	1.67 – 2.4	18,000 – 12,500 MHz	Satellite altimetry
X	2.4 – 3.75	12,500 – 8,000 MHz	Urban monitoring; ice and snow; little penetration into vegetation cover; fast coherence decay in vegetated areas
C	3.75 – 7.5	8,000 – 4,000 MHz	global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence; ice, ocean maritime navigation
S	7.5 – 15	4,000 – 2,000 MHz	agriculture monitoring; expends C-band applications to higher vegetation density
L	15 – 30	2,000 – 1,000 MHz	Geophysical monitoring; biomass and vegetation mapping; high penetration; InSAR
P	30 – 100	1,000 – 300 MHz	Biomass; vegetation mapping and assessment

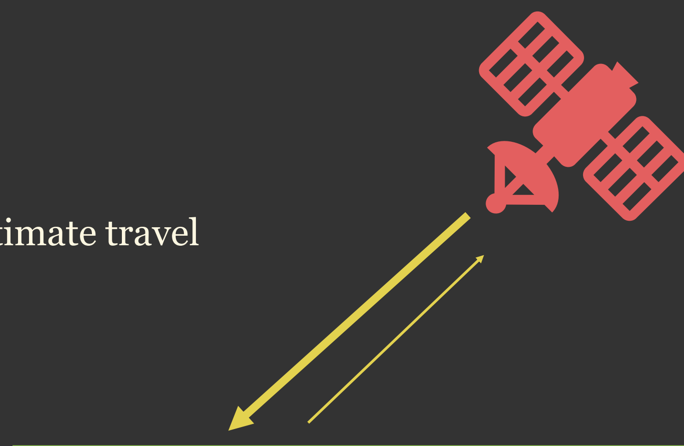
https://earthdata.nasa.gov/learn/what-is-sar

52

The uses of SAR data depend on the wavelength range used. This slide provides some examples of SAR uses by wavelength range.

Backscatter

- Backscatter = energy reflected back to the sensor
- Relates to:
  - Surface roughness
  - Dielectric properties
- Measure travel time to estimate travel distance or range

