Lesson 2:
REMOTE SENSING

Course: Laboratory of Atmospheric Remote Sensing
Laurea Magistrale in Atmospheric Science and Technology

CONTENTS

- Remote Sensing: definition, process components, applications,
- Reflectance of Earth-surface materials
- Sensors: active and passive sensors, differences, advantages and disadvantages
- Platforms: spaceborne, airborne, ground-based platforms
- Passive sensors: spectrometer, gamma-ray spectrometer, aerial cameras, thermal infrared video cameras, accelerometer, radiometer, hyperspectral radiometer, imaging radiometer
- Active sensors: LIDAR, SODAR & SONAR, radar, laser altimeter, scatterometer, atmospheric sounder
- Radiosonde: output and METAR data
- Monostatic and multistatic sensors, Doppler sensors
- Acoustic wave propagation in the atmosphere

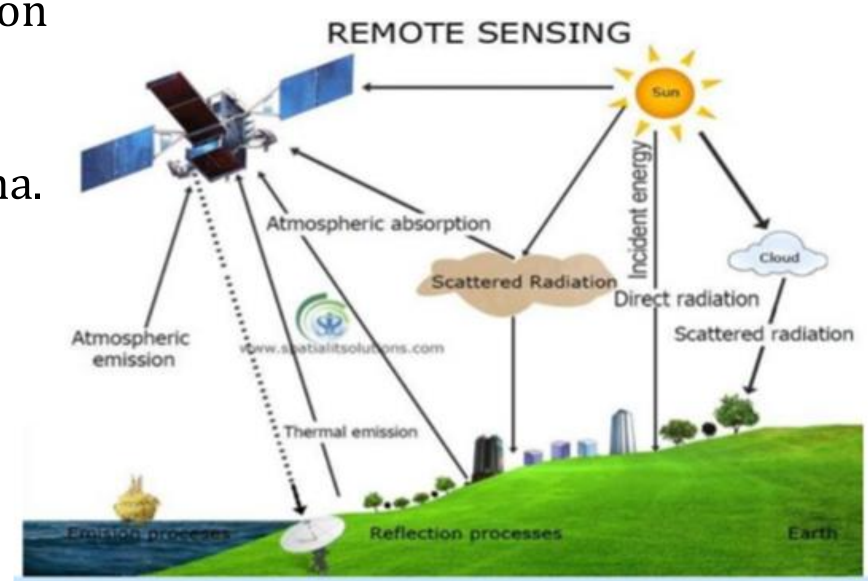
What is Remote Sensing?

Remote sensing is the **science and technology of obtaining information** about objects or areas from a distance, so <u>without direct contact</u> (USGS).

In particular, it can be use to observe Earth from space and air, typically from aircraft or satellites**.**

It is done by:

(i) sensing
(ii) recording reflected or emitted energy
(iii) processing & analysing
(iv) applying that information in order to improve the knowledge of atmospheric phenomena.



Concept of Remote Sensing

- **Measurements** are to obtain or acquire information of an object using experimental methods
- There must be some **interaction** between the object and the instruments in order to acquire the information of the object
- **In situ** methods obtain information locally

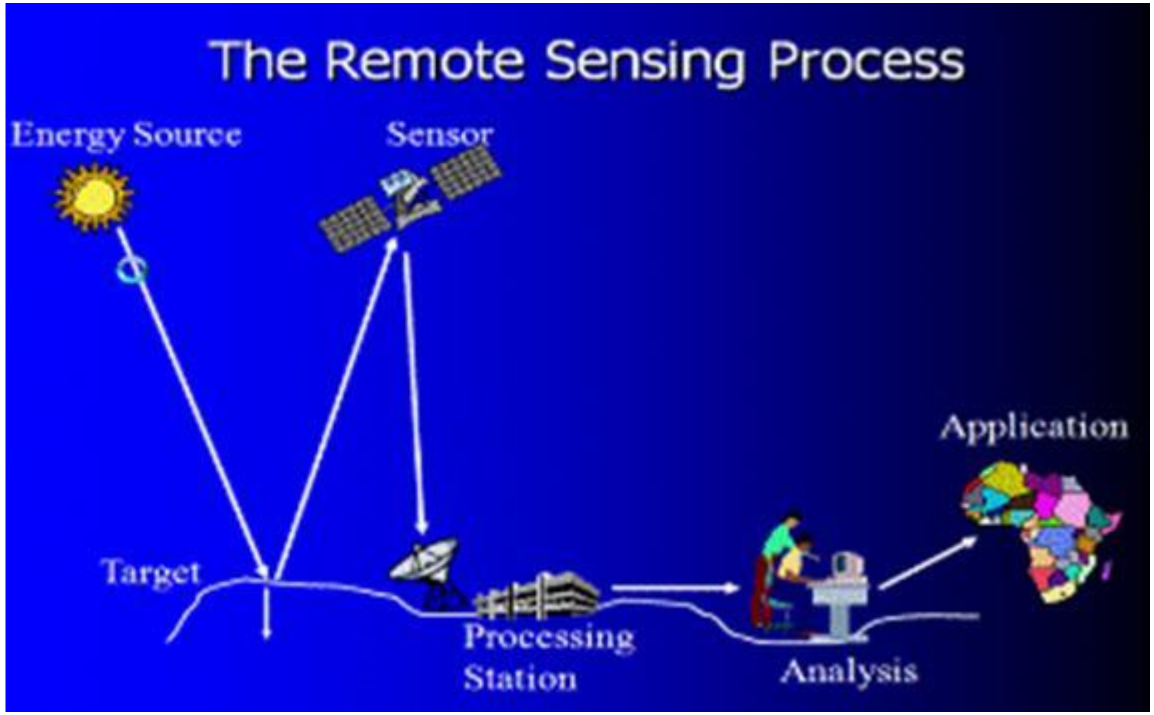
Without direct physical contact between the sensor and the the object, some **remote interaction** must be introduced to carry away the object information so that the information can be acquired by sensor remotely.

The interaction between **radiation** and object is the most common interaction.

The radiation includes **electromagnetic radiation** and **acoustic waves**

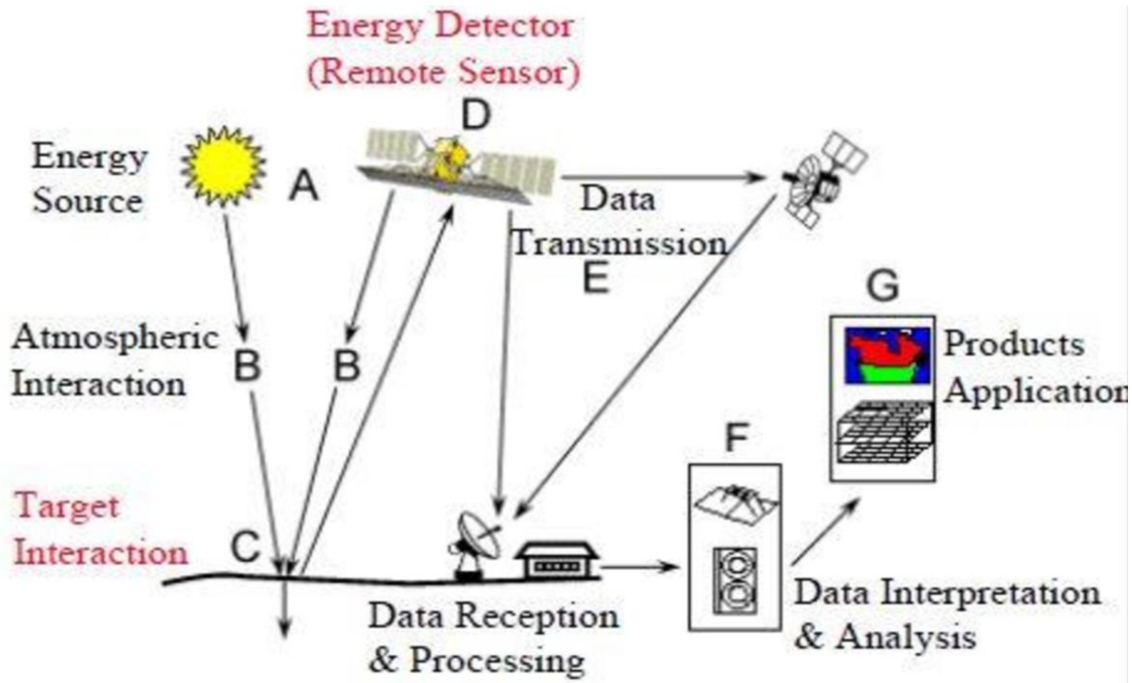
During the interaction, **radiation properties are modified by the object**, therefore, containing the information of the object. Through recording and analysing the modifications of the radiation, the object information can be retrieved.

Process components



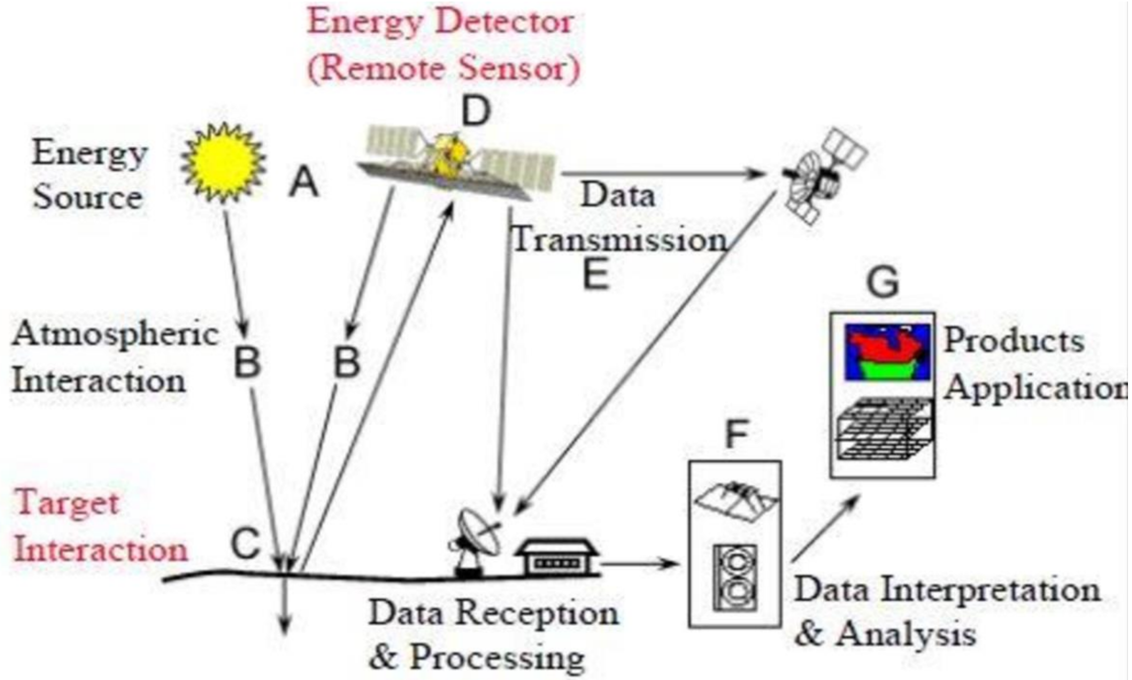
1) Energy or illumination source
2) Radiation and atmosphere
3) Interaction with the object of interest (target)
4) Recording energy by the sensor
5) Data transmission and process
6) Data analysis and post-processing interpretation
7) Application

Process of Remote Sensing (1)



1) **Energy Source or Illumination (A)** - for remote sensing, it is fundamental to have an energy source which illuminates or provides electromagnetic energy to the target of interest.
2) **Radiation and the Atmosphere (B)** - as the energy travels from its source to the target, it will come in contact with and interact with the atmosphere it passes through..
3) **Interaction with the Target (C)** - once the energy makes its way to the target through the atmosphere, it interacts with the target depending on the properties of both the target and the radiation.

