Remote Sensing

Satellite Remote Sensing

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

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In this module we will investigate topics relating to remote sensing from satellite platforms including orbits, types of sensors, and examples of available data at different spatial resolutions.

Module Topics

1. Types of orbits
2. Frame, across-track, and along-track sensors
3. Geometric distortions
4. Coarse spatial resolution sensors: GOES, POES, AVHRR, MODIS, and VIIRS
5. Moderate spatial resolution sensors: Landsat 1-9 and Sentinel-2 MSI
6. High spatial resolution sensors
7. Obtaining or connecting to data
8. Analysis ready data (ARD)

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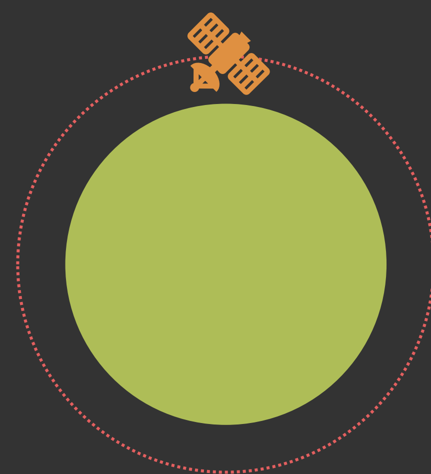
These are the topics covered in this module.

Orbits

Satellite Orbit

- A special type of projectile
- Projectile = object only being acted on by the force of gravity
- Falls around the Earth as opposed to into it



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A common misconception is that satellites have escaped the gravitational pull of the Earth and are floating freely in space. This is not the case. Instead, a satellite is just a special case of a projectile. A projectile is an object that has been put into motion by applying a force and is under the influence of gravity. For example, a baseball is put into motion by a pitcher and will eventually fall back to the Earth as a result of the force of gravity.

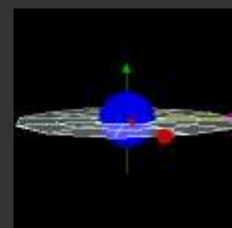
Once a force is applied to an object, there are three possible outcomes. First, the object could fall back to the Earth under the influence of gravity, such as a ball, bullet, or arrow. In the other extreme case, a force could be applied that allows the object to reach escape velocity, escape the gravitational pull of the Earth, and escape into space. The third option is a satellite. A satellite is a projectile that falls toward the Earth at the same rate as the Earth's curvature. So, it "falls around" the Earth as opposed to into the Earth. This is similar to driving behind a vehicle that is traveling at the same speed. You are moving toward the vehicle at the same speed that it is moving away from you.

This allows for a satellite to be placed in an orbit or continue to circle the globe as opposed to falling back to the Earth or escaping into space.

Types of Orbits

Geostationary Orbit

- Always directly above the same point on Earth's surface
- Always views the same area



https://commons.wikimedia.org/wiki/File:Geostationary227x221simple3D.gif

https://commons.wikimedia.org/wiki/Category:Geostationary_orbit#/media/File:Geostationaryjava3D.gif

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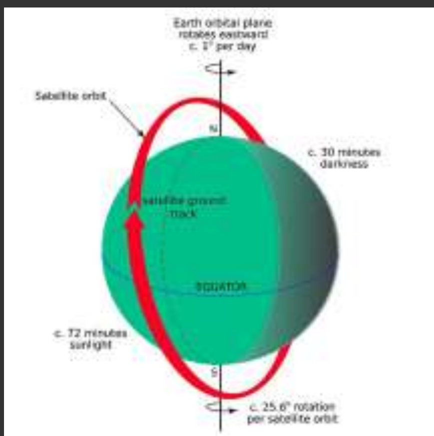
There are different types of orbits. A geostationary orbit is one in which the satellite views the same area at all times or is directly above the same location on the Earth's surface at all times. This allows for continuous monitoring as a stream of still images or a video feed, resulting in high temporal resolution. However, geostationary satellites often have a low spatial grain.

As a conceptualization, imagine placing a dot on the edge of your tire. This dot will always be in the same location relative to the center of the tire as the tire rotates.

Generally, geostationary orbits require the platform to be further from the Earth than near-polar orbits, which we will discuss next.

Types of Orbits



https://commons.wikimedia.org/wiki/File:Sunsynchronous_orbit_en.jpg

Near-Polar Orbit

- Orbital path close to the North and South poles that carries an object around Earth and does not cross the poles
- Does not view the same area of the Earth at all times

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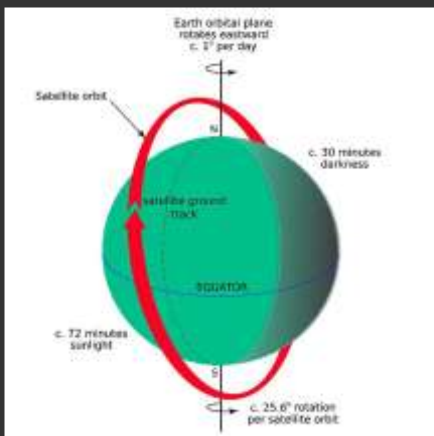
Near-polar orbits are more common than geostationary orbits for collecting Earth observation data. These orbits carry the satellites close to the North and South poles but do not cross the poles. Satellites that are in near-polar orbits do not view the same areas at all times. Instead, they build up images of the entire Earth as they orbit it. As the satellite orbits and the Earth rotates, imagery of the entire globe will be produced on a regular basis. For example, the Landsat sensors image the entire Earth roughly every 16 days.

Satellite platforms placed in near-polar orbits are generally closer to the Earth than those placed in geosynchronous orbit.

Sun-Synchronous Orbit



https://commons.wikimedia.org/wiki/File:Sunsynchronous_orbit_en.jpg

- Commonly near-polar
- Precession = orbit changes relative to the Earth over time
- Shift in orbit compensates for Earth’s orbit around the Sun
- Allows for similar illumination on same day from year to year