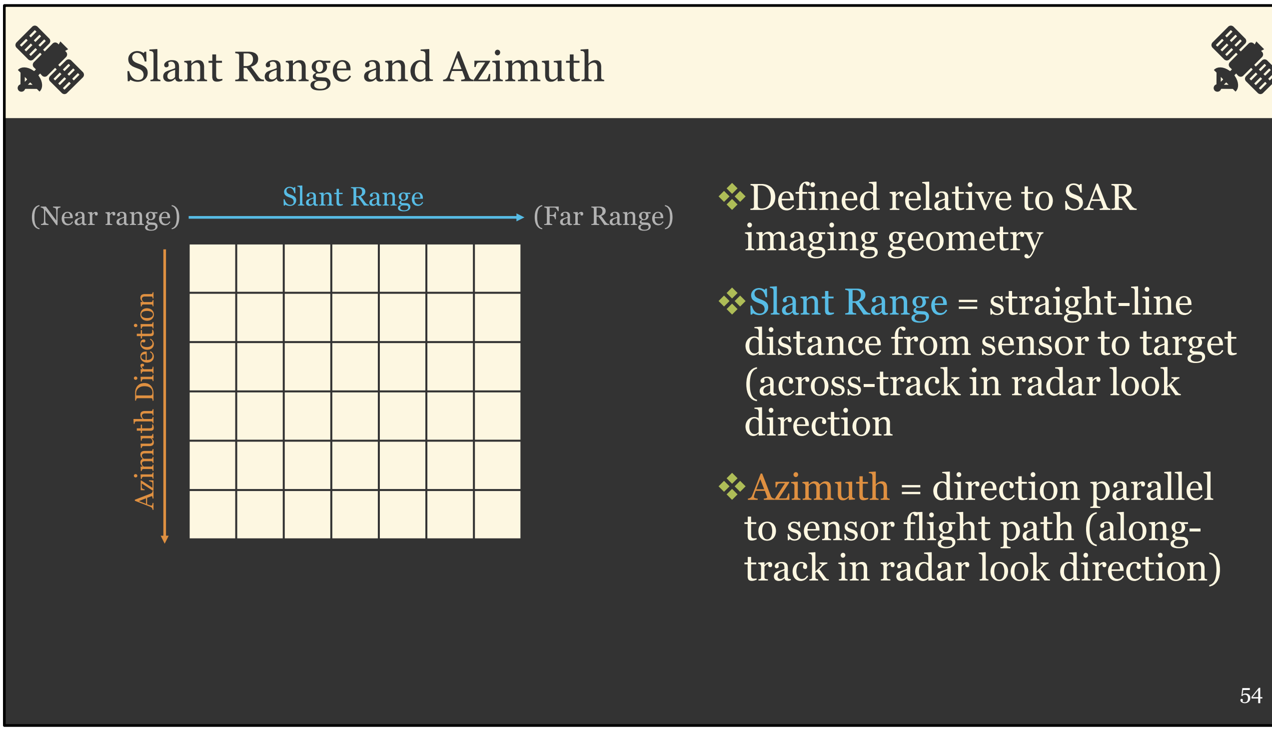


53

What is actually measured by a SAR instrument?

SAR releases microwaves and then measures the returned backscatter. In other words, it measures the energy that is scattered back towards it, as opposed to being absorbed or scattered away from the detector.

This backscatter is generally correlated with the surface roughness relative to the wavelength of the transmitted radiation and the dielectric properties of the surface material. Dielectric properties relate to water content, with more water content resulting in greater electrical conductivity.



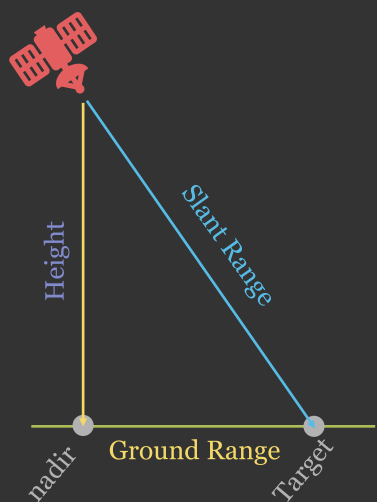
SAR data are collected and stored using a unique geometry in comparison to other sensor types.

The slant range is the distance from the senor to the target relative to the look direction of the sensor. This is the straight-line distance from the sensor to the target.

The azimuth is the direction parallel to the flight path or the motion of the platform.

The slant range and azimuth define the columns and rows, respectively, of the collected data. However, this array of measurements is not meant to align with locations on the surface of the earth or a map projection.

Slant Range vs. Ground Range



- ❖Slant range = sensor-to-target distance (radar line of sight)
- ❖Ground range = map distance on ground (distance along earth surface from nadir to target)
- ❖Raw SAR geometry uses slant range (travel time of energy)
- ❖Ground range is map-like; use imaging geometry and elevation to derive

55

In contrast to slant range, the ground range is the distance from the nadir point, or the location on the ground directly below the sensor, to the target location parallel to the ground surface.

It is possible to use information about the SAR collection geometry and elevation data to convert to ground range distance and obtain an array of values that align with a map projection and can be drawn on the surface of the Earth at the correct location.

Backscatter Scales

- Can be expressed as:
  - Linear power ratio = uses linear scale
  - Decibels = log scale

$$\text{Backscatter}_{dB} = 10\log_{10(\text{Linear Backscatter})}$$

Linear Value	dB Value
0.001	-30 dB
0.01	-20 dB
0.1	-10 dB
1	0 dB
10	10 dB

Very weak

↓

Very Strong

56

Since backscatter signals can vary over a large range of magnitudes, it is common to report them using a log scale as decibels (dB) as opposed to a linear scale (linear power ratio). The log scale is described on this slide.