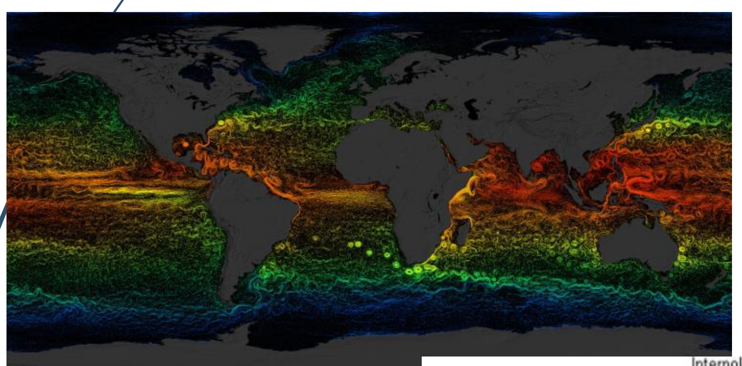
Process of Remote Sensing (2)

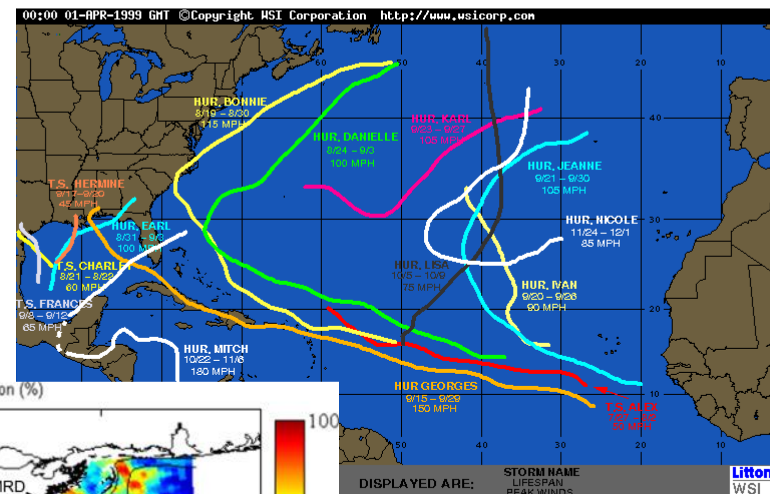


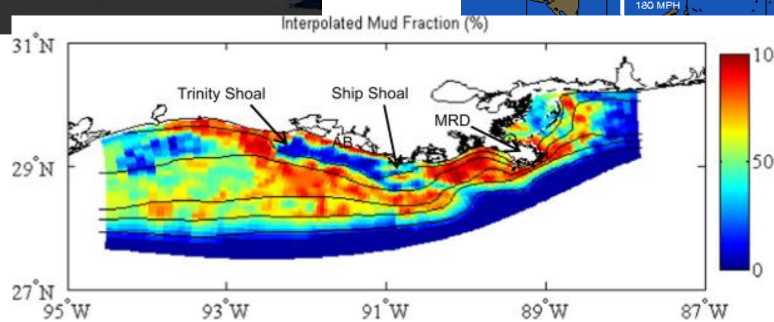
4) **Recording of Energy by the Sensor (D)** - after the energy has been scattered by, or emitted from the target, we require a remote sensor to collect and record the electromagnetic radiation.
5) **Transmission, Reception, and Processing (E)** - the energy recorded by the sensor has to be transmitted, often in electronic form, to a receiving and processing station where the data are processed into an image.
6) **Interpretation and Analysis (F)** - the processed image is interpreted, visually and/or digitally or electronically, to extract information about the target which was illuminated.

Remote sensing – applications (1)

- ✓ **Coastal applications**: monitor shoreline changes, track sediment transport, and map coastal features. Data can be used for coastal mapping and erosion prevention.
- ✓ **Ocean applications**: monitor ocean circulation and current systems, measure ocean temperature and wave heights, and track sea ice. Data can be used to better understand the oceans and how to best manage ocean resources.

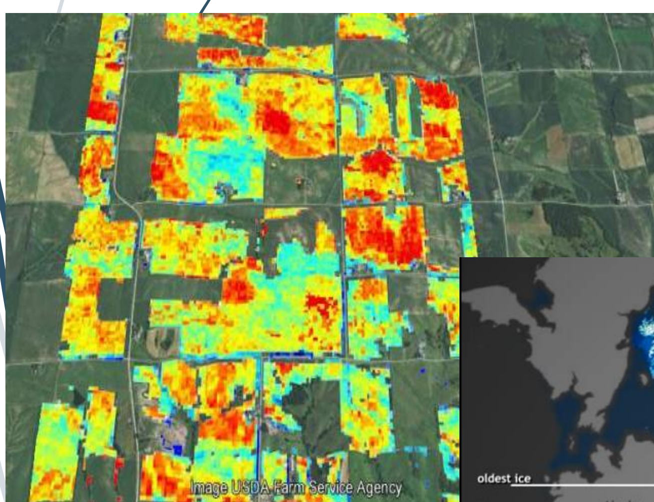


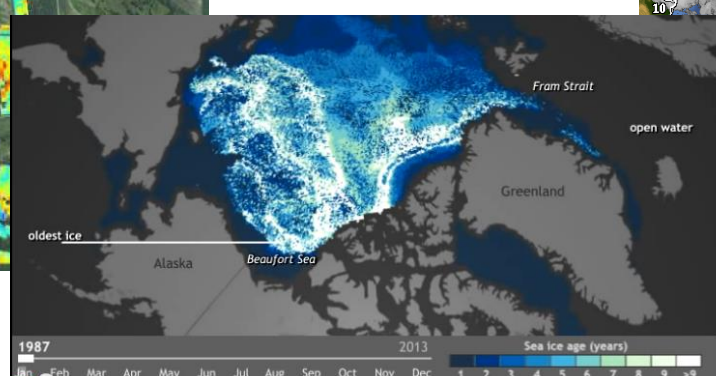


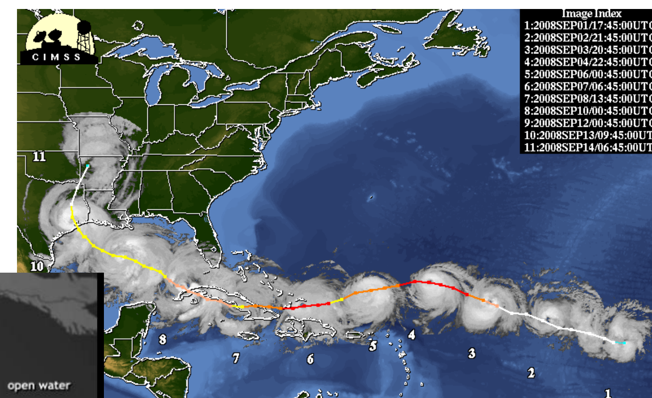


Remote sensing – applications (2)

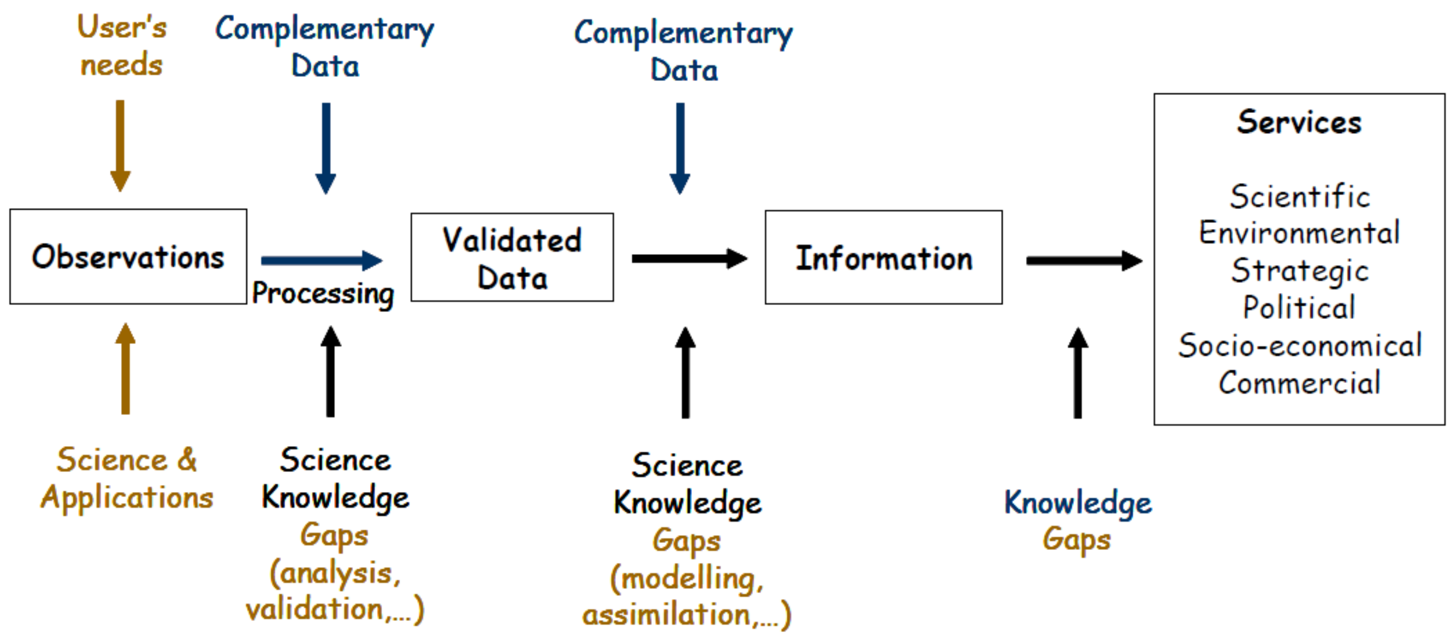
- ✓ **Hazard assessment**: track hurricanes, earthquakes, erosion, and flooding. Data can be used to assess the impacts of a natural disaster and create preparedness strategies to be used before and after a hazardous event.
- ✓ **Natural resource management**: monitor land use, map wetlands, and chart wildlife habitats. Data can be used to minimize the damage that urban growth has on the environment and help decide how to best protect natural resources.