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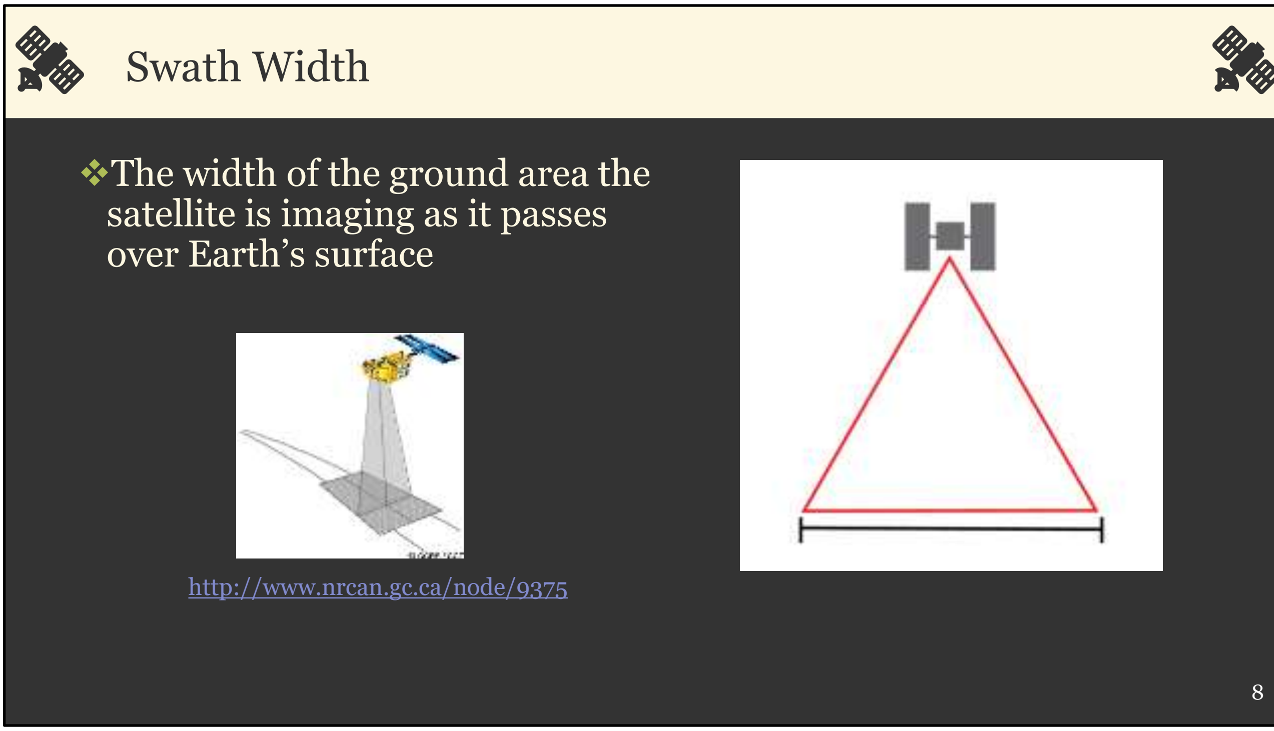
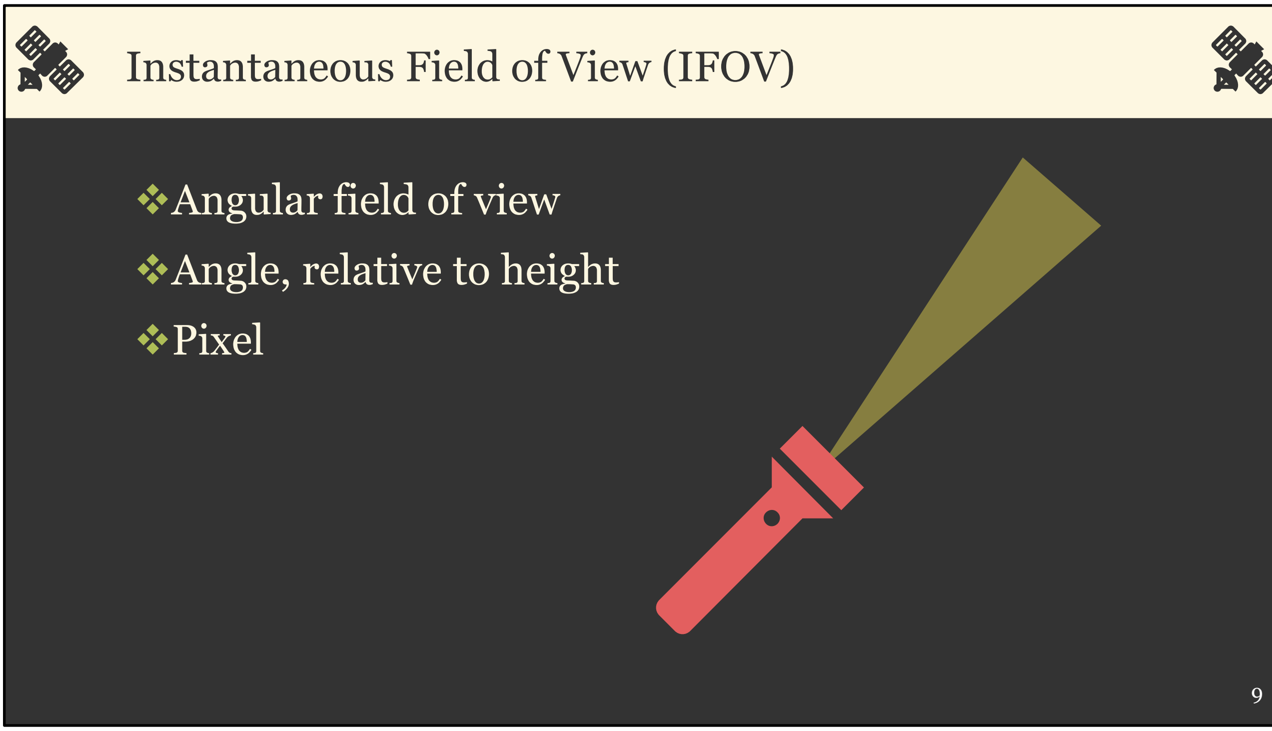
A Sun-synchronous orbit is a special type of near-polar orbit. The goal is to maintain consistent or near consistent illuminating conditions. This allows for more consistent comparisons, especially for anniversary date images.

In order for consistent illuminating conditions to be maintained, this requires that the satellite’s orbit be adjusted by roughly 1 degree per day in order to adjust to changes in the position of the Earth in its orbit around the Sun throughout the year.

Earth observation satellites are commonly placed in Sun-synchronous orbits to maintain consistent illuminating conditions and collect consistent data for change analysis.



For near-polar orbits, including Sun-synchronous orbits, the swath width is the width of the ground area the satellite is imaging as it passes over. Different sensors have different swath widths. As the satellite progresses through its orbit and the Earth rotates, the collected swaths will eventually cover the entire globe to image the entire Earth.



The instantaneous field of view (IFOV) is the area on the ground that is sensed at any given time and is generally equivalent to the size of the image pixel. This is specifically an angular field of view that varies based on viewing altitude or distance from the ground. Since satellites maintain a roughly constant altitude, if the surface topography is ignored, this means that the IFOV and image pixel size are nearly constant.

You can think of this as a spotlight or flashlight beam. The area illuminated by the beam on the surface would be the IFOV and would be referenced to a pixel in the image. Images are built up as the sensor is carried forward along its orbital path. For across-track scanners, the IFOV is also impacted by scanning back-and-forth.

Higher spatial grain imagery suggests a smaller IFOV and a longer time to build up images of the entire Earth, or reduced temporal grain.

Sensors

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Spatial Resolution

Resolution	IFOV (m)	Examples
Coarse	> 100	MODIS, AVHRR
Moderate	5 – 100	Landsat 8, Sentinel-2
Fine	< 5	IKONOS, QuickBird, WorldView-2, WorldView-3

- No agreement on exact breaks
- Often an inverse relationship between spatial resolution and temporal gain

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Sensors can be categorized based on their spatial resolution, as shown in this table. For example, moderate spatial resolution sensors have pixel sizes between 10 and 100 meters while coarse sensors have a resolution greater than 100 meters.

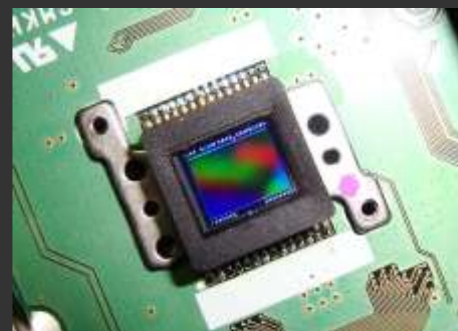
Note that these breaks are not universally defined. You will likely see different definitions for coarse vs. moderate vs. fine spatial resolution from different sources.

You may think that coarse and very coarse data are not very useful. However, this is not true. In fact, these types of datasets are very important for global scale monitoring and modeling. They are used extensively to understand weather, climate, and the energy budget of the planet.

No spatial resolution is better than another. Instead, it is important to use the appropriate resolution to address specific questions or needs.

Frame-Based

- Collect entire frame at once
- How personal cameras and phones generally work
- Not commonly used for sensors on satellite platforms



https://commons.wikimedia.org/wiki/File:CCD_sensor.JPG

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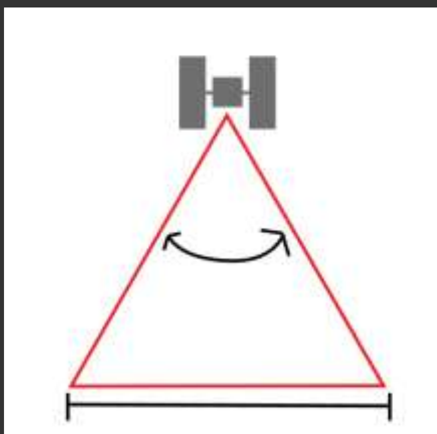
Most of the handheld cameras that we use on a regular basis are frame-based. This means that an entire image is created at once using a digital sensor that consists of a rectangular array of pixels. Each pixel in the rectangular array will correspond to an area on the ground or in the imaged extent.