Backscatter Units

- β^0 (Beta Nought) = backscatter normalized by slant-range area (sensor geometry)
- σ^0 (Sigma Nought) = backscatter normalized by ground-range area
- γ^0 (Gamma Nought) = backscatter normalized by area perpendicular to the radar beam; Removes terrain-induced brightness effects; Accounts for local incidence angle

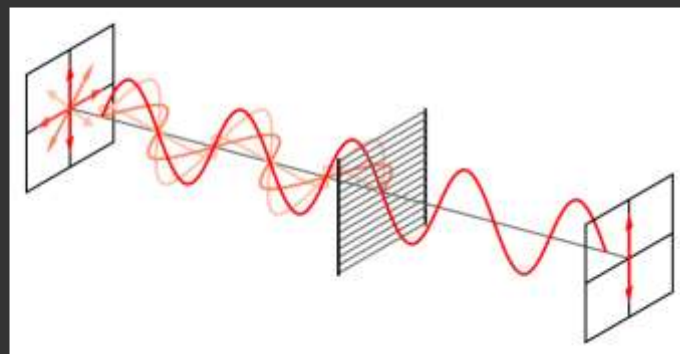
57

Backscatter values can be expressed using different units.

Beta nought values are normalized by slant-range area relative to the sensor geometry while sigma nought values are normalized by ground-range area. Gamma nought values are normalized by area perpendicular to the radar beam and removes terrain induced brightness effects and the impact of local incident angle.

Polarization

- Transmitted
  - Horizontal
  - Vertical
- Received
  - Horizontal
  - Vertical
- Combinations
  - HH
  - VV
  - HV
  - VH



https://commons.wikimedia.org/wiki/File:Wire-grid-polarizer.svg

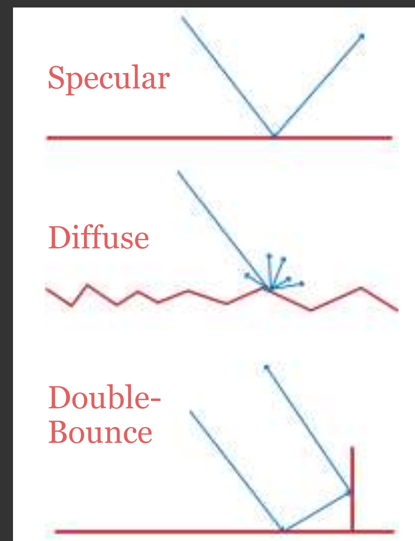
58

Another characteristic of SAR is the use of polarized signals. It is common for the transmitted radiation to be polarized so that it only consists of energy that is oscillating in a specific orientation, either horizontal or vertical. Also, the detector can be configured to only sense backscattered energy with a specific orientation, either horizontal or vertical.

This allows for four potential configurations: transmitted horizontally, received horizontally; transmitted vertically, received vertically; transmitted horizontally, received vertically; and transmitted vertically, received horizontally. What combinations are available varies by sensor and sometimes collection mode.

Backscatter

- Specular
  - Smooth surface
  - Reflect away from sensor
  - Low backscatter
- Diffuse
  - Rough surface
  - Reflect in multiple directions
  - Moderate backscatter
  - VV > HH > HV/VH
- Double-Bounce
  - Bounce back toward sensor
  - High back scatter
  - HH > VV > HV/VH
- Volume
  - Vertical structure
  - HV and VH



59

The impact of the ground surface on the recorded backscatter is very different from the spectral reflectance associated with visible, NIR, and SWIR radiation and emitted thermal radiation.

Specular reflectance will result in a low backscatter. This occurs as a result of the side-looking viewing geometry: when the transmitted radiation is reflected off a smooth surface in a specular manner, then the energy will reflect away from the sensor. This is common for water surfaces, which tend to show low backscatter due to specular reflectance.

Diffuse reflectance results when the transmitted energy is reflected in multiple directions by interacting with a rough surface. This results in a moderate backscatter and is common over agricultural fields. The strength of the diffuse reflection is also impacted by the polarization characteristics.