Problems

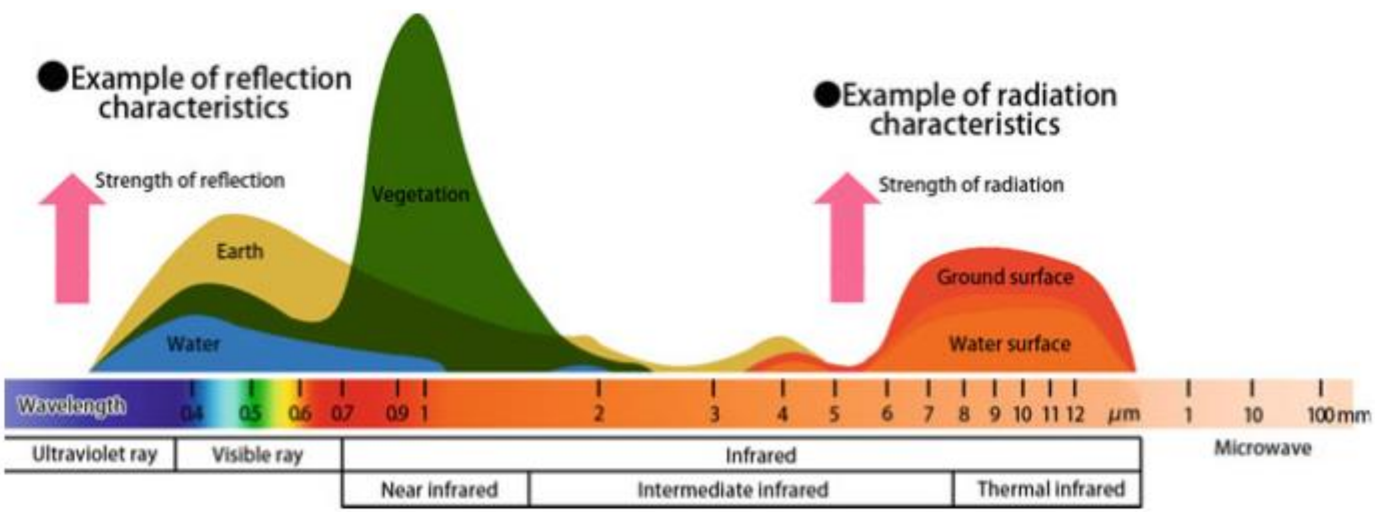


How can we bridge the gaps??

Sensors

''A **sensor** is a device comprising of optical component or system and a detector with an electronic circuitry that can be used to record the reflected and/or emitted energy from various objects.''

The electromagnetic waves are used to specify the size, characteristics and shape of objects on the ground.
The electromagnetic wavelengths typically utilized for remote sensing of the Earth's surface/atmosphere range from the ultraviolet to microwave regions of the spectrum.
It is possible to identify many types of objects based on their spectral signature, i.e., their unique reflectance/emittance properties in some specific regions of the electromagnetic spectrum.



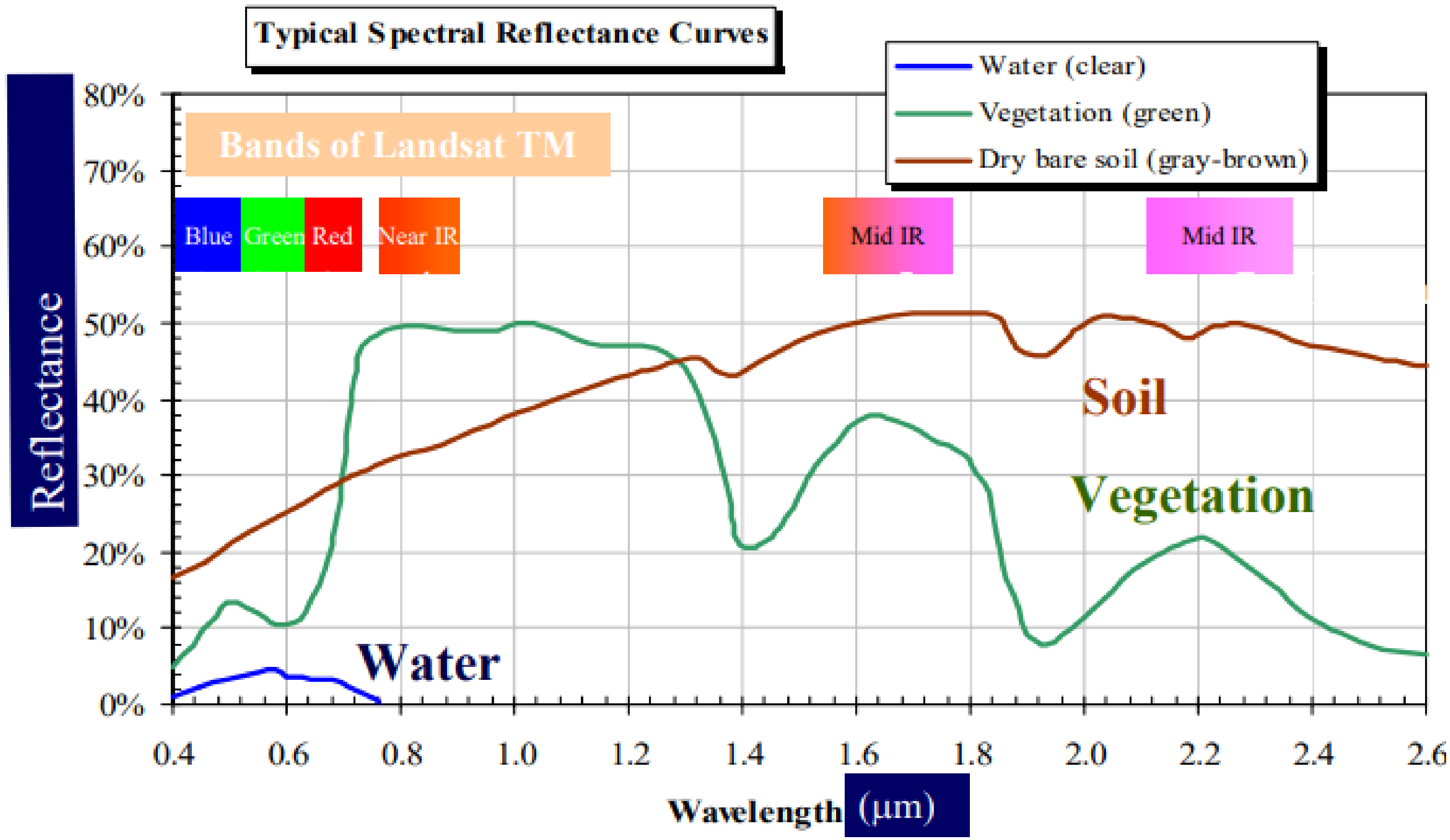
Reflectance

Is the ratio of reflected optical power to the incident optical power at a reflecting object. For reflections at flat unstructured surfaces, it is the same as the reflectivity.

However, the reflectance is a more general term and can be specified in a wider range of situations:

- ❑ Reflections can occur on rough surfaces, where light is scattered. One may then specify the hemispherical reflectance, which is based on the total reflected radiant flux. Also, there is the directional reflectance, defined as the ratio of reflected and incident radiance; it is a function of observation angle.
- ❑ There are extended objects, where light can penetrate, is internally scattered and thus partially transmitted and partially reflected. The reflectance simply quantifies the amount of light getting back into the half space of the incoming light.
- ❑ When light is incident on a transparent plate with parallel surfaces, for example, Fresnel reflections occur on both surfaces. The reflected power can be affected by interference effects, making the reflectance strongly wavelength-dependent.

Reflectance of Earth-Surface materials

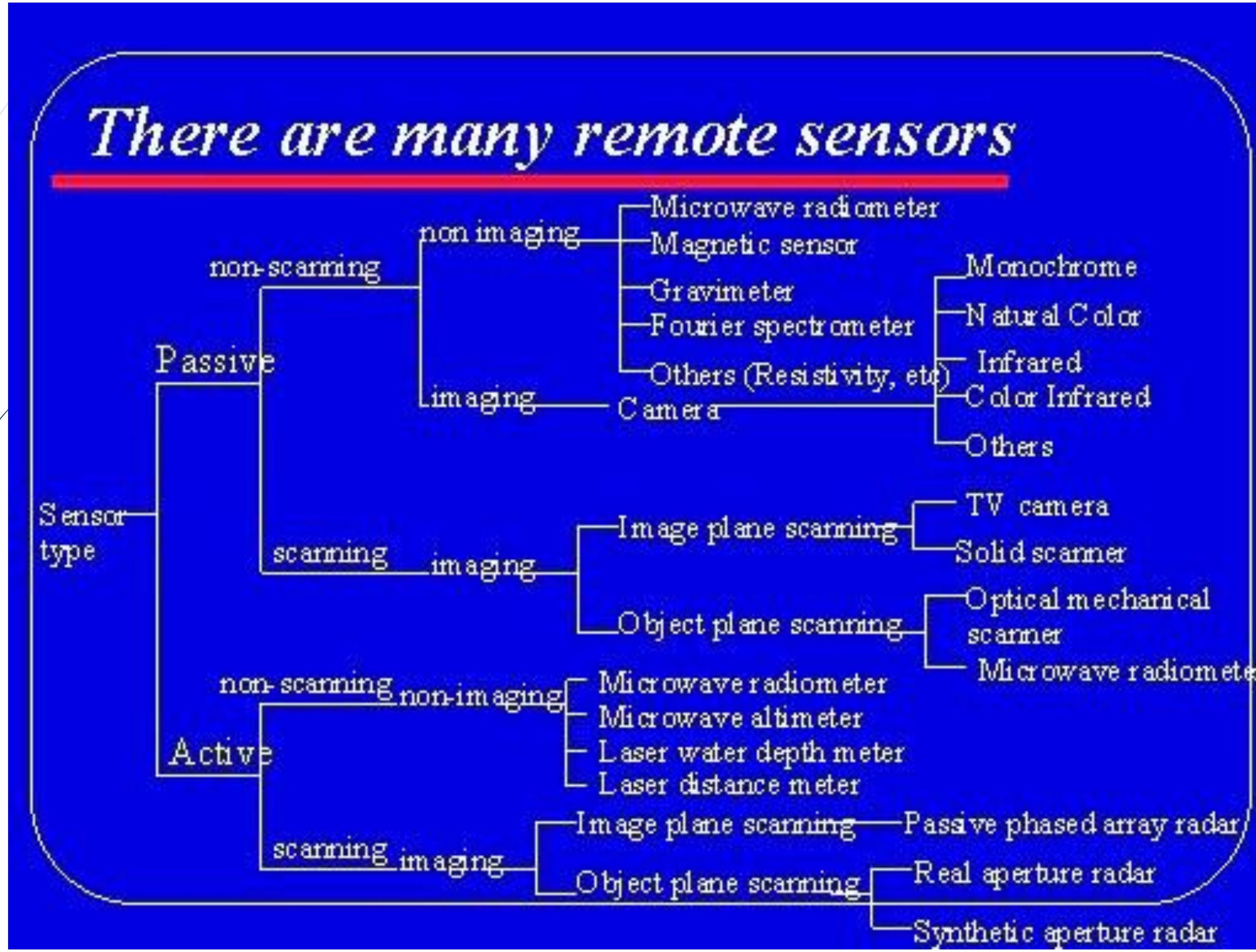


Sensors

Remote-sensing data from different parts of the electromagnetic spectrum convey different types of information about the Earth's land/water surface or atmosphere:

- *intermediate*, or shortwave, *infrared wavelengths* are often used for the monitoring of vegetation and other types of objects on the ground or atmosphere (clouds) that have distinctive colors.
- *multispectral optical sensors*, which measure reflected solar radiation over a few relatively broad portions of the optical spectrum, can differentiate between some types of objects on the surface/atmosphere.
- *hyperspectral optical sensors*, which take measurements over many more narrower portions of the spectrum, can discriminate between even more types of objects.
- *thermal infrared spectrum* can provide information on the surface temperatures of objects and are often used to monitor the health of crops (e.g., leaf water content) or detect forest fires.
- *microwave spectrum* can be used to monitor various vegetation/soil/water parameters.