Although frame-based sensors are commonly used for handheld cameras and small-format aerial cameras, these are not commonly used for sensors attached to satellite platforms.

Across-Track Scanning



- "Whiskbroom"
- Scans back-and-forth using a mirror
- Produces image pixel-by-pixel

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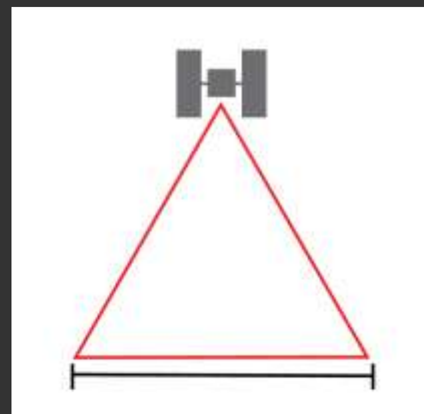
Across-track or "whiskbroom" sensors collect data pixel-by-pixel. The sensor acts like a flashlight beam that sweeps back-and-forth across the landscape as the satellite progresses forward along its orbital path. This represents the IFOV and corresponds to one pixel of collected data.

Using this scanning motion and the forward motion of the satellite, the collected pixels are built up into images along the swath.

Along-Track Scanning

- "Pushbroom"
- Does not scan back-and-forth
- Produces image row-by-row
- Like a document scanner



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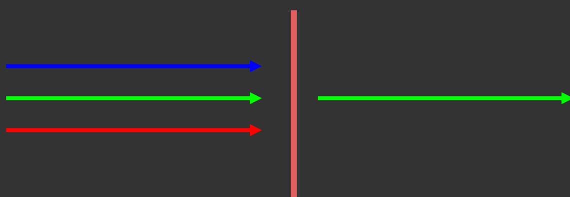
An along-track or "pushbroom" sensor also collects data using scanning. However, instead of collecting data pixel-by-pixel as the sensor sweeps back-and-forth, data are collected line-by-line using a linear array of pixels. This is similar to how a photocopier works. As the copy head progresses forward, the image is built line-by-line.

One advantage of an across-track scanner in comparison to an along-track scanner, is that there are fewer moving parts. As anyone who has ever owned a car can attest, fewer moving parts generally results in a lower likelihood that something will break.

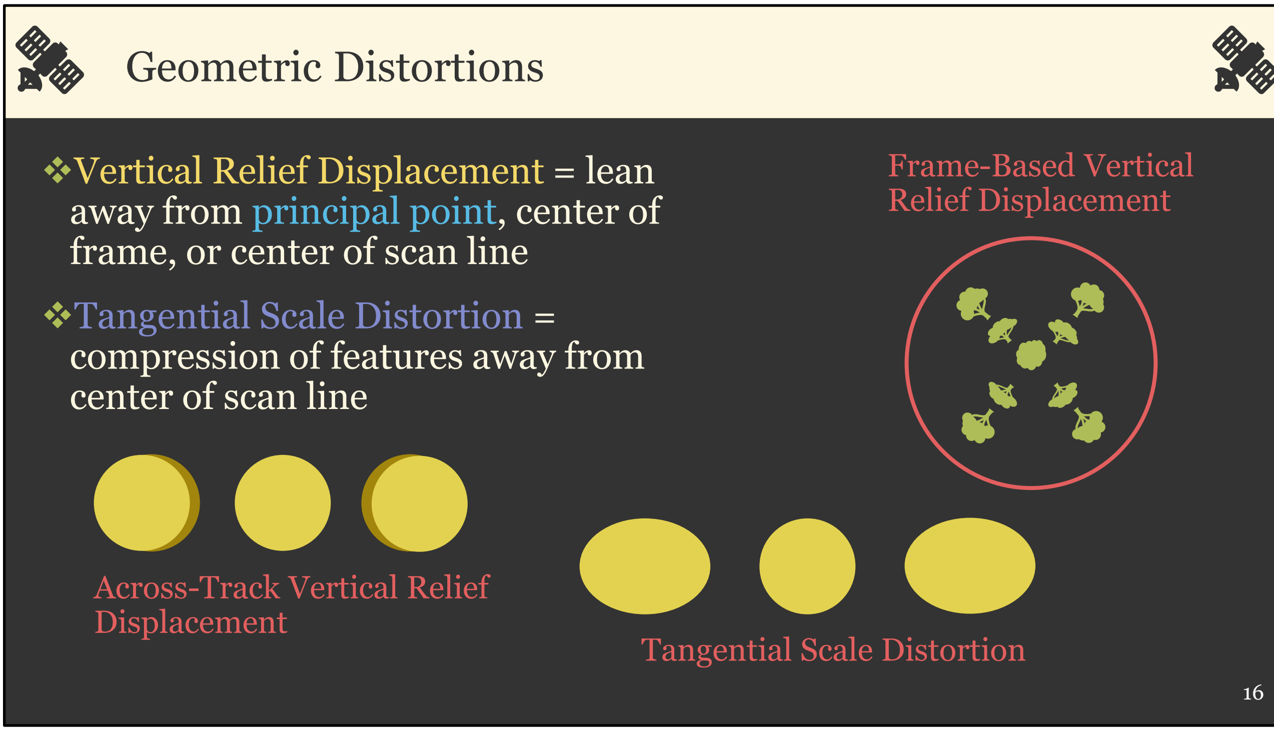
Collecting Multiple Bands

- Different sensor for each band
- Filters
- Diffraction Grating



https://commons.wikimedia.org/wiki/File:Diffraction_grating.jpg

In order to generate multiband images where different wavelength ranges are recorded separately, it is necessary to divide the incoming radiation based on wavelength. This is generally accomplished using diffraction gratings or filters. Filters can be used to block the transmission of certain wavelengths, as discussed in the aerial photography module. Diffraction gratings cause light to bend as it passes through. Since different wavelengths are bent more or less, this will separate out white light by wavelength so that different wavelength ranges can be sensed separately.



Similar to frame-based cameras, both across-track and along-track scanners are impacted by geometric distortions since data are collected using a perspective view as opposed to an orthographic view. However, since the data are collected differently, the distortion patterns are also different.

All sensor types have some form of vertical relief displacement. Remember that for a frame-based sensor, tall objects will lean away from the center of the image or principal point. Also, vertical relief displacement increases with distance from the principal point. This is demonstrated in the top image on the slide. In contrast, scanning devices will show vertical relief displacement relative to the center of each scan line. Objects located on the scan line center will have no vertical relief displacement while objects nearer the edge of the scan line swath will show more vertical relief displacement. In other words, this distortion is relative to the distance from the center of the scan line for each individual scan line since data are collected line-by-line as opposed to frame-by-frame.

Across-track scanners have an additional type of distortion known as tangential scale distortion. As a result of the scanning and the angle at which the beam intersects the surface of the Earth, the IFOV will be larger near the margins of the swath as opposed to near the center. This larger sensed area will then be compressed into a pixel of the same size, resulting in compression of landscape features near swatch edges in comparison to features near the swath center.

Geometric Distortions by Sensor Type

Distortion Type	Frame-Based	Across-Track	Along-Track
Vertical Relief Displacement	X	X	X
Tangential Scale Distortion		X	

- Frame-Based
  - Vertical relief displacement increases radially away from the principal point
- Along-Track
  - Vertical relief displacement increases away from center or scan line
- Across-Track
  - Vertical relief displacement increases away from the center or scan line
  - Tangential scale distortion increases near edge of swath

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The provided table summarizes the geometric distortions for each sensor type. All sensor types have some form of vertical relief displacement. For frame-based sensors, distortion increases in all directions away from the center of the image. In contrast, for scanning-based sensors relief displacement increases with distance from the scan line center. Across-track scanners also have tangential scale distortions due to compression of features near to the swatch edge resulting from a larger IFOV.

Fortunately, it is possible to correct for these distortions using information about the terrain surface, viewing geometry, and scan angle. These corrections are generally performed by the vendor prior to making the data available for use and further analysis.