Double-bounce occurs as a result of vertical structure and is a common signature for forests and urban landscapes. As the diagram demonstrates, the transmitted energy can bounce off of vertical features after bouncing off the ground, resulting in a strong signal directed back toward the detector. Again, the polarization characteristics impact the recorded signal.

Lastly, volume scattering incorporates both double-bounce and diffuse scatter and is characteristic of forested landscapes. It is also impacted by polarization.

Since these signatures are impacted by viewing geometry, it is important that this be considered when comparing multiple SAR images to assess change. For example, it is best to use data from only the ascending or descending tracks in a multitemporal analysis.

Surface Roughness

- Surface roughness relative to wavelength and incident angle of SAR
- If height variations are large relative to the radar wavelength, the surface appears rough and tends to scatter more energy back to the sensor.
- Specular reflectance from smooth surfaces = reflect away from the sensor = low backscatter
- Rough surfaces scatter more energy back to sensor = higher backscatter

SAR Band	Wavelength	Roughness Sensitivity
X-band	3 cm	Small surface roughness
C-band	5-6 cm	crop canopies, soil texture, small roughens
L-band	23-24 cm	larger roughness and deeper vegetation structure
P-band	70 cm	Larger roughness and deeper canopy penetration

60

This slide further explains the impact of surface roughness on the resulting signal or backscatter. Surface roughness must be considered relative to the wavelength of the transmitted microwave radiation.

Dielectric Properties

- How strongly material interacts with EM radiation
- Higher dialectic constant = stronger backscatter
- Moisture sensitivity

Material	SAR Signal
Dry soil	Weak to moderate
Wet soil	Strong

61

SAR signals are also impacted by the dielectric properties of the surface material, which is highly correlated with water content. A higher dielectric constant will result in a stronger backscatter signal.

For example, wet soil generally shows a stronger backscatter than drier soil.

Thus, SAR can be useful for assessing soil moisture content.

Complexities

- Layover Effect = returns from top of feature scatter back to sensor before those at bottom of the feature
- Foreshortening Effect = slopes facing sensor are shortened relative to those facing away
- RADAR Shadow = slopes facing away from the sensor will return a weak signal or no signal at all
- RADAR Image Speckle = from constructive and destructive interference between transmitted and backscattered waves

62

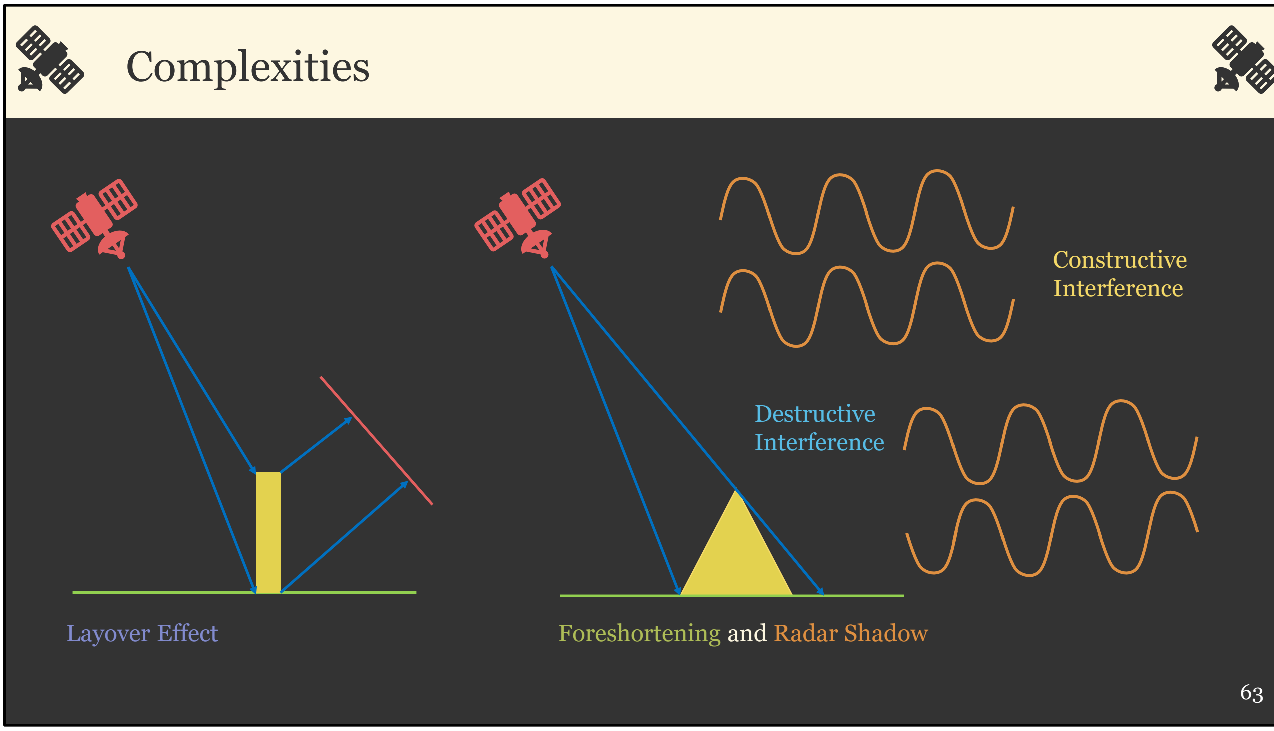
There are some notable complexities with processing, interpreting, and using SAR data.