Sensors

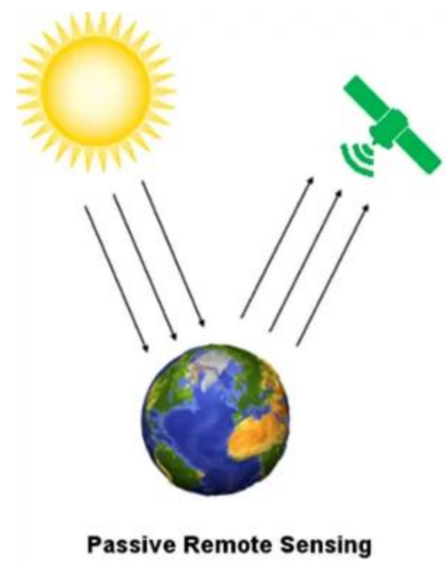


There are many remote sensors
Sensor type
Passive
non-scanning
non imaging
Microwave radiometer
Magnetic sensor
Gravimeter
Fourier spectrometer
Others (Resistivity, etc)
imaging
Camera
Monochrome
Natural Color
Infrared
Color Infrared
Others
scanning
imaging
Image plane scanning
TV camera
Solid scanner
Object plane scanning
Optical mechanical scanner
Microwave radiometer
Active
non-scanning
non-imaging
Microwave radiometer
Microwave altimeter
Laser water depth meter
Laser distance meter
scanning
imaging
Image plane scanning
Passive phased array radar
Object plane scanning
Real aperture radar
Synthetic aperture radar

Active and passive sensors

- **Active sensors** provide their own source of energy (electromagnetic energy) to illuminate the objects they observe. An active sensor emits radiation in the direction of the target to be investigated. The sensor then detects and measures the radiation that is reflected or backscattered from the target.

- **Passive sensors** detect natural energy (radiation) that is emitted or reflected by the object or scene being observed. Reflected sunlight is the most common source of radiation measured by passive sensors.



Active and passive sensors - differences

➢ Active sensors

- ❖ Active transducers generate electric current or voltage in response to environmental stimulation
- ❖ Active sensors provides their own energy source
- ❖ Are able to measure anytime (daytime and nighttime)

➢ Passive sensors

- ❖ Produce a change in some passive electical quantity, e.g. capacitance, resistance, inductance and require additional electical energy
- ❖ Can be used only if the naturally occurring energy is available
- ❖ Can measure only during daytime

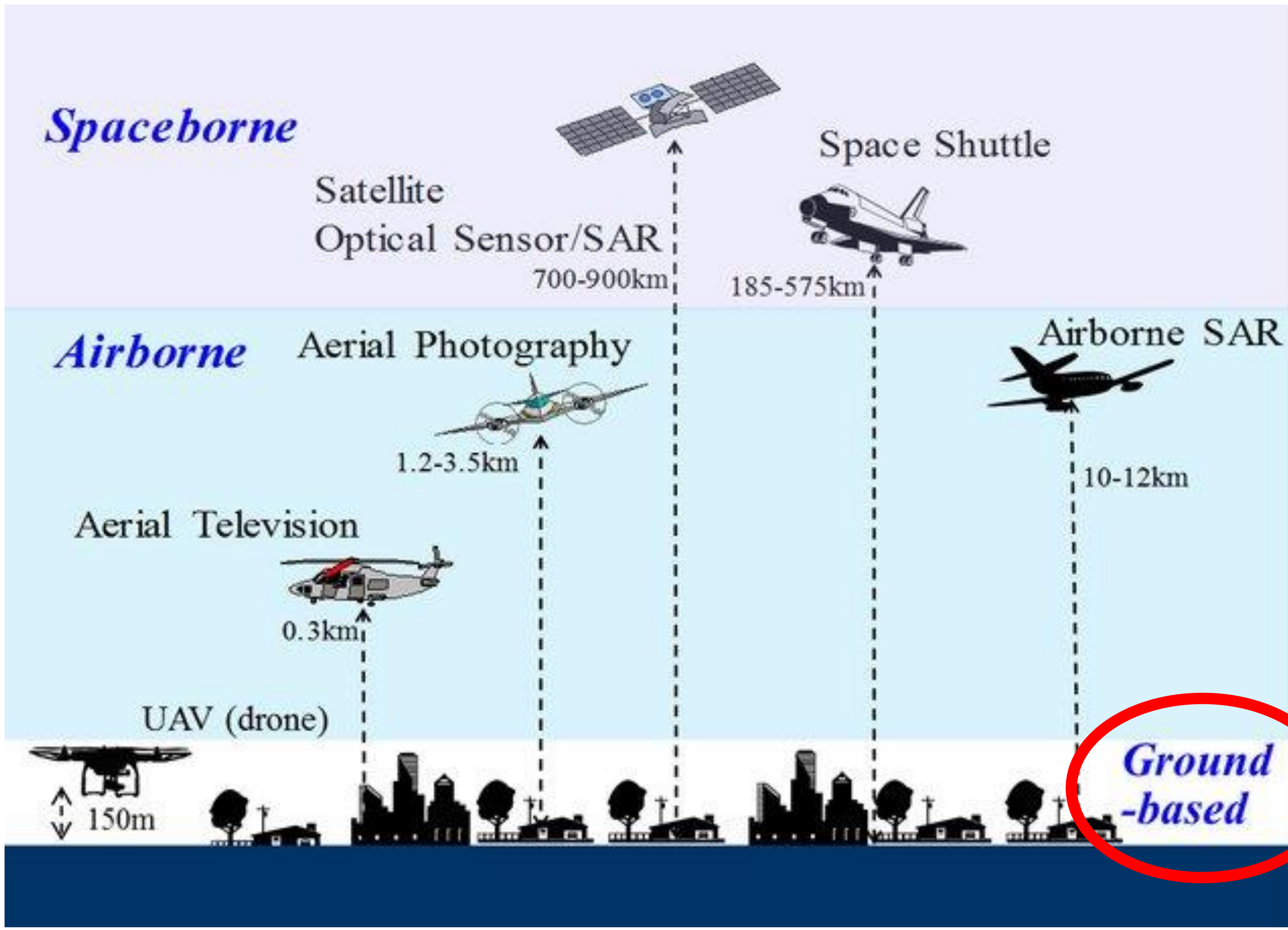
Active sensors – advantages and disadvantages

- ✓ Better control of noise through control of injected signal
- ✓ Better control of errors and outlayers signal thanks to measurements of propagating fields
- ✓ Different configurations of source/receiver available. This permits great flexibility in customizing surveys for particular problems
- ✓ Large amount of data capable
- ✓ Survey need only record a natural occurring field, hence only a sensor and a data recorder have to be supplied
- ✓ Field operation typically time efficient
- ✓ Radar penetrates vegetation and soil: can gain information about surface layer from mm to m depth.
- ✓ Low computational time and costs needed to elaborate and interpret dataset
- ✓ Weather independent: artificial microwave radiation can penetrate clouds, light rain and snow
- ✓ Sunlight independent: can be operated day and night

Active sensors – advantages and disadvantages

- ✗ Field equipment complex because both source and receiver are under the surveyor's control
- ✗ Field operations and logistic more complex
- ✗ Many different source/receiver configurations can be used . This leads to greater survey design costs and potentially to increased probability of field mistakes
- ✗ Large amount of data can become overwhelming to process and interpret
- ✗ Less control of noise because source is out of signal is out of the control of surveyor
- ✗ Hard identification of abnormalities because passive fields derived from different contributions
- ✗ Only a few well-established field procedures are generally used, limiting the amount of customizations for a single problem
- ✗ Smaller dataset that do not allow for detailed interpretation
- ✗ Radar signals contain no spectral characteristics

Platforms



Spaceborne
Satellite
Optical Sensor/SAR
700-900km
Space Shuttle
185-575km
Airborne
Aerial Photography
1.2-3.5km
Airborne SAR
10-12km
Aerial Television
0.3km
UAV (drone)
150m
Ground
-based

Spaceborne platforms

- ❖ Platforms tlocated abut from 100 km up to 36000 km from Earth's surface

Types of spaceborn platforms:

- High-level satellites: about 36000 km
- Low-level satellites: 700-1500 km
- Space station: 300-400 km
- Space shuttle: 250-300 km

Examples: satellites, shuttle

Airborne platforms

- ❖ Are primarily stable wing aircraft, although helicopters are occasionally used
- ❖ Used to collect very detailed images and facilitate the collection of data
- ❖ Up to 50km from Earth's surface

Examples: NOAA, NCAR and NASA research aircrafts

Ground-based platforms

Is the remote sensing platform that position the sensor at the Earth's surface. It is used for close-range, high-accuracy applications, as architectural restoration, landside and erosion mapping, ammong others.

ADVANTAGES:

- Background is homogeneous
- High temporal resolution
- Instrument can be fixed if it malfunctions
- Power is not a problem
- Low costs
- Quick installation

DISADVANTAGES:

- Data cover limited areas
- Instrument location on land or ship
- Environmental effects on vegetation and fauna
- Vandalism and damages

Passive sensors

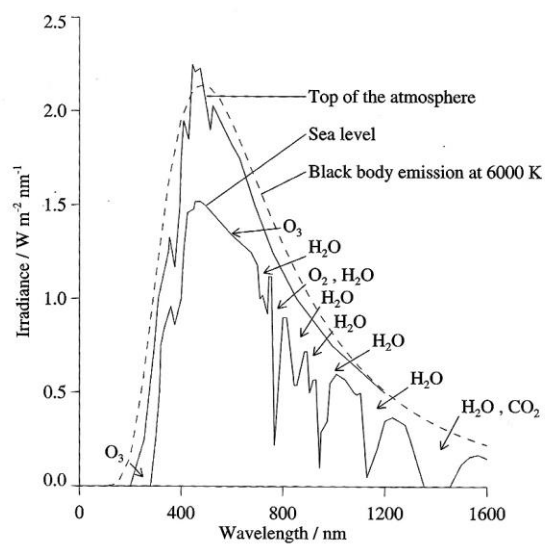
1) SPECTROMETER

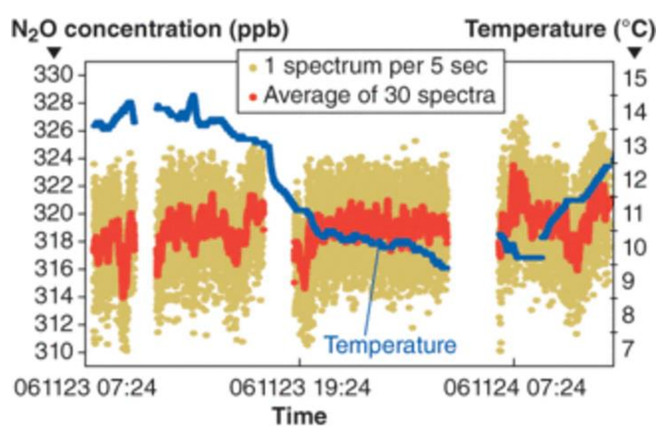
A device that is designed to detect, measure, and analyze the spectral content of incident electromagnetic radiation. Conventional imaging spectrometers use gratings or prisms to disperse the radiation for spectral discrimination.