Coarse Spatial Resolution

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TIROS

- Television Infrared Observation Satellite
- Launched April 1, 1960
- Is satellite remote sensing effective/possible?

https://science.nasa.gov/missions/tiros

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We will now provide some examples of sensors attached to satellite platforms. We will start with coarse spatial resolution sensors, followed by medium and fine resolution.

These are just examples and not exhaustive, as many satellite-based Earth observation missions have been undertaken. We have tried to focus on some of the most commonly used data.

The age of Earth observation from satellite platforms began in 1960 with the launch of the Television Infrared Observation Satellite (TIROS). A key objective of this mission was to determine if useful Earth observation data could actually be collected from satellite platforms. At this point in time, it was not clear if there was any value in satellite-based Earth observation. However, the TIROS mission showed that useful data could be collected despite issues of cloud cover/contamination and atmospheric interference. By the early 1970s, operational missions focused on Earth observation were undertaken based upon these early, more experimental missions.

GOES

- Geostationary Operational Environmental Satellite
- Geostationary
- Monitor weather conditions
- Each satellite views the same location at all times

http://www.goes.noaa.gov/

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The GOES, or Geostationary Operational Environmental Satellites, are operated by NOAA and use a geostationary orbit. Because they are geostationary, each sensor images the same area at all times. Data from multiple GOES satellites are combined to monitor the entire globe nearly continuously.

The main use of these satellites is weather observation and forecasting. We will not focus on weather observation applications in this course.

POES

- Polar Orbiting Environmental Satellite
- Carries the AVHRR sensor (Advanced Very High Resolution Radiometer)
- 1978-Present

AVHRR/3 Channel Characteristics

Channel Number	Resolution at Nadir	Wavelength (um)	Typical Use
1	1.09 km	0.58 - 0.68	Daytime cloud and surface mapping
2	1.09 km	0.725 - 1.00	Land-water boundaries
3A	1.09 km	1.58 - 1.64	Snow and ice detection
3B	1.09 km	3.55 - 3.93	Night cloud mapping, sea surface temperature
4	1.09 km	10.30 - 11.30	Night cloud mapping, sea surface temperature
5	1.09 km	11.50 - 12.50	Sea surface temperature

https://www.nesdis.noaa.gov/our-satellites/polar-operational-environmental-satellites-poes

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NOAA also operates the Polar Orbiting Environmental Satellites (POES). These satellites carry the AVHRR, or Advanced Very High Resolution Radiometer. A series of these sensors have been operational since 1978 and are still operating today. This has allowed for mapping and monitoring change over multiple decades. Sometimes these data are combined with MODIS data due to similar spatial resolutions.

AVHRR Bands

Band #	NOAA-6,8,10	NOAA-7,9,11,12,14	NOAA-15,16,17,18
Sensor	AVHRR/1	AVHRR/2	AVHRR/3
1 (Red)	0.58 - 0.68 µm	0.58 - 0.68 µm	0.58 - 0.68 µm
2 (NIR)	0.725 - 1.10 µm	0.725 - 1.10 µm	0.725 - 1.10 µm
3(A) (SWIR)			1.58 – 1.64 µm
3(B) (mid-IR)	3.55 - 3.93 µm	3.55 - 3.93 µm	3.55 - 3.93 µm
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

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The AVHRR sensor has 4 to 6 bands. Most important for terrestrial studies are red and NIR (for NDVI) and thermal for temperatures. Again, these data are still commonly used to assess vegetation health and landscape change due to the consistent and lengthy historic record.

MODIS

- Moderate Resolution Imaging Spectrometer
- Onboard Terra and Aqua satellites
- Over 40 data products produced
- Measures 36 spectral bands (visible, infrared, and thermal)
- The spatial resolution of MODIS (pixel size at nadir) is 250m for channels 1 and 2 (0.6µm - 0.9µm), 500m for channels 3 to 7 (0.4µm - 2.1µm) and 1,000m for channels 8 to 36 (0.4µm - 14.4µm)

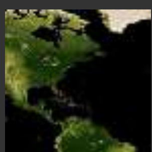
Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required NE[Δ]T(K)[4]
Surface/Cloud Temperature	20	3.660 - 3.840	0.45(300K)	0.05
	21	3.929 - 3.989	2.38(335K)	2.00
	22	3.929 - 3.989	0.67(300K)	0.07
	23	4.020 - 4.080	0.79(300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	0.25
	25	4.482 - 4.549	0.59(275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16(240K)	0.25
	28	7.175 - 7.475	2.18(250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58(300K)	0.05
Ozone	30	9.580 - 9.880	3.69(250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05
	32	11.770 - 12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25
	34	13.485 - 13.785	3.76(250K)	0.25
	35	13.785 - 14.085	3.11(240K)	0.25
	36	14.085 - 14.385	2.08(220K)	0.35

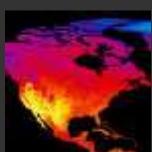
https://modis.gsfc.nasa.gov/about/specifications.php

MODIS stands for Moderate Resolution Imaging Spectrometer. This sensor is installed onboard the Terra and Aqua satellites operated by NASA.

It offers 36 spectral bands at variable spatial resolutions ranging from 250-by-250 meters to 1-by-1 kilometer pixels, as listed on the slide. Over 40 data products are generated from raw MODIS data.

MODIS





https://modis.gsfc.nasa.gov/data/

- Applications = vegetation health, water temperature, snow cover, sea surface temperature, sea ice cover, ocean color, volcanoes, heat emitted by wildfire
- Measure and map broad scale phenomenon at a coarse spatial resolution
- Views most of the globe in a single day
- Full global coverage within two days

https://modis.gsfc.nasa.gov/gallery/individual.php?db_date=2018-05-16

Example data products include measures of vegetation health (for example, NDVI), water temperature, snow cover, sea surface temperature, sea ice cover, ocean color, volcanic activity, and heat emitted by wildfires.

These data products measure and map broad scale phenomenon at a coarse spatial resolution.

Although the data are spatially coarse, the temporal resolution is high, as the entire globe is imaged within two days.

Even though the entire globe is imaged every two days, it takes longer to image the ground surface due to cloud cover. However, with cloud masking and image compositing techniques, it is possible to generate cloud-free data using images collected on multiple dates.

Video: MODIS

Video from USGS

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VIIRS

- Visible Infrared Imaging Radiometer Suite
- 750 m pixels
- Provides night light data

https://www.jpss.noaa.gov/viirs.html

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Another example of a coarse resolution data source is the Visible Infrared Imaging Radiometer Suite, or VIIRS, onboard multiple NOAA satellites. One use of VIIRS data in Earth observation is the collection of night-light imagery.

Moderate Spatial Resolution

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Landsat Mission

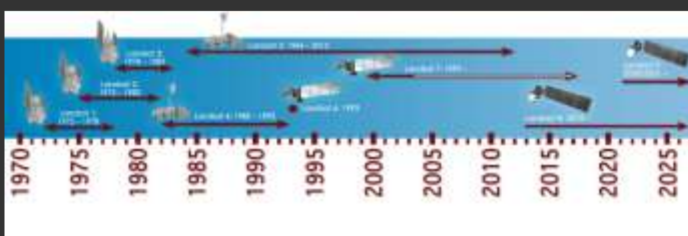
MSS (Multispectral Scanner): Landsat 1, 2, 3, 4, and 5

Thematic Mapper (TM): Landsat 4 and 5

Enhanced Thematic Mapper Plus (ETM+): Landsat 7

Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS): Landsat 8

Operational Land Imager (OLI-2)/Thermal Infrared Sensor (TIRS-2): Landsat 9



https://landsat.gsfc.nasa.gov/a-landsat-timeline/

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We will now discuss moderate spatial resolution sensors beginning with the Landsat series. The Landsat program has been operational since 1972 with the launch of Landsat 1 that carried the Multispectral Scanner, or MSS, sensor. At the time of this writing, Landsat 8 and Landsat 9 are still operational and providing data.

The next set of slides provide comparisons of the spatial and spectral resolutions of the different sensors used in the Landsat program.