First, based on viewing geometry and the fact that the backscatter depends on travel distance, it is possible for a signal from the top of a feature to reach the detector before the signal from the bottom of the feature. This results in a vertical relief displacement effect that is opposite of that from a multispectral image. Tall features will appear to lean toward nadir, as opposed to away from nadir.

Another issue is foreshortening, in which slopes facing toward the sensor will appear elongated in comparison to slopes facing away from the sensor, which will appear compressed. This is a less severe distortion than the layover effect.

Another issue is radar shadow, which results from a lack of returns from slopes and surfaces facing away from the sensor. This is again a result of the side-looking viewing geometry.

Lastly, image speckle is another common occurrence. This is a result of constructive and destructive interference resulting from the interaction of transmitted and backscattered waves, which can either strengthen, constructive interference, or weaken, destructive interreference, the backscattered signal. This will generate local noise and a salt-and-pepper effect. These types of interference patterns can occur for all types of oscillating waves. For example, destructive interference is used to reduce background noise by noise cancelling headphones.



This slide provides some visual representations of the complexities discussed in the prior slide.

Again, the layover effect is caused by the fact that a signal can return from the top of a feature before the bottom. Because of the reliance on range distance and side-looking viewing geometry, this will result in tall features bending toward nadir as opposed to away from it, as occurs for optical imaging sensors.

Foreshortening results in compression of slopes facing toward the sensor and and elongation of slopes facing away from it.

Layover is most likely to occur with steep incident angles whereas foreshadowing tends to occur when incidents angles are shallower.

Radar shadowing results from the side-looking viewing geometry, which causes a weaker or no backscatter signal.

Lastly, Radar speckle is associated with constructive and destructive interference between the transmitted radiation and returning backscatter. When waves line up (troughs line up with troughs and crests line up with crests), the signal is strengthened. When waves do not line up (troughs line up with crests and crests line up with troughs), the signal is weakened.

Pre-Processing

- Apply Orbit File = relationship between ground and image coordinates
- Radiometric Calibration = convert from DN to standard geophysical unit of backscatter
- De-Bursting = combine multiple swaths to a single image
- Multilooking = reduce image speckle and covert to ground range (produce image with standard pixel size)
- Speckle Filter = remove noise or speckle
- Terrain Correction = use DEM to remove geometric distortions
- Convert to dB = convert to dB logarithmic scale

https://cdn.earthdata.nasa.gov/conduit/upload/14115/pre-processing_onepager_ROUGH.pdf

64

In order to correct SAR data and georeference it the ground surface, data will undergo a processing chain. This slide provides an example of a processing chain for Sentinel-1 data specifically. This process allows for (1) image coordinates to be translated to ground coordinates, (2) DNs to be converted to physical backscatter measurements, (3) data from multiple swaths to be combined, (4) reduction of image speckle and conversion to ground range, in which each pixel has a standard size, (5) further reduction in noise and speckle, (6) removal of geometric distortions resulting from the terrain surface, and (7) log transformation to dB.