- ❑ Passive sonsors able to detect incident electromagnetic radiation

Applications:

- ❖ Concentration of greenhouse gases in the atmosphere
- ❖ Analysis of the content of vapour and CO_2
- ❖ Composition of solar planets atmosphere
- ❖ Study of extrasolar planets





Passive sensors

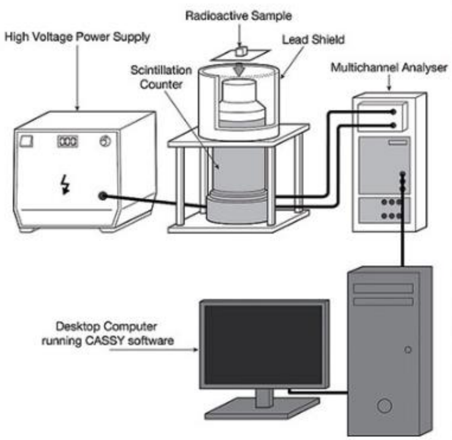
2) <u>GAMMA-RAY SPECTROMETER</u>

A device that is designed to detect, measure, and analyze the spectral content of radionuclides by analysis of the gamma-ray energy spectrum.

- ❑ Passive sonsors able to detect gamma rays
- ❑ Radiation source are typically upper-soil levels, such as rock layers
- ❑ Used to investigate mineral deposits
- ❑ Caused by radiactive decay

<u>Applications:</u>

- ❖ Environmental Radioactivity Monitoring
- ❖ Reactor Corrosion Monitoring
- ❖ Forensics and Nuclear Forensics
- ❖ Nuclear Materials Safeguards
- ❖ Materials Testing
- ❖ Geology and Minerology



Passive sensors

3) AERIAL CAMERAS

Highly specialised instruments developed to enable accurate and consistent imagery of the earth to be obtained from an aircraft. They detect and capture the natural light reflected from objects.

- ❑ Typically used in aerial photography
- ❑ Aircraft serve as a platform
- ❑ Can be installed on radio-controlled model aircraft

<u>Applications:</u>

- ❖ Photogrammetry
- ❖ Topographic mapping
- ❖ Environmental monitoring
- ❖ Real estate advertisements
- ❖ Military applications

Passive sensors

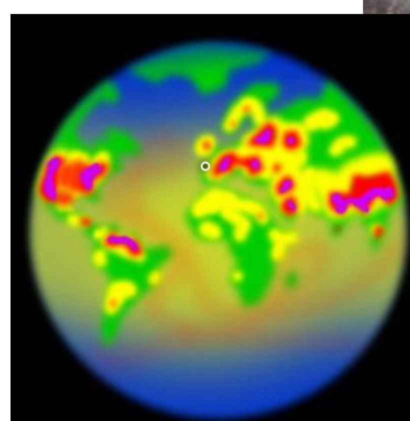
4) <u>THERMAL INFRARED VIDEO CAMERAS</u>

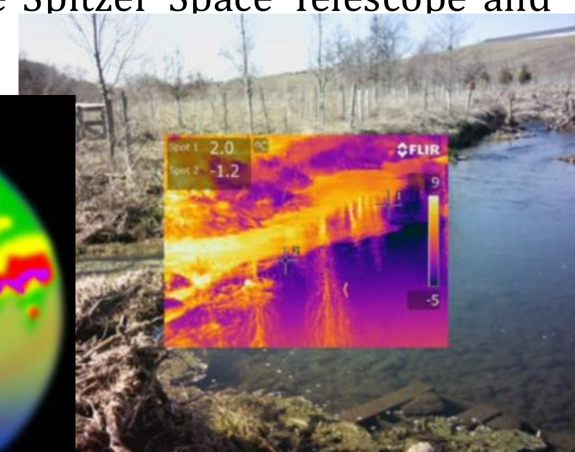
detects infrared energy and converts it into an electronic signal, which is then processed to produce a thermal image and perform temperature calculations.

- ❑ Detect near-infrared range
- ❑ Aircraft and satellites can be used as platforms
- ❑ Can be combined with active sensors (e.g. radar)

<u>Applications:</u>

- ❖ Cloud temperature/height and water vapor concentrations, depending on the wavelength
- ❖ Astronomy, in telescopes such as UKIRT, the Spitzer Space Telescope and the James Webb Space Telescope
- ❖ Identification of hot and cold spots
- ❖ Aerial archaeology
- ❖ Temperature distribution





Passive sensors

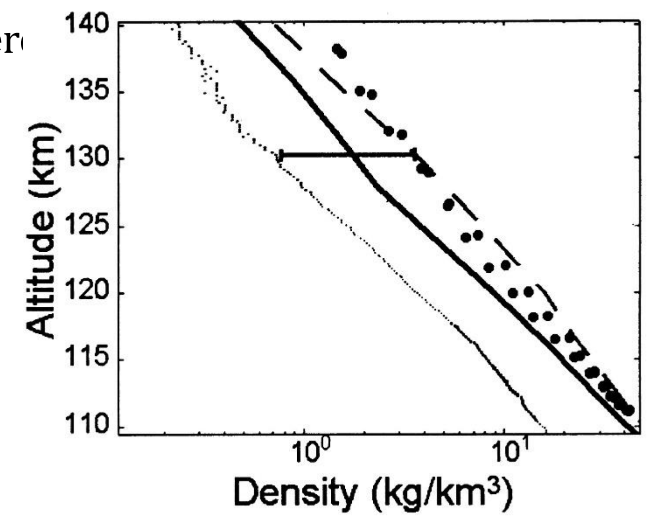
5) ACCELEROMETER

An instrument that measures acceleration. There are two general types of accelerometers. One measures *translational accelerations* (changes in linear motions in one or more dimensions), and the other measures *angular accelerations* (changes in rotation rate per unit time).

- ❑ Aircraft and ballons can be used as platforms

Applications:

- ❖ Density of atmospheric gases at different altitudes
- ❖ Understanding of seasonal wind variations
- ❖ Understanding of effects of dust storms
- ❖ Analysis of the structure of the atmospher



Passive sensors

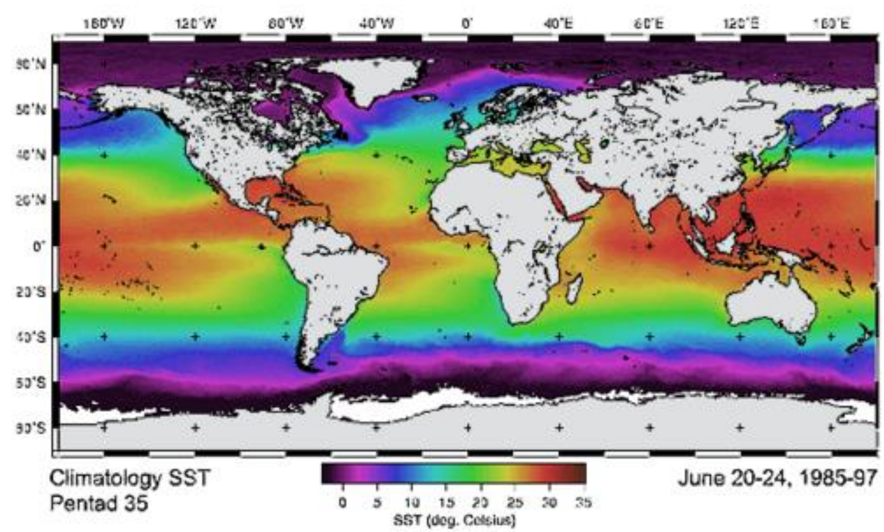
6) **RADIOMETER**

An instrument that quantitatively measures the intensity of electromagnetic radiation in some bands within the spectrum.

- ❑ Record information in the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum
- ❑ Scans with various wavelength bands
- ❑ Satellite and aircrafts are used as platforms

Applications:

- ❖ Monitor clouds and to measure the thermal emission of the Earth
- ❖ Surveillance of land surfaces, ocean state, aerosols
- ❖ Study climate change and environmental degradation

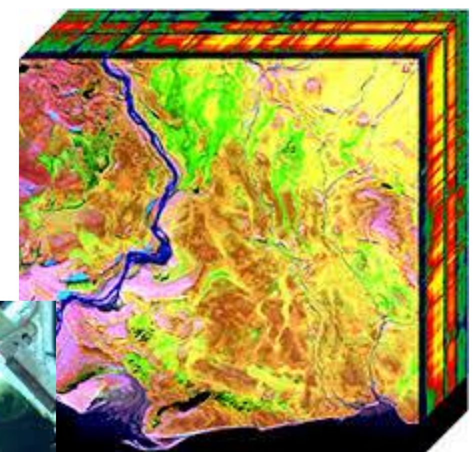


Passive sensors

7) <u>HYPERSPECTRAL RADIOMETER</u>

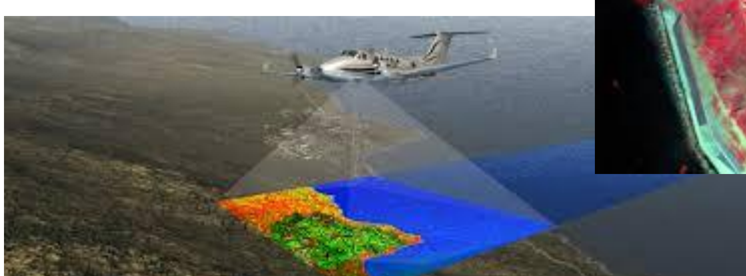
An advanced multispectral sensor that detects hundreds of very narrow spectral bands. This sensor's very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands.

- ❑ Record information in the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum
- ❑ Scans with various wavelength bands
- ❑ Satellite and aircrafts are used as platforms



<u>Applications:</u>

- ❖ Environmental monitoring
- ❖ Geology
- ❖ Flora & fauna



Passive sensors

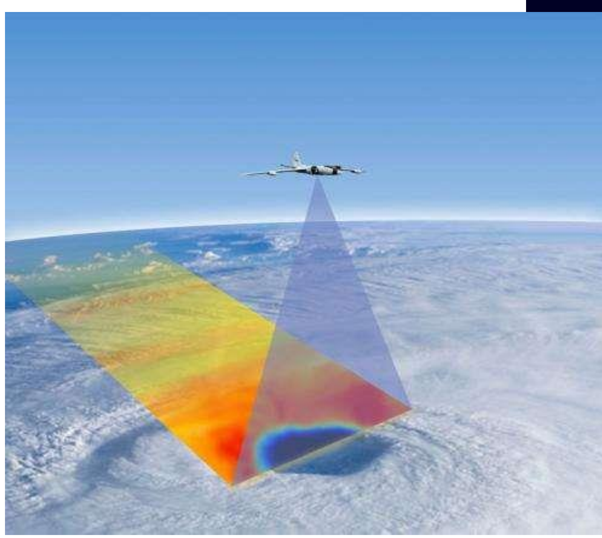
8) <u>IMAGING RADIOMETER</u>

A radiometer that has a scanning capability to provide a two-dimensional array of pixels from which an image may be produced. Scanning can be performed mechanically or electronically by using an array of detectors.