Sensor Comparisons

Landsat 1-5 Multispectral Scanner (MSS)	Landsat 1-3	Landsat 4-5	Wavelength (micrometers)	Resolution (meters)
	Band 4 - Green	Band 1 - Green	0.5-0.6	60*
	Band 5 - Red	Band 2 - Red	0.6-0.7	60*
	Band 6 - Near Infrared (NIR)	Band 3 - Near Infrared (NIR)	0.7-0.8	60*
	Band 7 - Near Infrared (NIR)	Band 4 - Near Infrared (NIR)	0.8-1.1	60*

* Original MSS pixel size was 79 x 57 meters; production systems now resample the data to 60 meters.

Landsat 4-5 Thematic Mapper (TM)	Bands	Wavelength (micrometers)	Resolution (meters)
	Band 1 - Blue	0.45-0.52	30
	Band 2 - Green	0.52-0.60	30
	Band 3 - Red	0.63-0.69	30
	Band 4 - Near Infrared (NIR)	0.76-0.90	30
	Band 5 - Shortwave Infrared (SWIR) 1	1.55-1.75	30
	Band 6 - Thermal	10.40-12.50	120* (30)
	Band 7 - Shortwave Infrared (SWIR) 2	2.08-2.35	30

* TM Band 6 was acquired at 120-meter resolution, but products are resampled to 30-meter pixels.

https://www.usgs.gov/faqs/what-are-band-designations-landsat-satellites?qt-news_science_products=0#qt-news_science_products

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The MSS sensor onboard Landsat 1 through 5 provides 4 bands at a 60-by-60 meter spatial resolution. Specifically, it provides green, red, and two near infrared bands.

Landsat 4 and 5 added the Thematic Mapper, or TM, sensor that offers 7 bands: blue, green, red, near infrared, shortwave 1, shortwave 2, and thermal. All bands are collected at a 30-by-30 meter resolution except for the thermal band, which is collected at 120-by-120 meters then resampled to 30-by-30 meters.

You may be wondering why the second SWIR band is listed after the thermal band. This is because this band was added late in the production of the sensor and they did not want to reorder the bands.

The Thematic Mapper is an across-track scanner.

Sensor Comparisons

Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	Bands	Wavelength (micrometers)	Resolution (meters)
	Band 1 - Blue	0.45-0.52	30
	Band 2 - Green	0.52-0.60	30
	Band 3 - Red	0.63-0.69	30
	Band 4 - Near Infrared (NIR)	0.77-0.90	30
	Band 5 - Shortwave Infrared (SWIR) 1	1.55-1.75	30
	Band 6 - Thermal	10.40-12.50	60 * (30)
	Band 7 - Shortwave Infrared (SWIR) 2	2.09-2.35	30
	Band 8 - Panchromatic	.52-.90	15

* ETM+ Band 6 is acquired at 60-meter resolution, but products are resampled to 30-meter pixels.

https://www.usgs.gov/faqs/what-are-band-designations-landsat-satellites?qt-news_science_products=0#qt-news_science_products

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The Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor added a 15-by-15 meter panchromatic band. No panchromatic data were made available by the MSS or TM sensors. This allows for pansharpening of the multispectral data.

The spatial resolution of the thermal data increased from 120-by-120 to 60-by-60 meters.

On May 31, 2003 the scan line corrector (SLC) component of ETM+ failed. With this failure, approximately 22% of the data are missing in each Landsat 7 scene.

If you are wondering why there is no Landsat 6, that is because it was launched but failed to reach orbit. It was supposed to carry the Enhanced Thematic Mapper, or ETM, sensor. This explains the plus in ETM+.

Similar to the Thematic Mapper, the Enhanced Thematic Mapper Plus sensor is an across-track scanner.

Sensor Comparisons

Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)	Bands	Wavelength (micrometers)	Resolution (meters)
	Band 1 - Ultra Blue (coastal/aerosol)	0.435 - 0.451	30
	Band 2 - Blue	0.452 - 0.512	30
	Band 3 - Green	0.533 - 0.590	30
	Band 4 - Red	0.636 - 0.673	30
	Band 5 - Near Infrared (NIR)	0.851 - 0.879	30
	Band 6 - Shortwave Infrared (SWIR) 1	1.566 - 1.651	30
	Band 7 - Shortwave Infrared (SWIR) 2	2.107 - 2.294	30
	Band 8 - Panchromatic	0.503 - 0.676	15
	Band 9 - Cirrus	1.363 - 1.384	30
	Band 10 - Thermal Infrared (TIRS) 1	10.60 - 11.19	100 * (30)
	Band 11 - Thermal Infrared (TIRS) 2	11.50 - 12.51	100 * (30)

* TIRS bands are acquired at 100 meter resolution, but are resampled to 30 meter in delivered data product.

https://www.usgs.gov/faqs/what-are-band-designations-landsat-satellites?qt-news_science_products=0#qt-news_science_products

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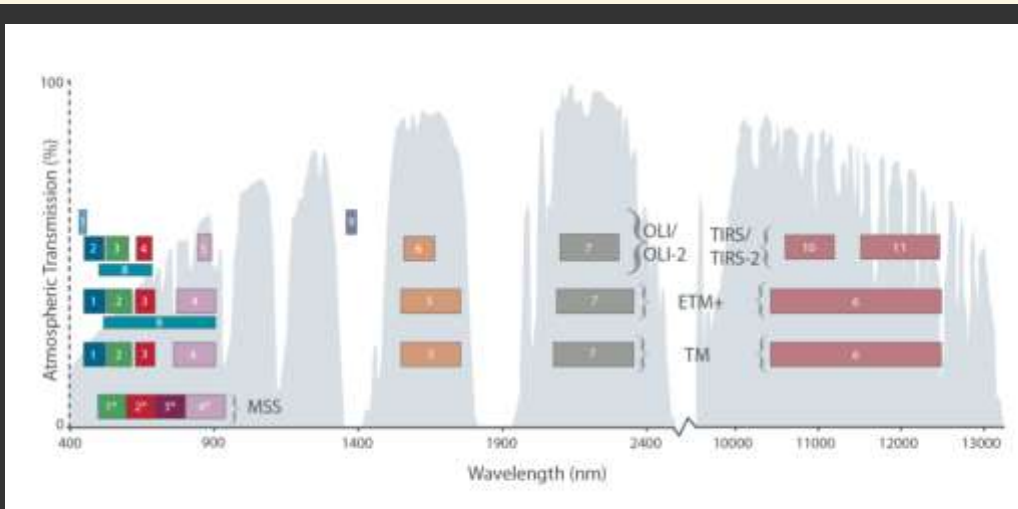
The most recent Landsat satellites are Landsat 8 and 9. Landsat 8 carries the Operational Land Imager (OLI) sensor and the Thermal Infrared Sensor (TIRS). Landsat 9 carries the Operational Land Imager-2 (OLI-2) sensor and the Thermal Infrared Sensor-2 (TIRS-2). The OLI and OLI-2 are functionally equivalent while TIRS and TIRS-2 are functionally equivalent.

In comparison to Landsat 7 ETM+, the Landsat 8/9 OLI/OLI-2 sensor adds an ultra blue band for coastal mapping and aerosol mapping and a cirrus cloud band for detecting high clouds and cloud contamination. They also provides 2 thermal bands as opposed to one.

The OLI/OLI-2, in contrast to TM and ETM+, is an along-track scanner.