Signatures

Surface	Dielectric	Roughness	SAR Appearance
Calm Open Water	High	Smooth	Dark
Wind-Roughened Water	High	Rougher	Brighter
Dry Smooth Soil	Low to Moderate	Smooth	Dark to moderate
Wet Smooth Soil	High	Smooth	Moderate to bright
Wet Rough Soil	High	Rough	Bright
Vegetation	Increases with moisture content	Rough (complex 3D structure)/ volumetric scatter	Moderate to bright
Urban Areas	Depends on surface material	Double-bounce	Very bright

Impacted by SAR band used, polarization incident angle

65

The table on this slide describes common dielectric constants, roughnesses, and SAR backscatter signals from different surface materials. Common materials are further discussed on the following slides.

Signatures

Sentinel-1
Copenhagen, Denmark
VV Polarization, IW Mode
Red = Spring
Green = Late Spring
Blue = Summer

- Can vary by viewing geometry, polarization, and wavelength
- Soil
  - Increases moisture content increases backscatter
  - Increased moisture content decreases penetration
- Vegetation
  - Volume scattering/Diffuse scattering
  - Moisture content increases backscatter
  - Longer wavelength = more sensitivity to vertical structure (C < L < P)

66

The backscatter signal is impacted by viewing geometry, polarization, and the microwave wavelengths used. However, it is also correlated with surface materials and conditions.

First, soil moisture can impact the signal strength. Increasing moisture content tends to increase the backscatter and decrease the penetration of the energy into the ground.

Tall vegetation tends to result in volume and diffuse scattering, resulting in a moderate signal strength. Increased vegetation moisture content tends to increase the backscatter. The amount of canopy penetration, the amount of volume and diffuse scattering, and the resulting backscatter signal are impacted by the wavelengths used. For example, C-band data show less penetration than L-band data, which show less penetration than P-band.

The image on this slide is a composite image showing VV polarization in dB for an area containing Copenhagen, Denmark. Each band represents a different season. Note the generally low backscatter from water, due to primarily specular backscatter. Urban areas tend to show a strong backscatter across all seasons, which can be attributed to double-bounce backscatter. Vegetation tends to show more variability throughout the seasons. This is likely a result of changes in moisture content, vegetative conditions, and agricultural planting cycles.

Signatures

- Water
  - Specular reflectance
  - Little to no backscatter
- Ice
  - Impacted by age, surface roughness, internal geometry, temperature, and snow cover
- Urban
  - Double-bounce
  - High backscatter

Sentinel-1
Berlin, Germany
VV Polarization, IW Mode
Red = Spring
Green = Late Spring
Blue = Summer

67

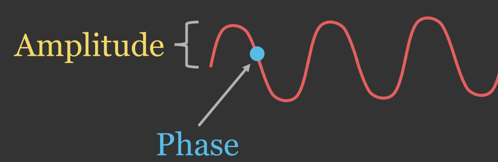
Again, water tends to show little to no backscatter as a result of specular reflectance. In the example image of the area around Berlin, Germany, the lakes and rivers are dark, suggesting low backscatter across all the seasons.

Ice can show variable signatures based on age, surface roughness, internal geometry, temperature, and snow cover. Generally, more backscatter is recorded in comparison to water.

Urban areas tend to have a lot of double-bounce scattering and, thus, show a strong return signal across multiple seasons. That is evident in the example image, as the city is very bright.