- ❑ High-spatial resolution data
- ❑ Satellite and aircrafts are used as platforms

<u>Applications:</u>

- ❖ Environmental monitoring and
- ❖ Wildfire monitoring
- ❖ Hurricanes track



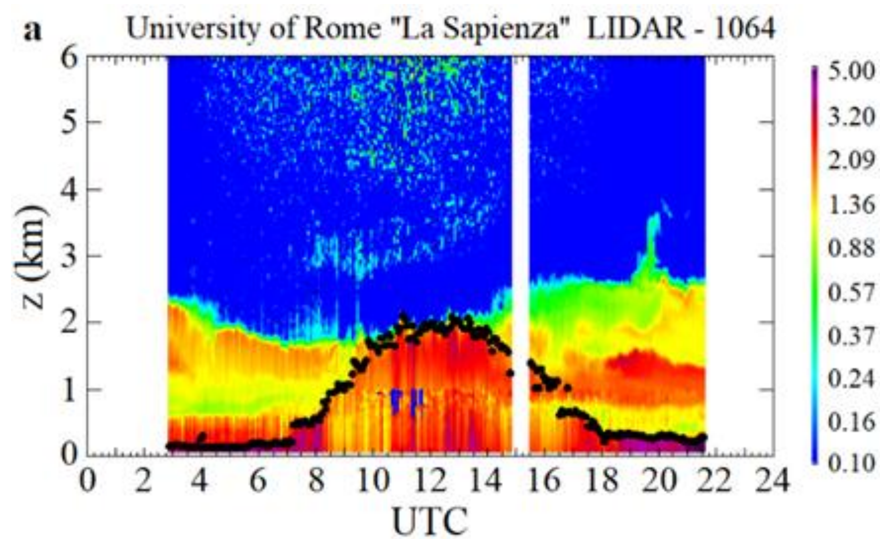
Active sensors

1) LIDAR

Light detection and ranging sensor that uses a laser (light amplification by stimulated emission of radiation) radar to transmit a light pulse and a receiver with sensitive detectors to measure the backscattered or reflected light. Distance to the object is determined by recording the time between transmitted and backscattered pulses and by using the speed of light to calculate the distance traveled.

Applications:

- ❖ Aerosol content in the atmosphere
- ❖ Water vapour content in the atmosphere
- ❖ Mixed layer height
- ❖ Clouds



An introduction to the Lidar Technique is part of the present class but for an advanced course it is raccomanded: *Lidar Remote Sensing (V. Rizi, M.Iarlori)*

Active sensors

2) <u>SODAR & SONAR</u>

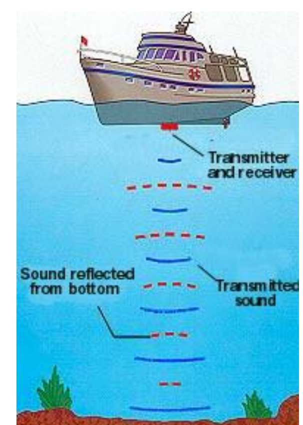
Sound waves or acoustic waves are used in order to measure the scattering of sound waves by atmospheric turbulence. This is real mechanical sound wave, i.e. longitudinal wave, produced by compressing the atmosphere medium. It is not electromagnetic wave at the sound frequency.

SODAR is usually referred to the sound detection and ranging in the atmosphere.

<u>Applications:</u>

- ❖ Vertical profile of wind speed and direction
- ❖ Atmospheric turbulence
- ❖ Mixed layer height
- ❖ Atmospheric stability

SONAR is used under water, for the ocean detection.



<u>Applications:</u>

- ❖ Biomass estimation
- ❖ Wave measurement
- ❖ Water velocity measurement
- ❖ Bathymetric mapping

Active sensors

3) <u>RADAR</u>

An active radio detection and ranging sensor that provides its own source of electromagnetic energy. An active radar sensor, whether airborne or spaceborne, emits microwave radiation in a series of pulses from an antenna. When the energy reaches the target, some of the energy is reflected back toward the sensor. This backscattered microwave radiation is detected, measured, and timed. The time required for the energy to travel to the target and return back to the sensor determines the distance or range to the target. By recording the range and magnitude of the energy reflected from all targets as the system passes by, a two-dimensional image of the surface can be produced high-spatial resolution data.

https://www.ilmeteo.it/portale/radar-italia

Applications:

- ❖ Accurate measurements of the radar backscatter from the ocean surface
- ❖ Precipitations, land use and agriculture
- ❖ Ozone and No_2 global monitoring
- ❖ Dynamics, decay and growth of ice sheets
- ❖ Earthquake detection

Recommended:

Electromagnetics and Radar Meteorology (F. Marzano, M Montopoli)

Active sensors

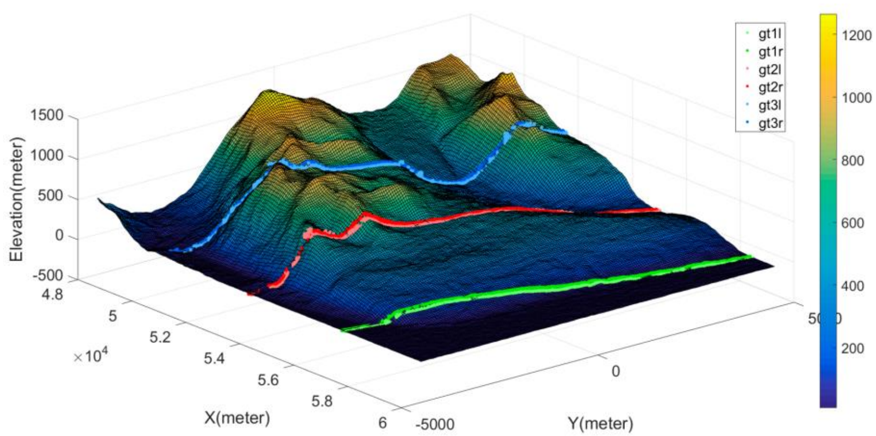
4) LASER ALTIMETER

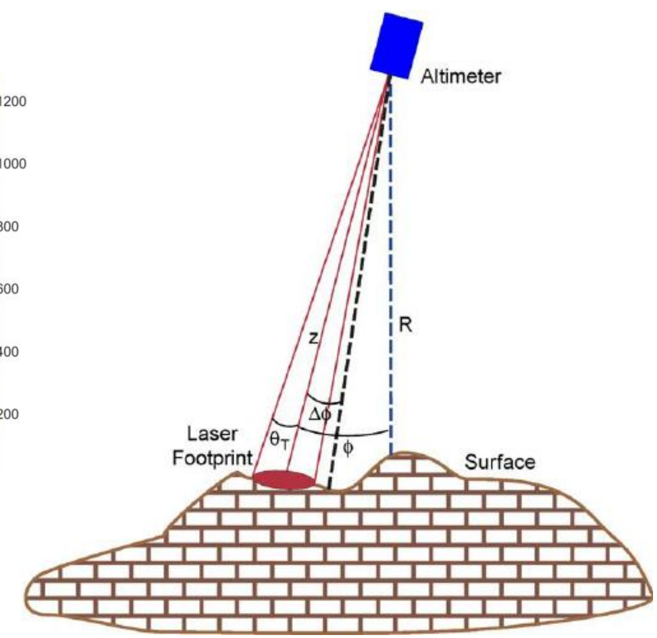
An instrument that uses a LIDAR to measure the height of the platform (spacecraft or aircraft) above the surface. The height of the platform with respect to the mean Earth's surface is used to determine the topography of the underlying surface.

- ❑ High-spatial resolution data

Applications:

- ❖ Topography and bathymetry





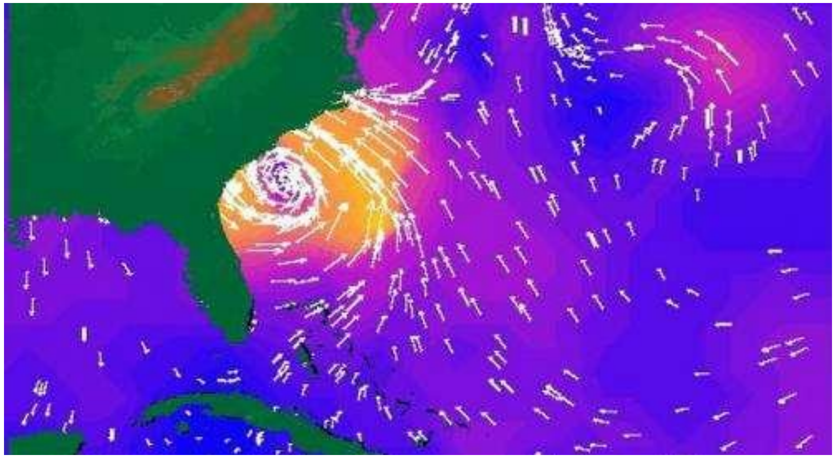
Active sensors

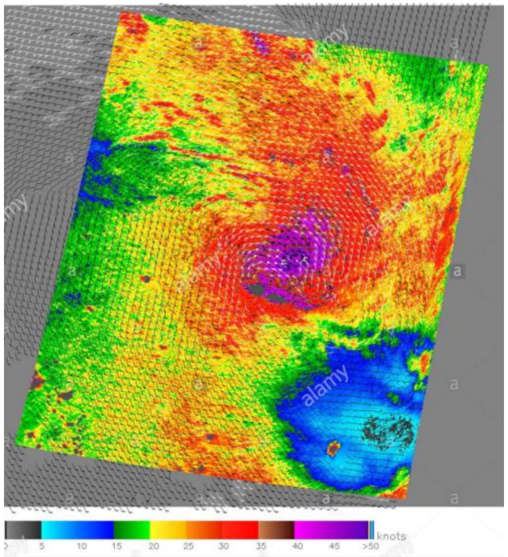
5) <u>SCATTEROMETER</u>

A high-frequency microwave radar designed specifically to measure backscattered radiation. Over ocean surfaces, measurements of backscattered radiation in the microwave spectral region can be used to derive maps of surface wind speed and direction.

<u>Applications:</u>

- ❖ Surface wind speed and direction
- ❖ Hurricanes
- ❖ Global sea-surface wind speed and direction in order to predict the marine phenomena