Sensor Comparisons

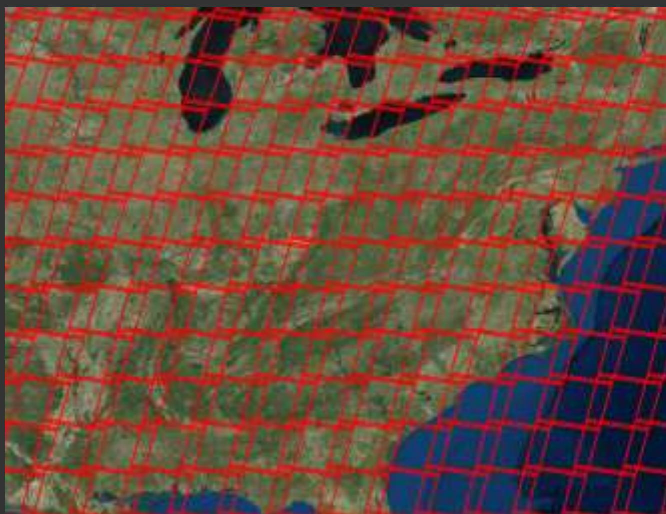


https://landsat.gsfc.nasa.gov/landsat-9/landsat-9-spectral-bands/

32

This NASA image provides a comparison of all the Landsat sensors. Note that not all bands of the same designation cover the same spectral ranges. For example, the NIR bands are a bit different between sensors. Also, most bands are positioned within atmospheric windows to take advantage of the Sun's illumination.

Landsat Path/Rows



- Landsat data divided into path/rows

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Landsat data are generally provided as path/row combinations that break the entire globe into regions.

Landsat Examples

Landsat 7 ETM+ 9/14/2000

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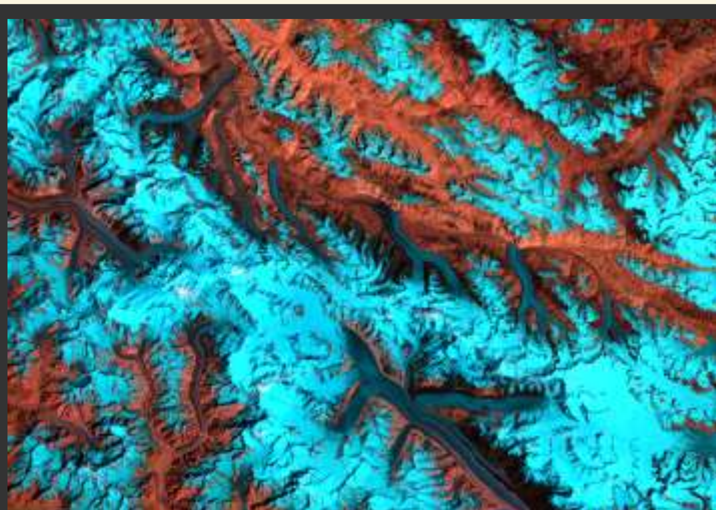
This is an example of a Landsat ETM+ image showing a burned area in the Black Hills of South Dakota. Landsat data have proven valuable for mapping burns and burn severity. Burn areas tend to have lower near infrared reflectance and higher shortwave infrared reflectance in comparison to healthy vegetation.

Landsat Examples



Landsat 5 TM 8/23/2010

35

This is an example Landsat 5 TM image of a mountainous area in the Himalayas. Using this band combination, it is easy to differentiate ice and snow from other surface materials.

Sentinel-2

- Similar to Landsat
- Operated by the European Space Agency (ESA)
- Pair of satellites
- 10-day revisit time
- MSI (Multispectral Instrument)
- 13 bands

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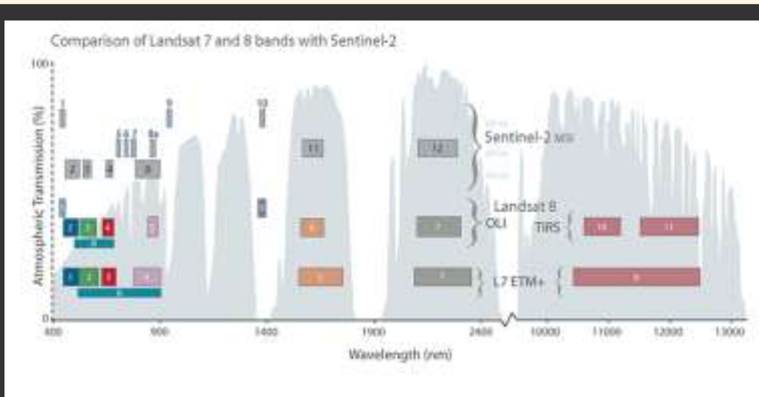
Sentinel-2 is generally described as the European equivalent of Landsat. It is operated by the European Space Agency, or ESA.

At the time of this writing, two Sentinel-2 satellites are in orbit, Sentinel-2A and Sentinel-2B, which both carry the Multispectral Instrument, or MSI. The MSI is an along-track scanner. Sentinel-2 provides 13 spectral bands and a 10-day revisit time.

Sentinel-2



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

Sentinel-2 Bands	Central Wavelength (µm)	Resolution (m)
Band 1 - Coastal aerosol	0.443	60
Band 2 - Blue	0.490	10
Band 3 - Green	0.560	10
Band 4 - Red	0.665	10
Band 5 - Vegetation Red Edge	0.705	20
Band 6 - Vegetation Red Edge	0.740	20
Band 7 - Vegetation Red Edge	0.783	20
Band 8 – NIR	0.842	10
Band 8A - Vegetation Red Edge	0.865	20
Band 9 - Water vapour	0.945	60
Band 10 - SWIR - Cirrus	1.375	60
Band 11 - SWIR	1.610	20
Band 12 - SWIR	2.190	20

https://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/sentinel-2a/

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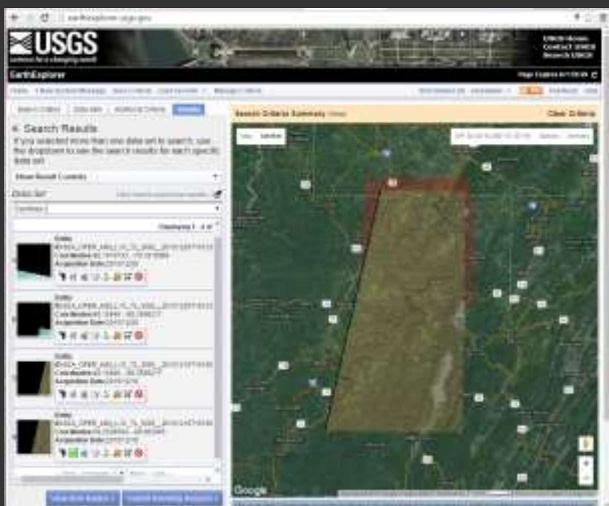
This NASA image provides a comparison between the Sentinel-2 MSI data and those provided by the ETM+ and OLI/TIRS sensors.

Sentinel-2 MSI provides bands in the visible, red edge, near infrared, and shortwave infrared ranges at resolutions varying between 10-by-10 meters to 60-by-60 meters.

If you are wondering if there is such a thing as Sentinel-1, there is. Sentinel-1 data offer C-band synthetic-aperture radar (SAR), which we will discuss toward the end of the course.

Sentinel-2



https://Earthexplorer.usgs.gov/

- Can be obtained free of charge from US government

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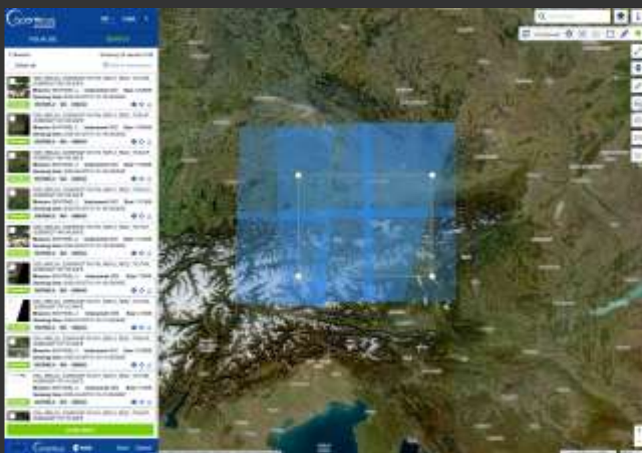
Based on an agreement with the United States government, at the time of this writing, Sentinel-2 MSI data are made freely available and can be accessed through the EarthExplorer USGS webpage.

Sentinel-2



- ESA Copernicus Browser
- https://browser.dataspace.copernicus.eu/

39

The European Space Agency (ESA) also has data portals available to download satellite data, such as imagery from the Sentinel-2 and Sentinel-3 sensors.