Creating DSMs with SAR

- **Single-Pass Interferometry** = two antennas collect data at the same time and from the same platform but using different positions
- **Repeat-Pass Interferometry** = compare data collected from to different time periods or satellite passes
- Makes use of phase differences
- Phase = wave's position in its cycle



SAR Value = $Ae^{i\phi}$
A = amplitude
ϕ = phase
i = imaginary unit ($\sqrt{-1}$)

$$\Delta\phi = \phi_1 - \phi_2$$

68

It is also possible to create digital elevation models using SAR data. This can be accomplished using two antennas connect to the same platform (single-pass interferometry) or via comparison of data collected at different times (repeat-pass interferometry).

The method makes use of the phase difference between the backscatter signal collected by the compared measurements. Phase relates to the position along a wave when the signal returns to the sensor. Change in phase between the two measurements can be used to estimate an elevation.

Creating DSMs with SAR

- Different vantage points create different path lengths
- This results in a phase difference
- Use sensor position, imaging geometry, wavelength, and baseline between the antennas to convert phase difference into elevation

This slide further elaborates on the process. Phase differences are combined with information about the sensor position, imaging geometry, wavelength of the microwave signal, and the baseline between the antennas to derive an elevation estimate.

Changes is Surfaces

- Surface deformation
- Erosion
- Deposition
- Landsliding
- Earthquake displacement
- Volcanic inflation or deflation
- Glacier motion
- Mining-related deformation
- Ground-water compaction

- Phase change is very sensitive to elevation change
- Measure displacement along the line-of-sight direction
- Must isolate the deformation component to estimate change

Phase component	Meaning
Topographic phase	Phase caused by elevation and viewing geometry
Deformation phase	Phase caused by ground movement between acquisitions
Atmospheric phase	Delay caused by water vapor, pressure, and ionosphere
Orbital phase	Error from imperfect satellite position knowledge
Noise/decorrelation	Phase instability from vegetation, water, snow, or surface change

Other than just elevation, it is also possible to estimate changes in elevation resulting from a variety of processes, as listed on the slide. The key is to isolate the deformation phase, which relates to ground change or movement between the two acquisitions.

SRTM

- Shuttle Radar Topography Mission
- February 2000
- 11-day mission
- Mapped 80% of world at 90 meter resolution
- 30 meter over US

https://www2.jpl.nasa.gov/srtm/

71

One example of a digital elevation model generated using SAR technologies is the Shuttle Radar Topography Mission (SRTM). These data were collected in February of 2000 using a SAR instrument mounted to a space shuttle. Over an 11-day mission, 80% of the globe was mapped at a spatial resolution of 90 meters. 30 m data were generated over the United States. These data are now made freely available.

TerraSAR-X and TanDEM-X

Characteristics	TerraSAR-X	TanDEM-X
Owner	German Aerospace Center/EADS Astrium	German Aerospace Center/EADS Astrium
Launch	June 2007	June 2010
Still Operational?	Yes	Yes
Wavelength	X	X
Polarization	Multiple Options	Multiple
Spatial Resolution	Up to 1 meter	Up to 1 meter
Modes	Stripmap, ScanSAR and Spotlight	Stripmap, ScanSAR and Spotlight
Revisit Time	~2.5 days	~2.5 days

https://earth.esa.int/web/eoportal/satellite-missions/t/terrasar-x

WorldDEM ~12 meter global DEM

https://www.intelligence-airbusds.com/en/8703-worlddem

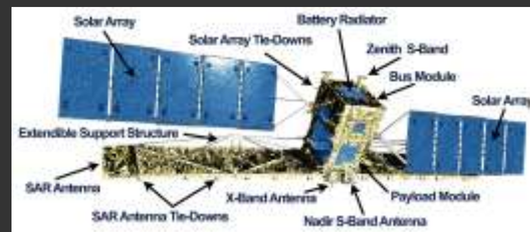
72

Another example mission is the commercial and German government joint program consisting of TerraSAR-X and TanDEM-S. These are identical sensors that collect X-band radar in a variety of modes and polarization combinations with a return interval of around 2.5 days.