Active sensors

6) <u>ATMOSPHERIC SOUNDER</u>

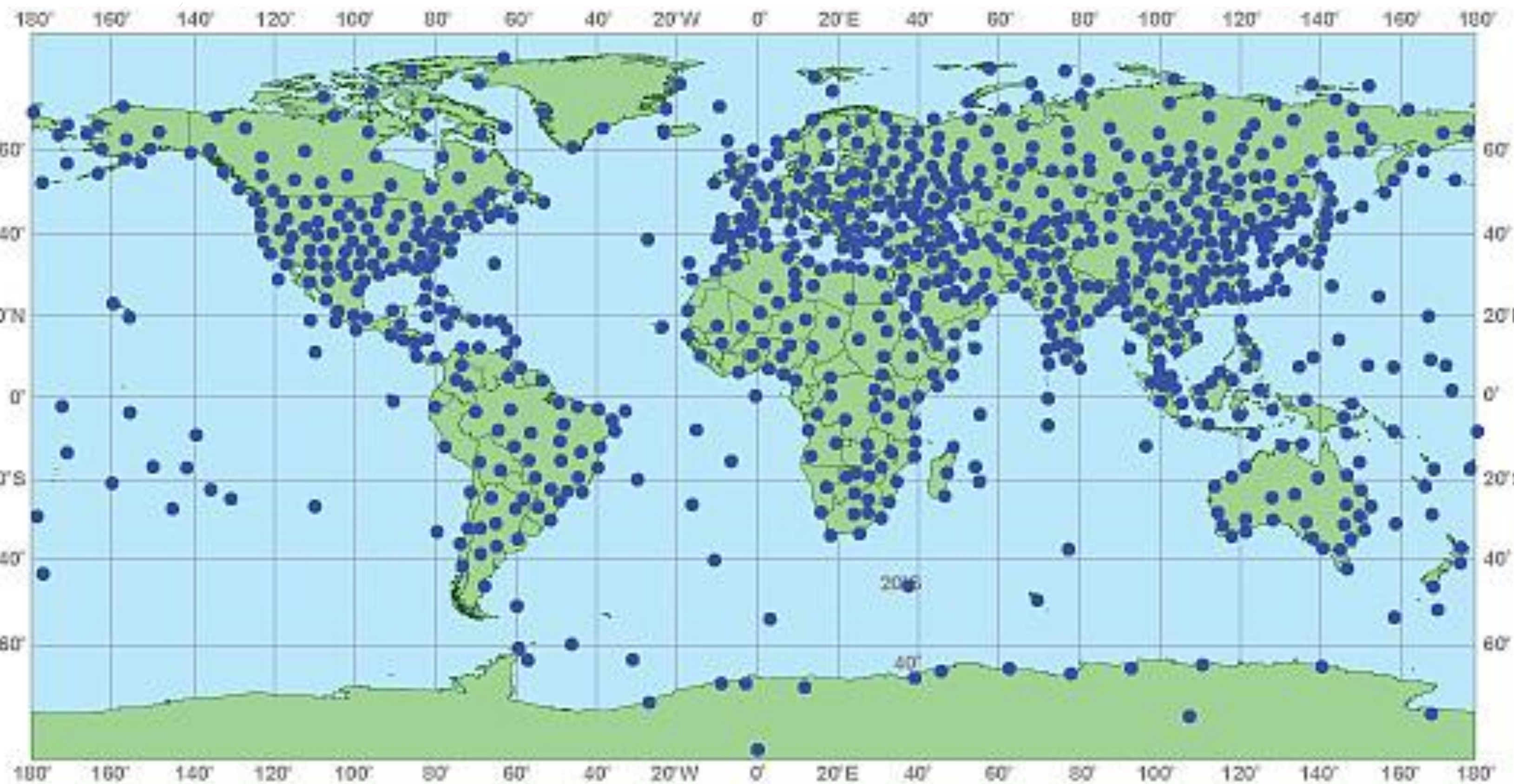
Measurement of vertical distribution of physical properties of the atmospheric column such as pressure, temperature, wind speed and wind direction (thus deriving wind shear), liquid water content, ozone concentration, pollution, and other properties. Such measurements are performed in a variety of ways including remote sensing and in situ observations.

The most common in situ sounding is a radiosonde, which usually is a weather balloon, but can also be a rocketsonde.

Applications:

- ❖ Input for computer-based weather prediction models
- ❖ Local severe storm, aviation, and marine forecasts
- ❖ Weather and climate change research
- ❖ Input for air pollution research
- ❖ Ground truth for satellite data

Radiosonde

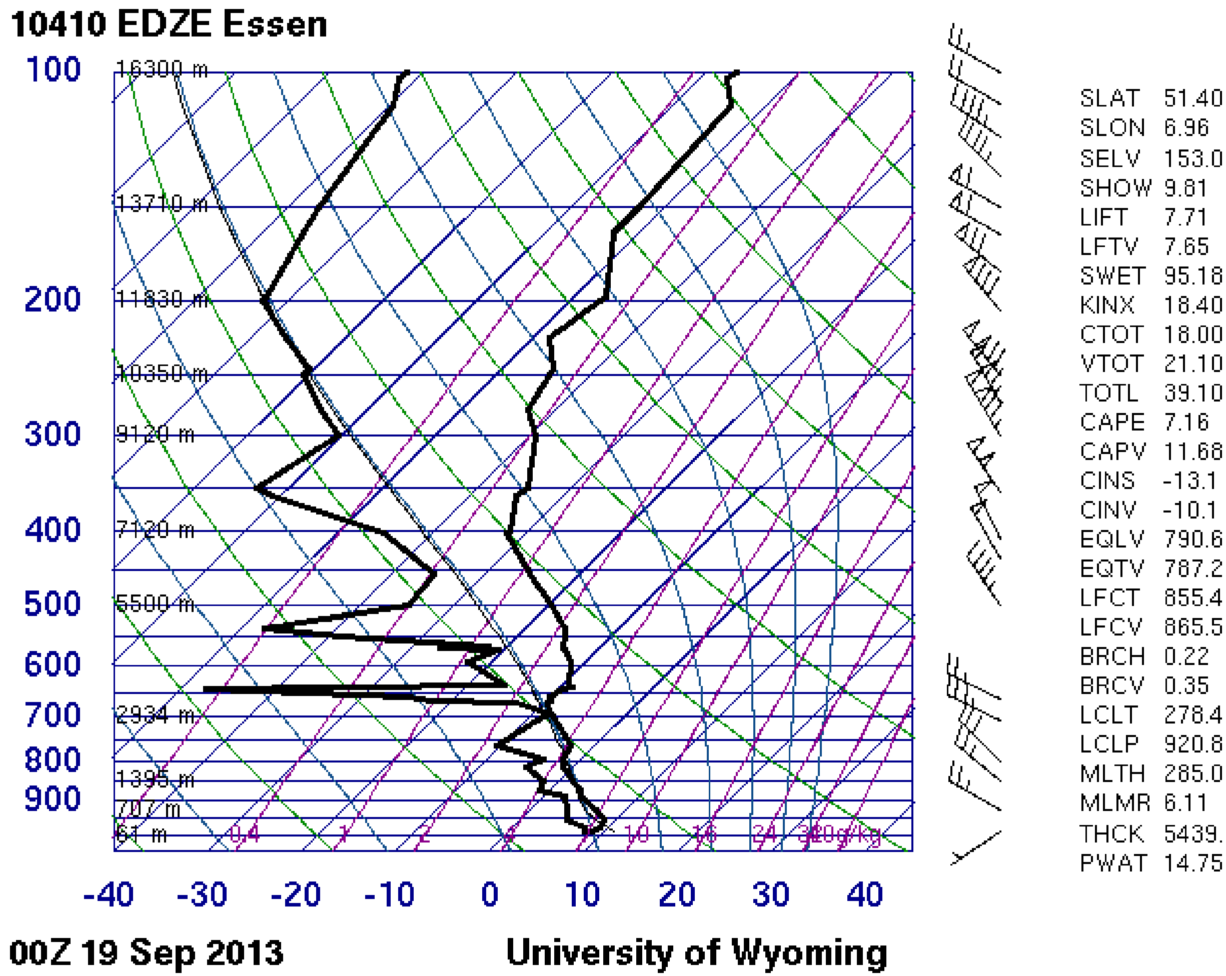

180° 160° 140° 120° 100° 80° 60° 40° 20°W 0° 20°E 40° 60° 80° 100° 120° 140° 160° 180°
60° 40° 20°N 0° 20°S 40° 60°

Radiosonde

In Italy:

- LIRE (WMO Code: 16245) -> Pratica di Mare military airport (41.6704°N 12.4504°E)
- LIML (WMO Code: 16080) -> Milano- Linate airport (45.4605°N 9.2602°E)
- LIPI (WMO Code: 16045) -> Rivolto military air base (45.9755°N 13.0488°E)
- LIED (WMO Code: 16546) -> Cagliari- Decimomannu airport (32.2433°E 9.0600°N)
- LICT (WMO Code: 16429) -> Trapani-Brigi airport (37.9140°N 12,4944°E)
- LIBR (WMO Code: 16320) -> Brindisi airport (40.6577°N 17.9516°E)
- Cuneo-Levaldigi (44.5386°N 7.6125°E)
- San Pietro Capofiume (44.6542°N 11.6230°E)
- Cesana-Pariol (44.95°N 6.80°E)

Radiosonde - output



Radiosonde – METAR data

METAR is the international standard code for hourly or half-hourly intervals.
It is a description of the meteorological elements observed at an airport at a specific time.

LIRE 051455Z 26007G15KT 10SM SCT350 OVC420 08/M02 A2999 RMK A02 SLP136 T00781018 P0012=

Data available on:
http://weather.uwyo.edu/upperair/sounding.html
https://www.ready.noaa.gov/READYamet.php

Radiosonde – METAR data

LIRE 051455Z 26007G15KT 10SM SCT350 OVC420 08/M02 A2999 RMK A02 SLP136 T00781018 P0012=

Station identifier

LIRE Station identifier, 4-Letter ICAO identifier

Date&Time

05 Date of observation: indicates it is the 05th day of the month

1455Z Time of observation Zulu (Greenwich time)

To obtain Central Standard Time (CST) subtract 6 hours. 1455Z =8:55AM

Wind

260 Wind direction to the nearest 10 degrees true. VRB is used for variable direction, if 3 knots or less. Calm is encoded as 00000KT.

07 Wind speed (in knots)

G15 Wind gust (in knots)

KT Units (knots)

Radiosonde – METAR data

LIRE 051455Z 26007G15KT 10SM SCT350 OVC420 08/M02 A2999 RMK A02 SLP136 T00781018 P0012=

Visibility

10SM visibility is at least 10 statute miles. Visibility may decrease if the air is hazy, foggy, dusty, or precipitation is falling.

Cloud Abundance & Height

SCT350 there are **scattered clouds** at 35,000 feet. Just add 2 zeros to the end

OVC420 overcast at 42000 ft.

SKC (sky clear)
FEW (few, <1 to 2 oktas)
SCT (scattered, 3 to 4 oktas)
BKN (broken, 5 to <8 oktas)
OVC (overcast, 8 oktas)
VV (sky obscured)

Temperature & Dew Point

08 Temperature in °Celsius.

Observed values with 0.5 degrees are rounded up to the next warmer degree.

M02 dew point temperature in °Celsius. M signifies a negative temperature.

Radiosonde – METAR data

LIRE 051455Z 26007G15KT 10SM SCT350 OVC420 08/M02 A2999 RMK A02 SLP136 T00781018 P0012=

Altimeter Setting

A2999 stands for an **Altimeter setting of 29.92 inches of mercury** (in Hg). Used by pilots and skydivers to help them figure out how high above the ground they are.

Remarks & Precipitation Discriminator

RMK stands for '**remarks**'. It is in every METAR report and separates the standard data from extra data.

A02 means this site has a **precipitation discriminator**. A01 would mean it didn't.

Sea Level Pressure

SLP **Pressure** the barometer would read if it were **at sea level**. It is used in order to compare the pressure at 2 stations with different elevations.

Add either 10 or 9 in front of **136** to get the **sea level pressure**. Add a decimal before the last #.