Comparisons

Sensor	Type
MSS	Across-Track
TM	Across-Track
ETM+	Across-Track
OLI	Along-Track
MSI	Along-Track

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This table provides a comparison of the sensor types for the Landsat and Sentinel-2 sensors.

Harmonized Landsat 8 and Sentinel-2


Remote Sensing of Environment

The Harmonized Landsat and Sentinel-2 surface reflectance data set

Claverie, M., Ju, J., Masek, J.G., Dungan, J.L., Vermote, E.F., Roger, J.C., Skakun, S.V. and Justice, C., 2018. The Harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote sensing of environment*, *219*, pp.145-161.

Bolton, D.K., Gray, J.M., Melaas, E.K., Moon, M., Eklundh, L. and Friedl, M.A., 2020. Continental-scale land surface phenology from harmonized Landsat 8 and Sentinel-2 imagery. *Remote Sensing of Environment*, *240*, p.111685.

41

Since the Landsat and Sentinel-2 missions offer data of similar spectral and spatial resolution, there is often interest in using these data collectively for analysis of change or to explore seasonal phenology. However, this is hindered by the differing characteristics of the data. As a result, researchers have worked to augment these datasets to provide consistency. These products are known as harmonized datasets and greatly simplify the combined use of Landsat and Sentinel-2 data. These harmonized datasets and derived products can be obtained from the US government and ESA free of charge.

High Spatial Resolution

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IKONOS

- Launched in 1999
- Off-nadir viewing capabilities
- 1-3 day revisit time
- 11-bit radiometric resolution
- Four-band (R,G,B, and Near Infrared)
- 3.2 meter spatial resolution
- 0.8 meter panchromatic band

Ayers Rocks, Australia

https://www.satimagingcorp.com/gallery/ikonos/

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Most high spatial resolution satellites are operated by commercial companies. Commercial satellite-based imaging began with IKONOS.

IKONOS was launched in 1999, offers a 1-to-3 day revisit time, four spectral bands, and 3.2-by-3.2 meter spatial resolution. It also offers a 0.8-by-0.8 m panchromatic band.

QuickBird

Giza Pyramids, Egypt

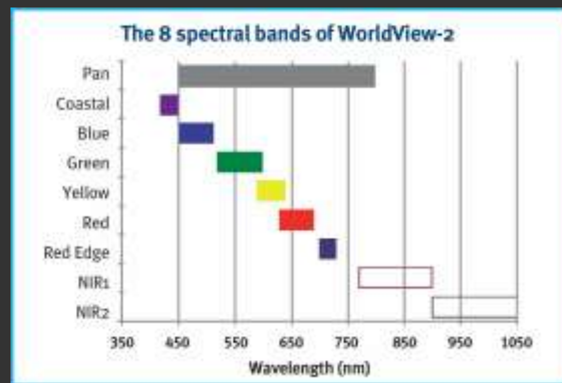
https://www.satimagingcorp.com/gallery/quickbird/

- Launched in 2001
- Off-nadir capabilities
- 1-3 day revisit time
- 11-bit radiometric resolution
- Four-band (R,G,B, and Near Infrared)
- 2.4 meter spatial resolution
- 0.61 meter panchromatic band

QuickBird offers similar specs to that of IKONOS.

WorldView-2

- Launched in 2009
- 8-band 1.85 meter multispectral sensor
- 0.46 meter panchromatic



https://content.satimagingcorp.com/static/galleryimages/worldview-2-satellite-spectral-bands.jpg

45

WorldView-2, which was launched in 2009, offers 8 bands at a 1.85-by-1.85 meter spatial resolution in the visible and near infrared ranges.

It also offers a 0.46 meter panchromatic band.

WorldView-3

https://www.satimagingcorp.com/gallery/worldview-3/

- Launched in 2014
- 8 Shortwave bands
- 8-band 1.24 meter multispectral sensor
- 0.31 meter panchromatic

Madrid, Spain

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WorldView-3 is in many ways a game changer, as it offers both high spatial and spectral resolution.

WorldView-3

Band Name	QuickBird	WorldView-1	WorldView-2	WorldView-3
Panchromatic	450-900nm	400-900nm	450-800nm	450-800nm
Coastal Blue			400-450nm	400-450nm
Blue	450-520nm		450-510nm	450-510nm
Green	520-600nm		510-580nm	510-580nm
Yellow			585-625nm	585-625nm
Red	630-690nm		630-690nm	630-690nm
Red Edge			705-745nm	705-745nm
NIR-1	760-900nm		770-895nm	770-895nm
NIR-2			860-1040nm	860-1040nm
SWIR-1				1195-1225nm
SWIR-2				1550-1590nm
SWIR-3				1640-1680nm
SWIR-4				1710-1750nm
SWIR-5				2145-2185nm
SWIR-6				2185-2225nm
SWIR-7				2235-2285nm
SWIR-8				2295-2365nm

Frequency range observed by band

http://www.harrisgeospatial.com/Learn/Blogs/Blog-Details/TabId/2716/ArtMID/10198/ArticleID/16050/What-can-we-look-forward-to-from-WorldView-3.aspx

47

WorldView-3 offers the same 8 visible and near infrared bands offered by WorldView-2. Additionally, it offers 8 shortwave infrared bands.

RapidEye

Hobet-21 Mine, West Virginia

- Owned by Planet Labs
- 5 meter spatial resolution
- 5 spectral bands (R, G, B, Red Edge, NIR)
- Five satellites
- Returns daily

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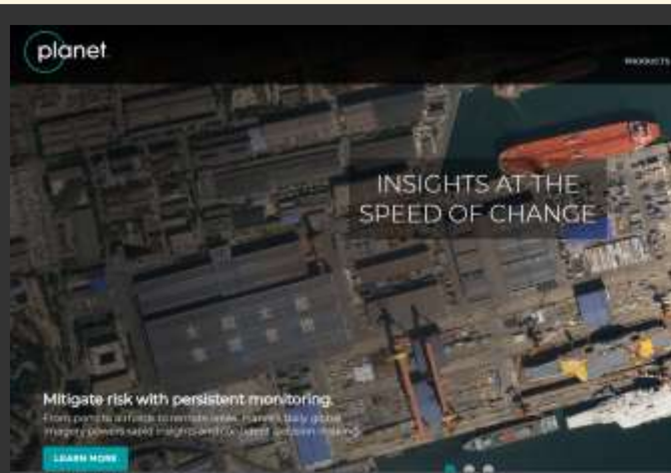
RapidEye is currently operated by Planet Labs. It is a constellation of five identical satellites that offers 5 bands at a 5-by-5 meter spatial resolution. It also offers a daily return interval.

Microsatellite Constellations

- Planet Labs
- RapidEye
  - 6.5 million km² per day
- PlanetScope
  - 150+ Doves
  - 4 bands (R, G, B, NIR)
  - 3 m spatial resolution
  - 200 million km² per day
- SkySat
  - 21
  - 400 thousand km² per day
  - 5 bands (R, G, B, NIR, Panchromatic)
  - 0.8 m spatial resolution



https://www.planet.com/

High spatial resolution and high temporal resolution are being provided by launching constellations of microsatellites. For example, Planet Labs operates PlanetScope, which, at the time of this writing, consists of over 150 doves or microsatellites. These satellites collect 4-band color infrared data at a 3-by-3 meter spatial resolution. Over 200 million square kilometers are collected per day.

They also operate SkySat, which, at the time of this writing, consists of 21 satellites that collect color infrared data and a panchromatic band. Over four-hundred thousand square kilometers are collected each day.

They also own and operate the RapidEye constellation that was already discussed.

Such projects are revolutionizing remote sensing.

Obtaining Data

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Finding Image Data: USGS EarthExplorer

http://Earthexplorer.usgs.gov/

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The USGS EarthExplorer page provides free access to a variety of datasets including Landsat, Sentinel-2, AVHRR, MODIS, and aerial imagery.