From these data, a worldwide, 12 m spatial resolution DEM has been generated. Unfortunately, it is not freely or publicly available.

RADARSAT-2

Characteristics	RADARSAT-2
Owner	Canadian Space Agency/MacDonald Dettwiler Associates Ltd
Launch	December 2007
Still Operational?	Yes
Wavelength	C
Polarization	Multiple Options (HH, VV, VH, HV)
Spatial Resolution	Up to 1 meter
Modes	Many
Revisit Time	~24 days



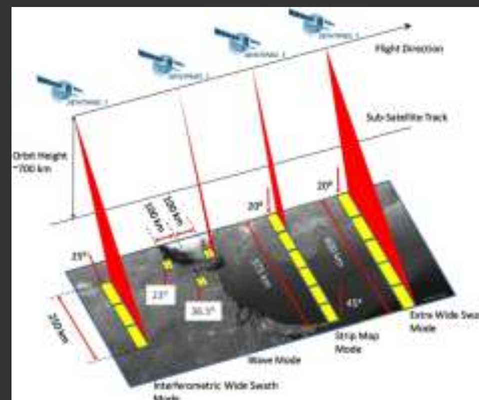
https://www.asc-csa.gc.ca/eng/satellites/radarsat1/components.asp

73

RADARSAT-2 is a mission administered by the Canadian Space Agency and MacDonald Dettwiler Associates Ltd. It is still operational and collects C-band data using variable collection modes and polarization characteristics. It offers a spatial resolution of up to 1 meter, depending on the collection mode.

Sentinel-1

Characteristics	RADARSAT-2
Owner	European Space Agency
Launch	1A: April 2014 1B: April 2016
Still Operational?	Yes
Wavelength	C
Polarization	Multiple Options
Spatial Resolution	5 by 20 meter (IW Mode)
Modes	Strip Map Mode, Interferometric Wide Swath, Extra-Wide Swath Mode, Wave-Mode
Revisit Time	12 days



https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes

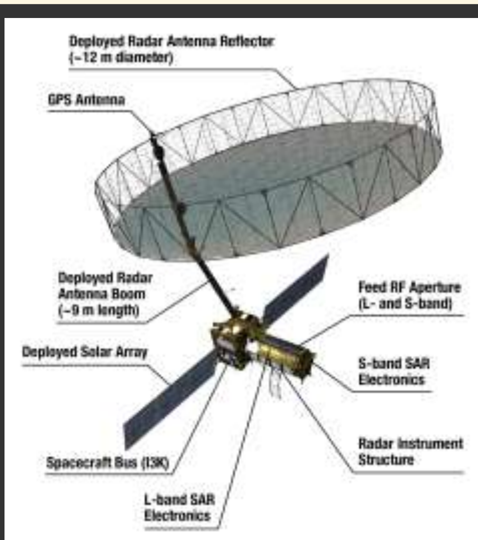
74

The European Space Agency (ESA) currently operates the Sentinel-1 mission, which collects C-band SAR data using two identical sensors on two different satellite platforms: Sentinel-1A and 1C (Sentinel-1B was decommissioned in December 2021 due to a power issue). Data can be collected using different collection modes and polarization combinations. The system offers a 12-day revisit time.

The spatial resolution varies based on collection mode. As an example, IW mode generates a cell size of 5-by-20 meters.

Data can be collected every 12 days. Currently, these data are made freely available.

NISAR



https://science.nasa.gov/mission/nisar/about-the-satellite/

- ❖NASA-ISRO Synthetic Aperture Radar
- ❖Launched in July 2025, operational January 2026
- ❖L band (24 cm)
- ❖S band (10 cm)
- ❖3 to 10 m spatial resolution
- ❖240+ km swath width

75

NISAR, or the NASA-ISRO Synthetic Aperture Radar, a joint program between the United States and India, was launched in July of 2025. It provides both L- and S-band data at variable spatial resolutions depending on collection mode.

This is the end of this lecture module.

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

76

Thanks! Hope you found this useful.