Radiosonde – METAR data

LIRE 051455Z 26007G15KT 10SM SCT350 OVC420 08/M02 A2999 RMK A02 SLP136 T00781018 P0012=

Altimeter setting

T indicates temperature & dew point group. Temperature and dew point are given in tenth of a degree. Use this if you're going to convert to °F

Temperature & Dew Point

0078 indicates the **temperature** is 7.8 °C

1018 means the **dew point** is –1.8 °C

Amount of precipitation

P indicates **precipitation.** It gives you the precipitation since the last hourly report to the .01"

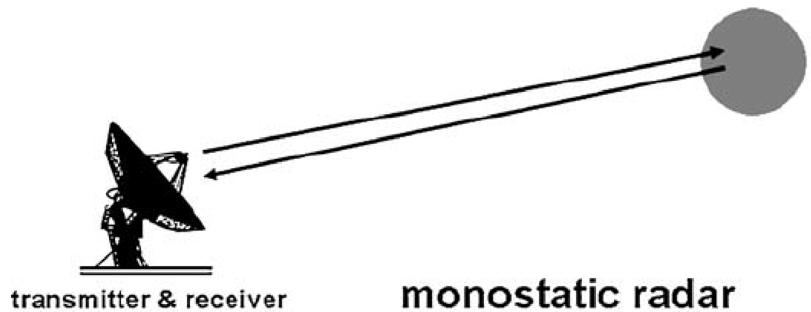
0012 give the **amount of precipitation**. It means 0.12" of precipitation fell in the last hour

= Each METAR file ends with this symbol

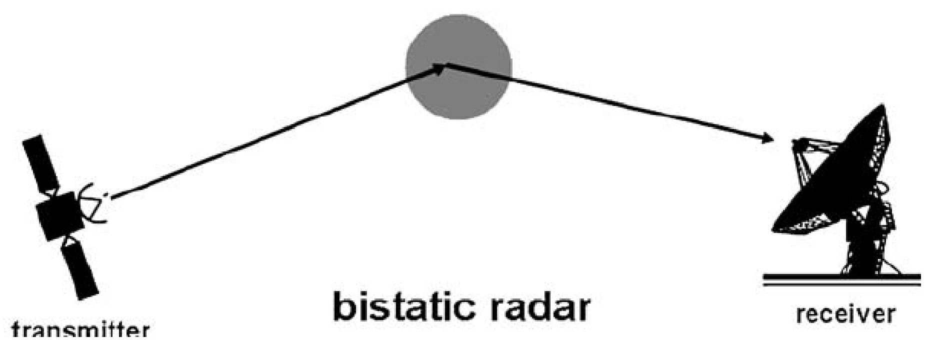
Monostatic and multistatic sensors

Sensors can be also classified in:

- **Monostatic radar**: in which the same antenna can be used to transmit and receive the signal



- **Bistatic (or multistatic) radar**: comprising a transmitter and a (or more than one) receiver separated by a distance comparable to the expected target distance.

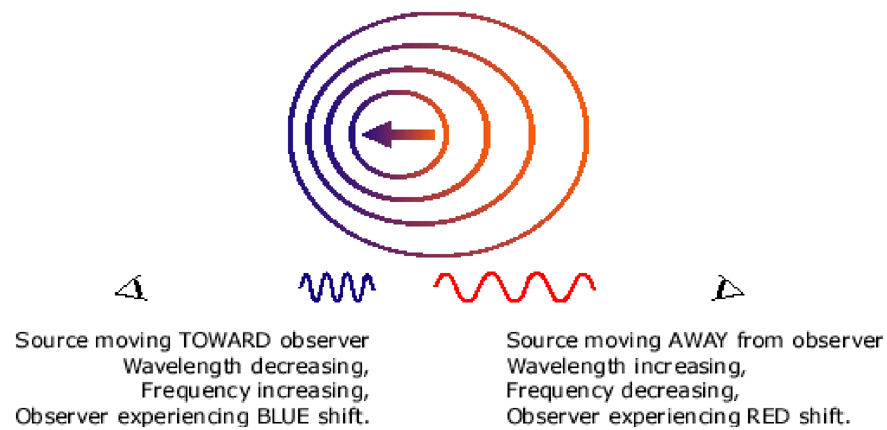


Doppler sensors

A **Doppler radar** is a specialized radar that uses the Doppler effect to produce velocity data about objects at a distance.

It does this by bouncing an acoustic (or microwave) signal off a desired target and analyzing how the object's motion has altered the frequency of the returned signal. This variation gives direct and highly accurate measurements of the radial component of a target's velocity relative to the radar.

This change in the pitch (frequency) of a wave due to motion of the source or observer is called **Doppler Effect**.



$$f_1 - f_0 = f_0\left(1 \pm \frac{v}{c}\right)$$

Relative velocity between source and observer

Sound speed

Acoustic wave propagation in the atmosphere (1)

In atmosphere, the acoustic wave propagation depends on small variation of atmospheric parameters, such as pression P_0 , temperature T, wind velocity and direction U_0 and density ρ_0 .

Hypothesis:
- stationary atmosphere
- no waves
- uniform distribution of temperature and constituents
- wave motion in adiabatic conditions (i.e. negligible viscosity and thermal conductivity)
- negligible gravity

↳ equation of motion relative **only to acoustic waves**, excluding gravity waves

Acoustic wave propagation in the atmosphere (2)

We can write a system with:

- equation of conservation of impulse
- continuity equation
- conservation of energy equation

One can obtain the equation of the acoustic wave:

$$\frac{\partial^2 p}{\partial t^2} = c_0^2 \nabla^2 p$$

$$c_0^2 = \gamma \frac{P_0}{\rho_0}$$

γ is the ratio of specific heats for gases in constant pressure and volume
p is the variation in pressure with respect to a reference value

The solution is the overlap of two spherical waves reads:

$$p = \frac{P}{r} \exp i(\omega t - \kappa \cdot r)$$

$$c_0^2 = \frac{\omega^2}{\kappa^2} \qquad \kappa = \frac{2\pi}{\lambda}$$

P is the maximum amplitude of pressure oscillation

r is the distance from the origin of the spherical wave

Similar solutions are found for wind perturbation (u) and density perturbation (ρ)

Acoustic wave propagation in the atmosphere (3)

The equation of conservation of impulse reads:

$$\rho_0 \frac{\partial u}{\partial t} = -\nabla p$$

by substituting the solutions of the acoustic wave equation to the variables, we obtain:

$$i\omega\rho_0 \boldsymbol{u} = (\boldsymbol{ik} + \frac{1}{r}) p \boldsymbol{\mu}_r$$

$\boldsymbol{\mu}_r$ is radial unit vector

If we consider r sufficiently large, we can write:

$$u = \boldsymbol{k} p/(\omega\rho_0) = p/(c_0\rho_0)\ and\ u/c_0 = p/(\gamma P_0) = \rho/\rho_0$$

- acoustic waves are longitudinal waves
- if the material is isotropic and homogeneous, the direction is isotropic and the propagation speed is independent of the wavelength

Acoustic wave propagation in the atmosphere (4)

As seen, sound speed can be written as

$$c_0 = \sqrt{\gamma \frac{P_0}{\rho_0}} = \sqrt{\frac{\gamma RT}{M}}$$

where $P_0 = RT\rho_0$
R is the universal constant of gases (8.314 J mol^{-1} K^{-1})
T is the temperature
M is the molecular weight of air (28.9644 kg kg^{-1} mol^{-1} for dry air and 28.9644(1-0,38 e/p) kg kg^{-1} mol^{-1} where e is the water vapor pressure)
γ is the ratio of specific heats for gases in constant pressure and volume (1.40 for air)

$$c = 20.05(1-0{,}38\, e/\mathrm{p})^{-1/2} T^{1/2}$$

that can be approximated to

$$c = 20.05(1 - 0{,}38\, \mathrm{e/p}) T^{1/2}$$

If the acoustic wave propagates in the moving air (i.e. if there is wind), the speed of propagation of the acoustic wave for a stationary observer is:

$$c = 20.05(1 - 0{,}38\, \mathrm{e/p}) T^{1/2} + V\cos\phi$$

where $V\cos\phi$ is the wind component normal to the wavefront

Acoustic wave propagation in the atmosphere (5)

In real conditions, the atmosphere is disomogenous and the acoustic refractive index varies, giving rise to diffusion.

Acoustic refractive index → wave velocity → temperature
umidity
wind speed

The diffusion of the acoustic wave in the atmosphere is very high because the refraction index varies by 3 orders of magnitude.

So, an acoustic sensor is particularly useful for the study of the atmosphere but strongly limits its range of action because of the strong attenuation of the acoustic wave.

Acoustic wave propagation in the atmosphere (6)

We can define the **acoustic wave intensity** as the power carried by sound waves per unit area in a direction perpendicular to that area.

I_0 acoustic wave intensity crossing the reference plane perpendicularly

$$I = I_0 e^{-\alpha t}$$

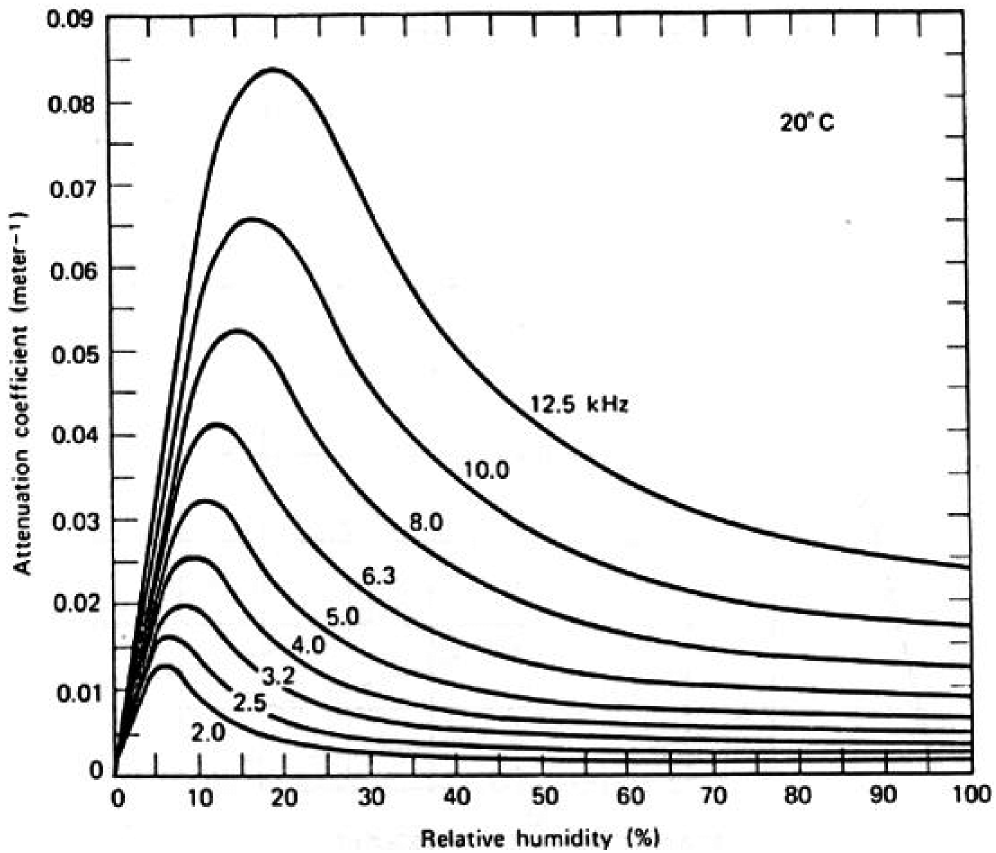
$\alpha[m^{-1}] = \alpha_c + \alpha_d + \alpha_m$= attenuation factor, can be considered as the imaginary part of a complex refractive index

$\alpha_c = 4{,}24 f^2 \cdot 10^{-11}$ ⇨ classical attenuation, due to the viscosity of air heated while the wave is passing through and to the heat conduction between zones subject to different intensity of compression. It is generally negligible in the audible frequencies.

α_d ⇨ attenuation due to diffusion, depends on thermal and mechanical turbulence in atmosphere

Acoustic wave propagation in the atmosphere (7)

α_m ➡ molecular attenuation given to due to the excitation of the vibrational and rotational motions of the gas molecules present in the atmosphere. It strongly depends on the humidity of the air.



At 20 °C, with RH=15% $\alpha_c = 1{,}7 \cdot 10^{-4} m^{-1}$ and $\alpha_m = 6 \cdot 10^{-3} m^{-1}$