Finding Image Data: USGS Global Visualization Viewer (GloVis)

http://glovis.usgs.gov/

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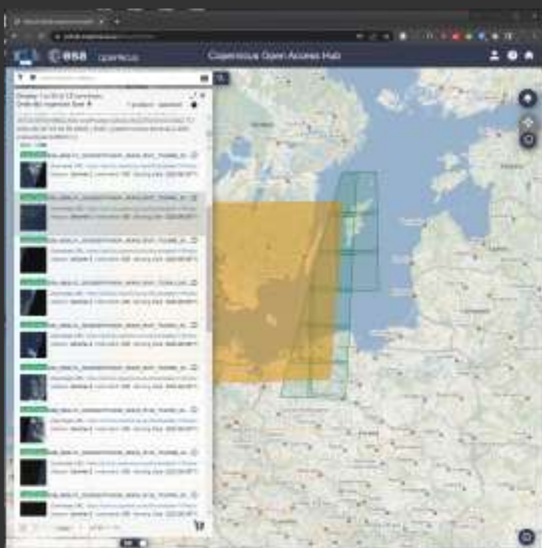
The USGS Global Visualization Viewer, or GloVis, offers access to similar datasets made available by EarthExplorer.

Finding Free Imagery



- ESA Copernicus Hub
- https://browser.dataspace.copernicus.eu/

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The European Space Agency (ESA) also has data portals available to download satellite data, such as imagery from the Sentinel-2 and Sentinel-3 sensors.

ArcGIS Living Atlas of the World

https://livingatlas.arcgis.com/en/

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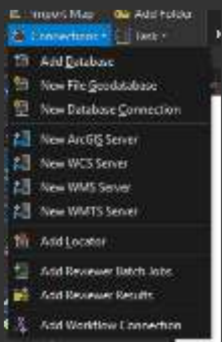
Some image datasets can be streamed to a web map or ArcGIS Pro using the Living Atlas of the World made available by ESRI.

Connecting to Servers in ArcGIS Pro

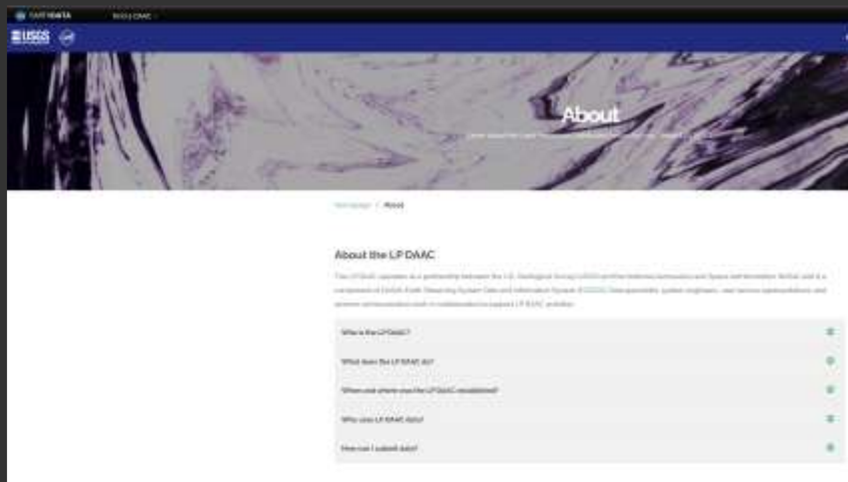


https://www.mapwv.gov/gis_services.html

55

It is possible to connect to GIS web services to stream web data into a web map or ArcGIS Pro, including some satellite imagery datasets.

Land Processes Distributed Active Archive Center (LP DAAC)



https://lpdaac.usgs.gov/

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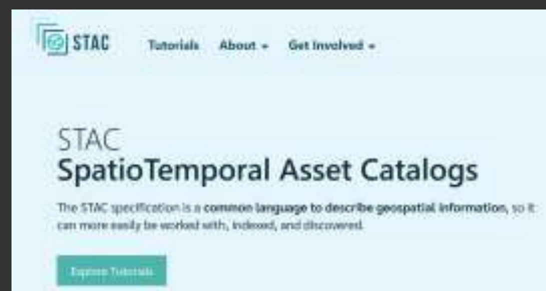
Analysis Ready Data (ARD) and derived products are provided by the Land Processes Distribution Active Archive Center (LP DAAC) operated by NASA and the USGS. This includes data and products from the Landsat, AVHRR, and MODIS missions/sensors.

STAC

- SpatialTemporal Asset Catalog (STAC)
- Commonly used for imagery stored in the cloud
- A metadata and discovery standard that lets users and software find remote-sensing data by location, time, collection, sensor, band, cloud cover, and other attributes, then access the actual files.

1. Describe
2. Search
3. Link to files
4. Cloud-native workflows
5. Interoperable



https://stacspec.org/en

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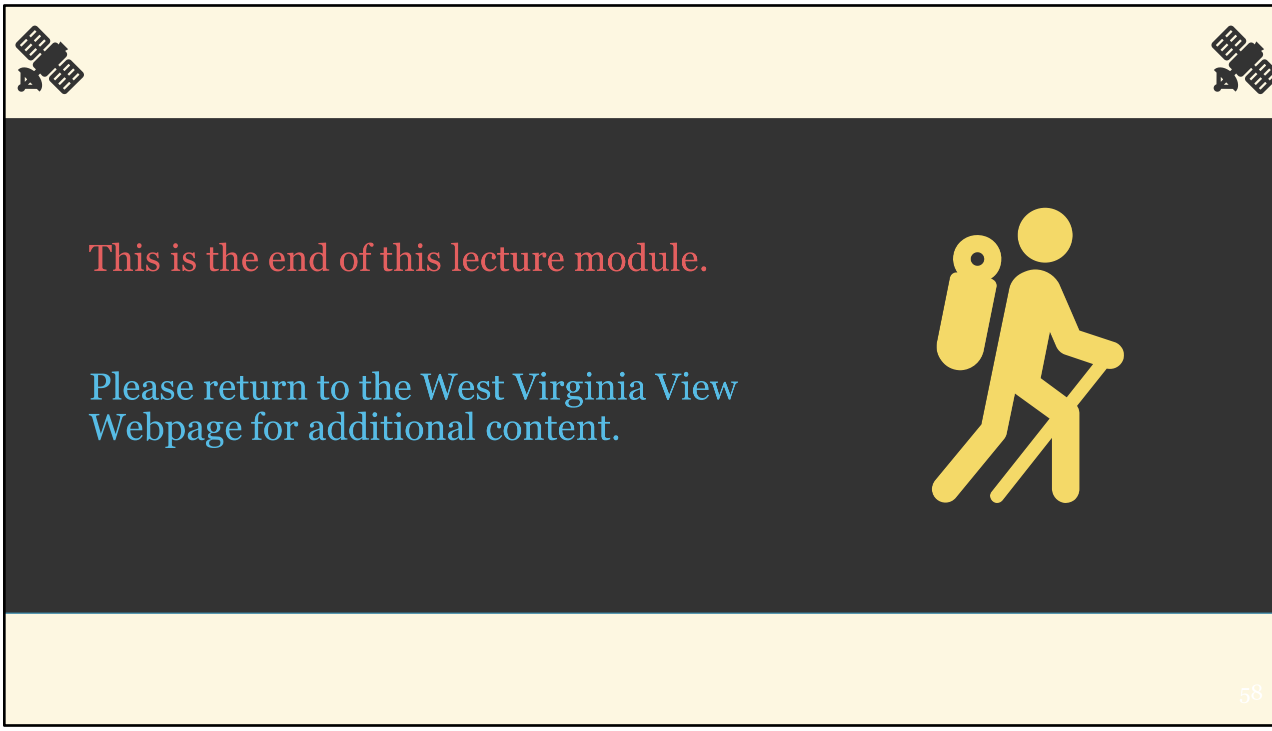
STAC stands for SpatialTemporal Asset Catalog. This format is interoperable and supports cloud-native workflows. STAC can reference multiple images or an entire time series of measurements. The data are indexed and searchable based on location, time, collection, sensor, band, cloud cover, and other attributes.

For more information about STAC, visit the site linked on this slide.



Thanks! Hope you found this useful.